

Proceedings/Actes

10th
International Vacuum
Insulation Symposium



10^e
International Vacuum
Insulation Symposium

Vacuum Insulation Panels: Advances in Applications **Panneaux d'isolation sous vide :** Progrès dans les applications

Edited by/Revisé par : Phalguni Mukhopadhyaya

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Foreword

The 10th International Vacuum Insulation Symposium (IVIS-X) – Advances in Applications is being organized and hosted by the National Research Council – Institute for Research in Construction (NRC-IRC) located in Ottawa, Ontario, Canada, 15-16 September 2011. IVIS-X is a continuation in a series of symposiums, which was originally started by the former Vacuum Insulation Association (VIA). The last symposium was held in London, England, UK in 2009. IVIS-X is the first to be held in Canada.

The continuing search for energy efficiency, in every aspect of our life and supporting infrastructure, points to high-performance thermal insulating materials as one way to reduce global energy usage. Recent global trends of imposing/updating strict energy performance codes for buildings and other infrastructures, green rating systems and net-zero initiatives have all created unprecedented professional interests and opportunities for Vacuum Insulation Panels (VIPs). This can be a watershed moment in the history of insulation research, development and application if only the opportunities are utilized, and technologies and experiences are shared across the continents and various professional levels. Simply put, the need of the hour is integration of research knowledge with application requirements.

34 papers will be presented in this symposium and these papers have come from Asia, Europe and North America and focus on diverse issues ranging from materials, systems, applications and performance. More importantly, these papers have been authored by academicians, researchers, engineers, designers, manufacturers and other stakeholders. Hence, in a true sense, IVIS-X is going to be a melting pot for varied experiences, interests, views and visions. It is hoped that at the end this symposium the stakeholders of the VIP industry can truly take the global leadership in an effort to enhance energy efficiency and sustainability in global infrastructure construction.

Finally, as the Chair, and on behalf of the Organizing and Scientific Committees of this symposium, I would like to thank and express my gratitude to all authors, reviewers, sponsors and exhibitors for their timely actions and hard work.



A handwritten signature in black ink, appearing to read 'Phalguni'.

Phalguni Mukhopadhyaya, Ph.D

Ottawa, September/septembre 2011

Chair/Président, IVIS-X 2011

Avant-propos

Le 10^e *International Vacuum Insulation Symposium* (IVIS-X) – Progrès dans les applications est organisé et sera tenu par l'Institut de recherche en construction du CNRC (IRC-CNRC), situé à Ottawa, Ontario, Canada, les 15 et 16 septembre 2011. IVIS-X se veut la suite d'une série de symposiums, lancés par l'ancienne Vacuum Insulation Association (VIA). Le dernier symposium a eu lieu à Londres, Grande-Bretagne, en 2009. C'est la première fois que l'IVIS se tient au Canada.

Les matériaux d'isolation thermique haute performance sont un des moyens de réduire la consommation d'énergie globale, qui ont été mis en avant par la recherche continue sur l'efficacité énergétique dans tous les aspects de notre vie et dans les infrastructures dérivées. Les tendances mondiales récentes visant à imposer ou mettre à jour de rigoureux codes de rendement énergétique pour les bâtiments et autres infrastructures, les systèmes de notation écologique et les initiatives à consommation énergétique nette zéro ont tous créé des opportunités et des intérêts professionnels sans précédent pour les panneaux d'isolation sous vide (PIV). Il peut s'agir d'un tournant dans l'histoire de la recherche, du développement et de l'application de l'isolation si seules les opportunités sont utilisées et si les technologies et les expériences sont partagées parmi les continents et les différents niveaux professionnels. En fait, le besoin actuel est l'intégration des moyens scientifiques aux exigences de l'application.

Lors du symposium, 34 manuscrits provenant de l'Asie, de l'Europe et de l'Amérique du Nord seront présentés; ils traiteront de diverses

questions dont les matériaux, les systèmes, les applications et le rendement. Il faut signaler que ces documents ont été préparés par des académiciens, des chercheurs, des ingénieurs, des concepteurs et d'autres intéressés. Ainsi, le symposium IVIS-X sera véritablement la fusion d'expériences, d'intérêts, de visions et de points de vue variés. Il est à espérer qu'à la fin du symposium les intervenants de l'industrie des PIV pourront vraiment prendre une initiative globale en vue de rehausser l'efficacité énergétique et la durabilité dans la construction de l'infrastructure mondiale.

Enfin, à titre de président et au nom des comités organisateur et scientifique, je tiens à exprimer notre gratitude envers tous les auteurs, lecteurs critiques, commanditaires et exposants pour leurs interventions opportunes et leur travail ardu.

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Langues officielles :

Les renseignements généraux et les services offerts lors de la conférence sont dans les deux langues officielles du Canada : en anglais et en français. Toutefois, dû à la nature internationale de la conférence, le programme scientifique sera offert en anglais seulement.

Technical Session 1

Materials and Measurements

*(Session Chair – Dr. Roland Caps,
va-Q-tec AG, Germany)*

Experimentally Evaluated Barrier Performance of SiO₂ Coated PET Film based Vacuum Insulation Panel (VIP) Envelope

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Abstract

VIP envelope acts as a barrier against air and water vapour transmission to the core. Previous research has revealed that thin metalized films of polymers or metal (aluminium) foils, currently employed in VIP envelopes; significantly reduce their thermal performance by increasing their overall coefficient of thermal conductivity. Clearly, higher conducting metalized or metallic layers in the envelope have the propensity to increase the thermal bridging effect along the VIP edges. To achieve an overall thermal conductivity of lower than 0.008 Wm⁻¹K⁻¹, typical value relevant to the current commercially available VIPs, VIP envelopes consisting of multiple films of PET coated with variants of silicon are being considered as alternative to the conventional aluminium and metalized Polyethylene Terephthalate (PET) films. Experimental investigation into the barrier performance of VIP envelope comprising Silicon dioxide (SiO₂) coated PET films has been undertaken. SiO₂ was coated on PET in varying thicknesses by magnetron sputtering process. Water vapour, oxygen and nitrogen transmission rates of the coated PET films have been measured. The sample coated with 170 nm thick SiO₂ was measured to have a Water Vapour Transmission Rate (WVTR) of 7.86 g m⁻² d⁻¹ and an Oxygen Transmission Rate (OTR) of 0.0373 cm³ m⁻² d⁻¹. In composite configuration, two PET films with 170 nm and 255 nm thick coatings joined together without using any adhesive, yielded a WVTR of 4.36 g m⁻² d⁻¹.

1. Introduction

The transmission of gases (such as oxygen and nitrogen) and water vapours through the envelope of a Vacuum Insulation Panel (VIP) to its core is a technical issue that must be solved if VIPs are to achieve a longer useful service life. The pressure inside the core builds up due to the transmission of gases and water vapours through small pores or defects in the barrier envelope. Currently steel, aluminium foil and metallised polymeric films are used as barrier envelope materials to avoid the rise of internal pressure and the accumulation of moisture in the core material. Due to the presence of these high thermal conductivity metals in

envelope, the thermal bridging effect on edges of VIP becomes dominant and leads to a rise in overall thermal conductivity of the VIP. It is required to use materials with a low thermal conductivity and high barrier properties in VIP envelope to avoid gas transmission. Due to the requirement of long service life of 100 years, envelope of VIP, for building applications, requires the similar properties of high barrier against water vapour and oxygen transmission. Envelope materials are expected to have a WVTR of approximately 0.0001 g m⁻² d⁻¹ and OTR of 0.001 cm³ m⁻² d⁻¹ to yield a useful life time of approximately 30-50 years for building applications [1]. Thin films of variants of Silicon coated on PET films have been used in the field of microelectronics, optics [2] and food packaging [3] to achieve specified barrier properties against water vapour and gas transmission. Silicon coated PET films are strong candidates for VIP envelope due to low thermal conductivity and excellent barrier properties against oxygen and WVTR offered [4]. A comprehensive study to realise a VIP comprising PET substrate based envelope and a hybrid (fumed silica plus an additive material) has been undertaken at the Kingston University. Initially 13 µm thick PET films have been coated with SiO₂. This paper presents the preliminary barrier performance indicators, WVTR, OTR and Nitrogen Transmission Rate (NTR), measured for the VIP envelope.

2. Theoretical Analysis

Oxygen, nitrogen and water vapour are transmitted to the interior of a VIP mainly by diffusion driven by a concentration gradient. The process can be assumed as steady as the concentration of gases on the outer surface and interiors does not vary significantly with time. For example, to achieve a useful life of 50 years the transmission rate of water vapours and oxygen are limited to 0.0001 g m⁻² d⁻¹ and 0.001 cm³ m⁻² d⁻¹ respectively. The general rate equation for diffusion of any gas 'a' across a solid material in direction x can be written as equation (1) [5].

$$\left(\frac{w_a}{A}\right)_x = -D \frac{\partial C_a}{\partial x} \quad (1)$$

where

w_a is the mass flow rate of gas a (kg s^{-1})

A is the area of diffusion (m^2)

D is the diffusion coefficient ($\text{m}^2 \text{s}^{-1}$)

C_a is the mass concentration of gas (kg m^{-3})

Equation (1) can be used to predict the diffusion rate for water vapours as well as assuming it to behave like a gas. For a steady state diffusion process, equation (1) can be solved to calculate the concentration of any gas ' a ' at any location in the direction of flow (across the solid barrier membrane) employing appropriate boundary conditions. If the boundary conditions are $x = 0$, $C_a = C_{a1}$ and $x = l$, $C_a = C_{a2}$ equation (2) is achieved.

$$\frac{w_a}{A} = \frac{D}{l} (C_{a1} - C_{a2}) \quad (2)$$

3. Preparation of SiO₂ Coated PET Barrier Films

The thin film of SiO₂ on polymer substrate such as PET are mainly deposited by three methods namely thermal evaporation (electron beam heating) [6,7], magnetron sputtering [8,9] and Plasma-Enhanced Chemical Vapour Deposition (PECVD) [10,11,12]. Barrier properties of such layers depend upon the method of deposition, thickness of coating and the nature of substrate. PECVD has the advantage of high deposition rate and producing superior adhesion of SiO₂ film with substrate and hence producing the excellent barrier results in terms of WVTR and OTR. The disadvantages of PECVD include the requirement of a high operating temperature and a higher cost of the operation. Magnetron sputtering has the advantage of low deposition temperature and simple operation and can be used to deposit excellent gas barrier films [4]. In this study PET films of 13 μm thickness were coated with SiO₂ using magnetron sputtering system. Magnetron sputtering system consisted of a pair of planar electrodes, the anode where the substrate was placed, and the cathode (target) that is made up of SiO₂ that was used for the thin film deposition onto the PET substrate. The two electrodes were located inside the low pressure vacuum deposition chamber (~ 0.1 Torr). The chamber was filled with the sputtering gas, Argon (Ar). Once negative voltage was applied to the target surface, any existing Ar positive ions started accelerating towards the cathode and after falling on it, a small stream of atoms were ejected from the cathode material. A small portion of them impacted on the PET, leading to the formation of a thin film onto the substrate. PET sheets with three coating thicknesses of 85 nm, 170 nm and 255 nm were prepared.

4. Measurement of Barrier Performance Parameters of Coated PET Sheets

WVTR of the coated PET samples was measured following the procedure set out in BS EN ISO 15106-3:2005. The dry side of the specimen was swept by a flow of dry carrier gas removing all permeated moisture. This moisture leads to the electrolysis of P₂O₅ which is coated on electrodes in the measurement cell and decomposed electrolytically into hydrogen and oxygen by the application of 70 V (D.C.) to the electrodes. The mass of the moisture which permeates through the specimen and decomposed per unit time was calculated from the electrolytic current. OTR of the samples was measured according to the ASTM D3985-05 using helium as a carrier gas. The test specimen was placed in between two chambers with the one having helium and the other oxygen. The oxygen gas permeating through the film into carrier gas generated electrical current at the coulometric detector. OTR was calculated from the amount of generated electrical current. NTR measurement was carried out according to ISO 15105-2. Pure helium was used as the carrier gas and pure nitrogen as the test gas. PET sheets with coating thicknesses of 170 nm and 255 nm were measured over a 50 cm² area. The tests were carried out at 50% relative humidity and temperature of 23 $\pm$ 1 °C.

5. Results and Discussions

The measured barrier performance is shown in Table 1. The sample coated with 170 nm thick SiO₂ have water vapour transmission rate of 7.86 g m⁻² d⁻¹ and clearly the water vapour barrier properties have improved as compared to that of an uncoated PET film (15 g m⁻² d⁻¹ for 12 μm thick PET [13]). However, the single coated PET films did not achieve the WVTR levels required for a VIP to last a useful life of 50 years or more (0.0001 g m⁻² d⁻¹ [1]). It is envisaged that a real life VIP barrier will have a multilayered structure comprising a number of coated PET films glued to each other using a suitable adhesive. Two PET films with coating thicknesses of 170 nm and 255 nm joined together, but without using any adhesive, were tested next. The WVTR reduced drastically to almost half that of the single layer (Table 1). OTR achieved for single film was 0.0373 (cm³ m⁻² d⁻¹) and 0.0310 (cm³ m⁻² d⁻¹) for 170 nm and 255 nm SiO₂ thickness respectively. It is expected that a three layered composite laminate of SiO₂ coated PET sheets will achieve the OTR and NTR value as desired for a VIP envelope.

Table 1: WVTR, OTR and NTR of samples of different thicknesses

Thickness of SiO ₂ coating (nm)	Substrate	WVTR (g m ⁻² d ⁻¹)	OTR (cm ³ m ⁻² d ⁻¹)	NTR (cm ³ m ⁻² d ⁻¹)
170	PET	7.86	0.0373	-
255	PET	8.37	0.0310	0.0053
425 (two film laminate)	PET	4.36	-	-

The barrier performance against permeation of water vapours is expected to improve by using thicker PET films, thicker coatings and adhesives between PET films. Test results were used in equations (2) to calculate the mass concentration inside the VIP core at steady state conditions. For WVTR of 7.86 g m⁻²d⁻¹ the mass concentration of 6.41 × 10⁻⁷ kg m⁻³ was calculated.

6. Conclusions

Progress achieved towards realising a VIP barrier consisting of PET substrate coated with SiO₂ has been reported. PET films (13µm thick) were coated with different coating thicknesses. PET films in stacking configuration yielded least WVTR of 4.36 g m⁻² d⁻¹. A comprehensive study to optimise the thickness of PET substrate, thickness of coating and the number of layers in the VIP barrier to achieve design barrier properties is under progress. Other materials being investigated for VIP barrier are PET substrate coated with Silicon Nitride (SiN_x) with increased thickness of substrate and the use of Polyethylene Nephthahlate (PEN) substrate coated either of SiO₂ or SiN_x to achieve better barrier properties and enhanced useful service life.

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Microporous Silica Based Core Materials for High Performance VIPs

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1. Introduction

In the early 1990s Degussa, Hanau manufactured VIPs for refrigerator applications. These VIPs contained precipitated silica ($\rho \approx 200 \text{ kg/m}^3$), which fared favourably compared to perlite. The envelope consisted of a deep-drawn high-barrier plastic envelope as bottom and a flat Al-lined film (Al-thickness $12 \mu\text{m}$) as top. The VIPs had a thermal conductivity of 0.006 to $0.007 \text{ W/(m}\cdot\text{K)}$ at 1 mbar and a life expectancy of 15 years ($\lambda \leq 0.008 \text{ W/(m}\cdot\text{K)}$). Maximal dimensions were $80 \times 60 \times 2.5 \text{ cm}^3$. The tolerance of the precipitated silica kernel against a moderate pressure increase was already remarkably high [1].

At the same time Owens Corning began to produce fiber-filled VIPs with a kernel density of about 240 g/l . The envelopes consisted of sheet steel. [1]

In the last two decades many lessons have been learned to optimizing the envelope and the VIP core materials. Most efforts were taken to understand the moisture sensitivity of the VIP and to suppress the water penetration through the envelopes. In other projects, the influence of the core materials had been studied and has lead to high performing VIP compositions.

2. Silica Core Composition

It is well understood that silica powder based core materials with small pore sizes already provide lowest thermal gas conductivity at 10 mbar gas pressure while fiber and foam based core materials with larger pores provide excellent insulation properties under lower pressure conditions of 0.01 to 0.1 mbar (Fig. 1).

But the comparison of the performance of different silica as precipitated and fumed silica indicates further optimization potential.

For the use in VIP cores, the silica powders have to be mixed with infrared radiation suppressing opacifiers and other additives that increase the mechanical strengths. Those compounds were

compacted during the evacuation process and during the core block formation to dense blocks. It is obvious that the silica material density and the compressibility of the compound does influence the pore sizes and pores structure in the block significantly.

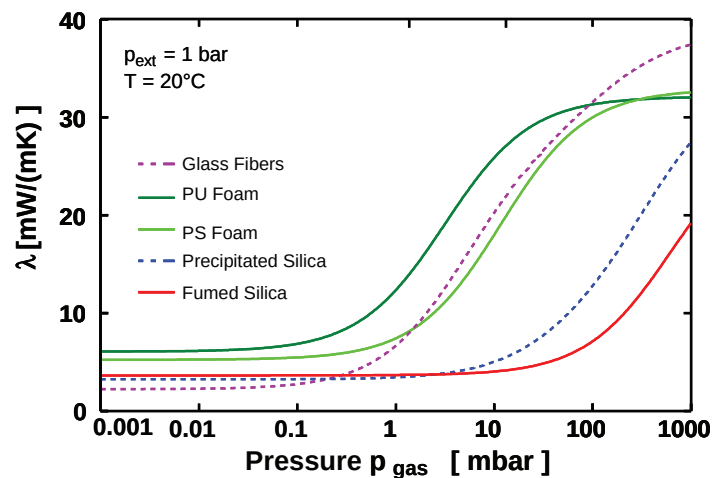


Figure 1: Thermal conductivity of silica powders, fibers, and foams as a function of gas (air) pressure according to [2]

Thus, the overall performance of the VIP will vary with the structure of the silica aggregates and agglomerates. As the density and structure of the opacifier material tend to differ significantly from that of the silica, it may increase the density and compressibility of the core material and thus its solid state thermal conductivity, as well.

Even a low density opacifier such as Carbon Black increases the density of the insulation material by 10 - $20 \text{ wt-\%}$ if added in the same amount (see Figure 2). Coarser material of higher density as TiO_2 or SiC has an even higher density impact.

The opacifier reduces the IR irradiation portion of the thermal conductivity, and the weight increase it does increase the heat conduction simultaneously. Thus, for the most performing core composition, the amount of opacifier has to be adjusted to the application temperature and the required core block strength.

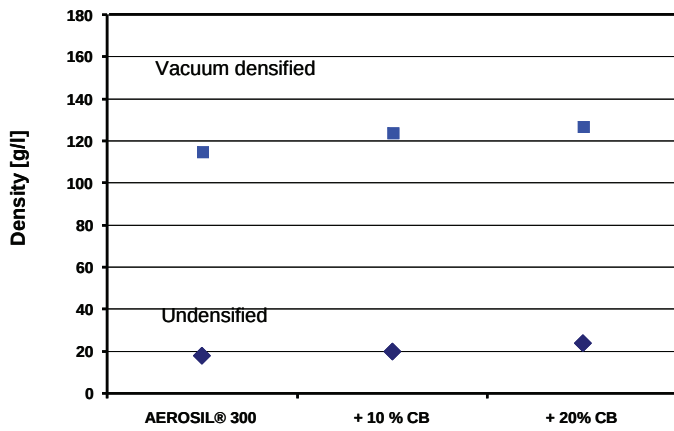


Figure 2: Core composition density of different silica - Carbon Black compositions, densified at 1047 mbar.

3. Silica Core Processing

The silica density will also influence the performance as the material density itself contributes to the thermal conductivity as shown in Figure 3. Higher densities are preferred if the cores have to be handled while processing. Lower densities give much better thermal performance but require other processing techniques.

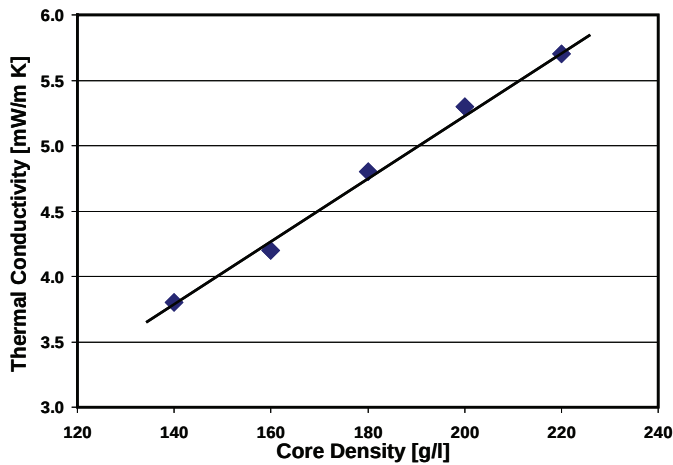


Figure 3: Influence of silica - Carbon Black core density on the thermal performance of the VIP.

As the densification influences the interstitial pore sizes between the silica aggregates one could assume that a higher density reduces the thermal conductivity, but Figure 3 indicates a different mechanism. The pore structure of the compound is less influenced by the pores between the aggregates, but within the aggregates, and these voids will not be changed by the pressures applied to achieve those relatively low densities of state of the art VIP cores.

However, the type of silica and the structure of the silica aggregates itself does also influence the pore sizes as shown in Figure 4. As the BET surface area in fumed silica in a broad range correspond to the primary particle sizes, the voids in between the silica aggregates vary accordingly.

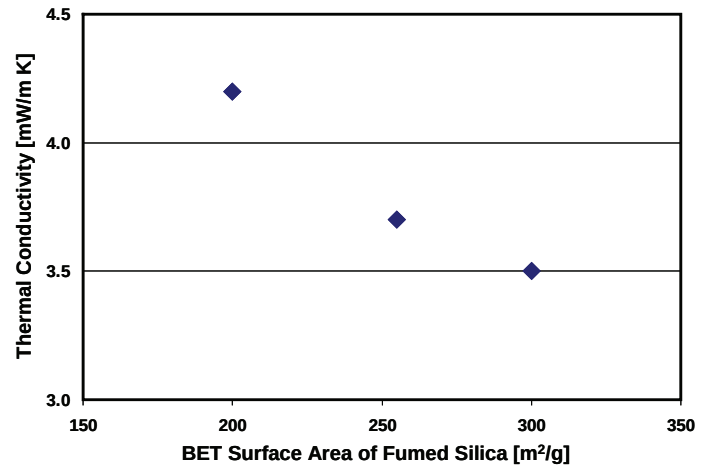


Figure 4: Direct comparison of different silica grades on the thermal VIP performance (Density = 170 g/l; Carbon Black opacifier 20%)

4. Conclusion

The main performance driver for the thermal performance of a silica based VIP is the optimal pore structure according to the theoretical approach. In good agreement with this approach it has been shown that the silica structure and the silica density drive the VIP performance the most.

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Measurements of Thermal Properties of Vacuum Insulation Panels by using Transient Plane Source Sensor

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Abstract

At the construction site only visual, physical and dimension controlling of Vacuum Insulation Panels (VIP) are possible. However, there is a need of fast and accurate determination of the thermal properties of the product. The properties can be measured using a direct measurement method such as the Transient Plane Source (TPS) method. To investigate whether the method could be suitable to measure VIP, the recorded temperature increase and the supplied heat flow by the TPS sensor was used in a numerical analysis. An analytical solution was developed to study the heat propagation in the foil material. In order to simplify the TPS measurements, the VIP was replaced with polystyrene with and without aluminium foil. As expected, there was little consistency between the measurement results of VIP with the TPS method and values for VIP found in the literature. The numerical and analytical analysis, together with the TPS measurements, pinpoints the problems with use of conventional TPS. The presented analysis gives some promising results indicating the feasibility of modification of the method.

1. Introduction

Vacuum Insulation Panels (VIP) consists of two main parts, the porous core material and the encapsulating impermeable foil, maintaining the vacuum in the core. The panels are very prone to damages during manufacture and on the construction site. A perforated panel has a five times higher thermal conductivity than new evacuated ones. During the service life of the panel, the intrusion of gases and moisture into the panel raise the thermal conductivity so that it is around twice the original thermal conductivity after 25 years [1].

Users of building materials need assurance concerning quality and performance of the product in a building e.g. thermal performance. Thus, the thermal properties of a product need to be determined and evaluated. At the construction site only visual, physical and dimension controlling of VIP products are possible, which only can give an indication of the state of the panel. At

the manufacturing facility, the pressure can be measured in a vacuum chamber with the “foil lift-off method”, with the suction cup measurement or with an integrated pressure sensor in the panel [2]. However, these methods rely on the empiric relation between pressure and thermal conductivity which give rise to some uncertainties in the results, why direct measurements of the thermal properties are preferred.

The thermal conductivity, λ (W/m/K), of low conductive materials is commonly measured in a guarded hot plate apparatus [3]. VIP have different thermal properties in the foil and core material, which increases the difficulties in measuring the thermal properties of the assembled material. Transient measurement methods e.g. the Transient Plane Source (TPS), also give the possibility of measuring the thermal diffusivity (m^2/s), of the material. The methods have been developed to speed up the measurement time and thereby lower the cost of the measurement process. This paper aims to explore the propagation of heat in layered thermal insulation materials using transient measurement. Numerical and analytical solutions are compared to results from TPS measurements. The general and specific procedures for measurements of thermal properties by the TPS method are described in ISO 22007-2 [4]. However, a short description of the method is necessary for understanding the measurement results presented in this paper.

2. TPS method

Silas Gustafsson, Chalmers University of Technology, Sweden, first demonstrated the TPS principle in 1979 [5]. The TPS method involves the use of a very thin double metal spiral, 10 μm thick, sandwiched between two layers of Kapton, 25 μm thick, in close contact with the material to be investigated. The double metal spiral serves both as the heat source and as a resistance thermometer. When making measurements in solid bodies, the sensor is clamped between two surfaces of the same material, as shown in Figure 1.

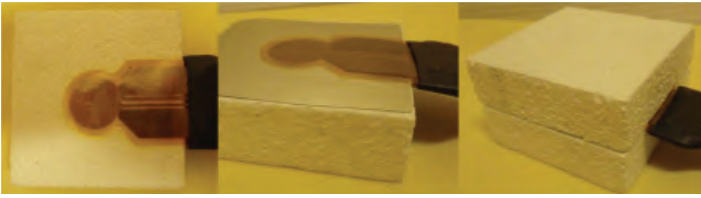


Figure 1. a) TPS sensor on polystyrene, b) TPS sensor on polystyrene covered with aluminium c) TPS sensor clamped between two samples of polystyrene.

Passage of a constant electric power through the spiral develops heat, raising the temperature and thus the resistance of the spiral. The rate of this temperature rise depends on how quickly the heat developed in the spiral is conducted away through the surrounding material. Heating is continued for a period of time, with the voltage across the coil being registered. As the power is held constant, the voltage changes in proportion to changes in the resistance of the coil. With knowledge of the voltage variation with time i.e. variation of temperature with time and the heat flow, it is possible to calculate the thermal conductivity and specific heat capacity of the material.

3. Thermal properties of VIP

The principle of the TPS method is not suitable for measurement of thermal conductivity of the VIP. However, as long as the applied heat flow and the temperature increase can be measured, it is possible to analyze the measurement data by the TPS sensor for determination of thermal conductivity of the VIP products.

3.1 Measurement of VIP with the TPS method

The thermal conductivity of a VIP was determined by the TPS method with the associated mathematical model. The power output, measuring time and sensors radius were 0.02 W, 1280 s and 6.4 mm, respectively. The result of the measurement is presented in Table 1. The presented results are related to different choice of time windows.

Table 1. The measured thermal conductivity of the VIP.

Measuring Time s	Thermal conductivity W/m/K	Thermal diffusivity mm ² /s
32-160	0.0268	0.1477
32-320	0.0269	0.1388
32-640*	0.0271	0.1244
32-960*	0.0272	0.1138
32-1280*	0.0274	0.1055

* The time window did not fulfil the requirements related to the mathematical model associated with the method

The predicted thermal conductivity in the literature is about 4-8 mW/m/K [1]. The measured thermal conductivity by the TPS method was three to six times higher than the predicted value. This deviation was expected. The TPS sensor was in contact with the protection layer of the VIP which has a high thermal conductivity in comparison to the core of the VIP.

3.2 Using TPS sensor compared to numerical simulation

It is assumed that the deviation in the results from the TPS measurement of the VIP depends on the influence of the protection layer. Thus, new measurements with new setups were conducted. The basic idea was to use the measurement results: temperature increase and heat flow, for further numerical analysis to determine the influence of the protection layer of the VIP. In order to simplify the measurements, the VIP was replaced with polystyrene.

In the first measurement, thermal properties of the polystyrene specimens were determined by TPS method. Furthermore, the measurement setup was simulated by heat transfer software HEAT3, using the measured thermal properties of the polystyrene as input data. The numerical software uses finite differences to solve three-dimensional transient heat conduction [6]. Finally, the recorded temperature increase by TPS sensor was compared to the calculated temperature increase by HEAT3.

The power output and measuring time was 0.02 W and 40 s respectively, i.e. the totally emitted heat flow was 0.8 J. In the numerical model, the power needs to be lowered to take the heat capacity of the Kapton layer surrounding the sensor into account. The TPS measurement of polystyrene gave the thermal conductivity and volumetric heat capacity of 0.032 W/m/K and 0.051 MJ/m³/K respectively. This data corresponds well with measurements of the thermal conductivity of expanded polystyrene found in the literature and from reference measurements in guarded hot plate at SP Technical Research Institute of Sweden. This data was used in the three-dimensional fine grid numerical simulation and analytical solution. The comparison between the measured and calculated temperature increase is presented in Figure 3.

3.3 Influence of the protection layer

In order to investigate the influence of the protection layer a new setup was used. The setups involved specimens of polystyrene covered once by pure aluminium foil and once by the protection layer of the VIP, see Figure 2. The thermal properties of the protection layer were not known, thus by using pure aluminium foil with known properties, the influence of the protection layer could be studied.

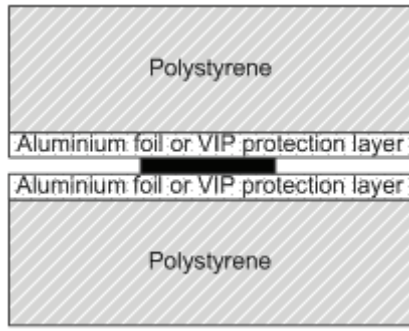


Figure 2. The setups for determination of the protection layer's influence.

The measured thickness of the aluminium foil and protection layer of the VIP were 0.01 mm and 0.1 mm respectively. The average dimensions of the polystyrene were about 70x70x20 mm (length, width and thickness) and the average weight of the specimens was 2.9 g which gives a density of 28.7 kg/m³. The thermal conductivity and heat capacity of aluminium, used in the numerical model are 226 W/m/K and 2.48 MJ/m³/K.

The temperature increase measured by the TPS sensor and the numerical simulations of the setups with only polystyrene and polystyrene covered with aluminium foil and are shown in Figure 3. For comparison, the result from TPS measurement of polystyrene covered with a VIP protection layer is also shown in Figure 3.

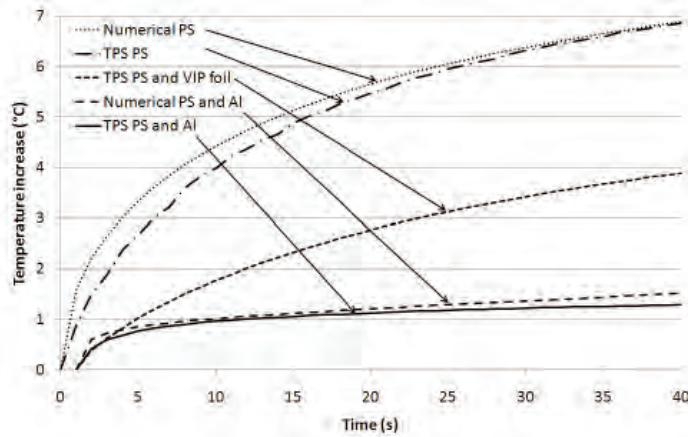


Figure 3. The recorded temperature increase by TPS sensor and the calculated temperature increase by HEAT3. Comparisons for only polystyrene (PS) and polystyrene covered with pure aluminium (PS and Al) or VIP protection layer (PS and VIP foil).

As expected, the temperature increase was much lower when the polystyrene was covered by aluminium. A comparison between measured and calculated values showed good agreement. The measurement results for the polystyrene covered with the VIP protection layer showed that the heat was transferred slower in this foil compared to the pure aluminium foil.

4. Analytical Solution

The measurements on aluminium foil and polystyrene indicated that a large part of the heat is transported away from the sensor area through the highly conductive foil. In order to study the temperature process in the foil, an analytical solution for the case of an infinite long hollow cylinder with infinite outer radius, with heat injected at the inner radius, was analyzed. This corresponds to the case with a foil surrounded by highly insulating materials on both sides, i.e. approximately the case with negligible heat flowing from the foil to the surroundings.

From [7] we can deduce the following analytical temperature solution:

$$T = \frac{Q}{d\lambda} f\left(\frac{\sqrt{a}}{r_0}, \frac{r}{r_0}\right) \quad f(\alpha, \beta) = -\frac{1}{\pi^2} \int_0^\infty \left(1 - e^{-s^2 \alpha^2}\right) \frac{J_0(s\beta)Y_1(s) - Y_0(s\beta)J_1(s)}{s^2(J_1^2(s) + Y_1^2(s))} ds \quad (1)$$

Here, Q (W) is the heat injected at the inner radius, r_0 (m). The thickness of the foil is denoted by d (m). The thermal diffusivity is denoted by a (m²/s) and the thermal conductivity is λ (W/m/K). The formula is expressed by an integral containing the Bessel function of the first and second kind.

The formula will give the maximum propagation of heat into the foil, neglecting the heat loss into the surrounding thermal insulation. Figure 4 shows the function f for different distance, r/r_0 , from the interior of the cylinder where the heat is released and different times $\sqrt{at}/r_0$.

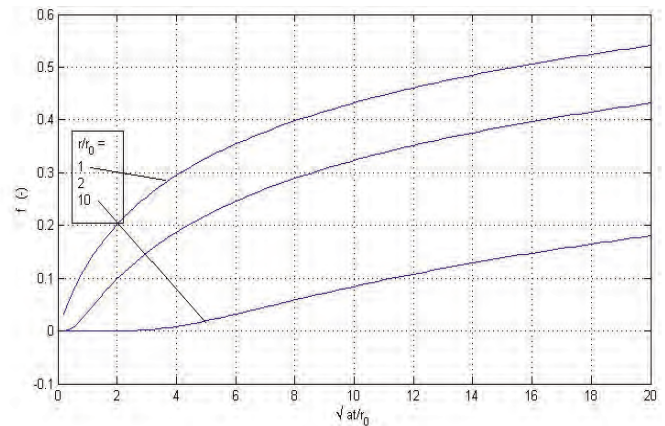


Figure 4. The function f for different distance, ($r/r_0=1, 2, 10$) from the interior of the cylinder where the heat is released and different times $\sqrt{at}/r_0$

Using the data for a single layer of aluminium foil with the thickness 0.01 mm, a released heat of 0.02 W at the radius 3 mm, we have at the periphery of the sensor area after 40 seconds:

$$E = 2 \frac{2A\lambda_{PS}}{\sqrt{a_{PS}\pi}} \Delta T \sqrt{t} = 2 \frac{2 \cdot 0.07 \cdot 0.07 \cdot 0.032}{\sqrt{0.032/900/28.7 \cdot \pi}} \Delta T \sqrt{40} = 2.0 \cdot \Delta T \quad (2)$$

The value for f becomes 0.42 and T becomes 1.9. This is approximately a 48% to high temperature compared with the measurements results. Figure 5 shows the temperature distribution and how it progress at different dimensionless times.

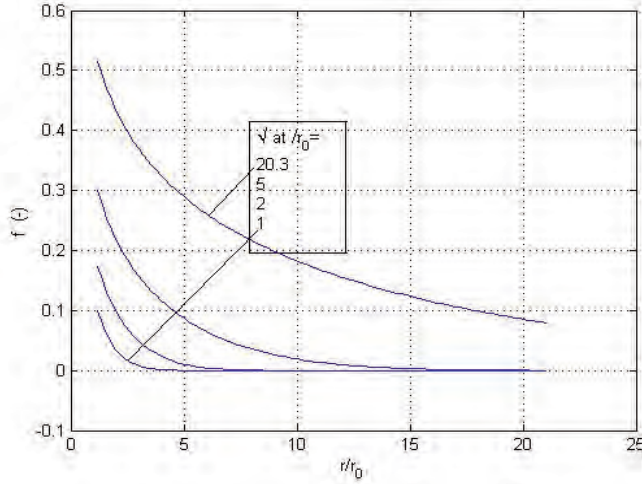


Figure 5. Temperature distribution at different dimensionless times ($\sqrt{at}/r_0 = 1, 2, 5, 20.3$).

In order to estimate the heat uptake by the polystyrene insulation materials on both sides of the foil, due to a step change in the temperature of ΔT , a simple one dimensional step-change approximation can be used [7].

$$\bar{Q} = \frac{2.0 \cdot \Delta T}{40} = 0.05 \cdot \Delta T \approx 0.05 \cdot 4.43 \cdot \bar{f} \approx 0.05 \cdot 4.43 \cdot 0.2 = 0.044 \text{ W} \quad (3)$$

This corresponds to an average power during the 40 seconds of:

$$E = 2 \frac{2A\lambda_{PS}}{\sqrt{a_{PS}\pi}} \Delta T \sqrt{t} = 2 \frac{2 \cdot 0.07 \cdot 0.07 \cdot 0.032}{\sqrt{0.032/900/28.7 \cdot \pi}} \Delta T \sqrt{40} = 2.0 \cdot \Delta T \quad (4)$$

Here, $\bar{f}$ is the average value between r/r_0 , equal to 6.4/3 and 70/3, i.e. between the sensor perimeter and the perimeter of the insulation layer, for the time $\sqrt{at}/r_0 = 20.3$ (corresponding to 40 seconds). The heat flow is around 2 times higher than the total heat released into the foil. It means that in a more detailed analysis, also taking into account the interaction between the insulation layer and the foil, the spread of heat through the foil out from the sensor area and into the insulation is substantial. It leads to a lower temperature increase in the area below the sensor i.e. the analysis will give a lower temperature, more in line with the measurements. This effect will be less dominant when using VIP protection layer instead of aluminium foil. However, when measuring on a VIP the thermal conductivity below the foil will be much lower, which once again make the heat flow out into the foil more of an dominant effect.

5. Conclusion and Discussion

TPS measurements and numerical simulations of the temperature increase in polystyrene samples with and without aluminium foil were conducted. The measurements and numerical simulations were in good agreement. An analytical solution was conducted which showed less agreement with the measurements and needs further refinement.

The current mathematical model used by the TPS method did not give accurate values for VIP. Therefore, the algorithm used to interpret the temperature increase of the sensor needs to be modified. It should take into account the thermal properties and thickness of the protection layer. The thermal analysis presented in this paper gives promising results indicating the feasibility of this type of modification. Further investigations are ongoing to e.g. find the relations between the heat flow in the foil and the temperature increase by time in the core material.

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Wireless Integrated Pressure Sensor for Quality Control of Vacuum Insulation Panel

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1. Abstract

The pressure inside a vacuum insulation panel (VIP) is an important indicator for thermal insulation properties. The sensor transponder described in this paper fulfils the function of contact less measurement of pressure and temperature through covering layers and presents the best opportunity of quality assurance. The sensor transponder is placed inside the VIP and consists of a fully integrated microelectronic circuit and an antenna, both mounted on a printed circuit board. Measurements are taken with a mobile reader unit.

2. Introduction

For the purpose of thermal insulation of e.g. building, container or cooling devices vacuum insulation panels are a good choice in comparison to cut-to-fit materials such as polystyrene with respect to the thickness of the panel and insulation effect. A typical panel consists of an almost gas-tight enclosure and a rigid core with submicron pore size from which the air has been evacuated [1]. However, the insulation quality of the panel depends strongly on the quality of the vacuum and as the thin enclosure is prone to mechanical damage a quality control during production of the panel as well as before and after installation is crucial. An analysis of pilot projects in application of VIPs in construction over the last five years shows that nearly all appearing damages of VIPs can be traced back to uncaredful treatment in transportation and installation of VIPs [2]. So it is strongly recommended to have a test procedure at the end of the installation. An exchange of a panel before applying the covering layer is much less expensive and much more efficient than afterwards. Thermal measurement principles like heat-flow measurement or infrared pictures are not appropriate due to practical aspects. Furthermore a long term monitoring of the intra-panel gas pressure as an indicator for the insulation effect is

also desirable. The following chapters describe the development and application of a miniaturized integrated pressure sensor operating as a transponder for wireless measurement of the intra-panel pressure as a solution for the above mentioned necessary improvements [1].

3. System Components

3.1 Transponder System

The combination of sensors and transponders – the so called sensor transponders – finds more and more interest in many applications [3,4] like automotive (tire pressure monitoring), logistics (cool chain monitoring) and newly in construction industry [6]. The transponder system for the monitoring of vacuum insulation panels consists of a mobile reader unit and the VIP-built-in sensor transponders. Figure 1 shows the handling while taking current pressure and temperature values. A measurement is initiated by the reader unit, while the RF field of the reader activates the sensor. The sensor electronics takes the measurement from the integrated sensors and transmits a data packet to the reader unit. The reader displays the sensor values and additional information like the unique identification number of the sensor transponder and a time stamp. For later documentation and analysis all data is stored on a memory card.



Fig. 1 Readout of the inside pressure and temperature of a VIP

The activation of the sensor transponder takes place by inductive coupling. The principle of inductive coupling for energy and data transfer is illustrated in figure 2. As a built-in device the sensor transponder consists of an integrated capacitive pressure sensor chip and an antenna coil including some discrete electronic components for the transmission of power and data. The on-chip electronics contains an RF interface for the wireless communication. A magnetic field with a frequency of 133 kHz is generated by an external antenna coil that is connected to a handheld reader. The radiated field transfers power to the second antenna coil of the sensor transponder located inside the VIP by inductive coupling. The induced voltage is rectified and is used to supply the microelectronic circuit. Apart from the power, the transponder extracts its clock from the frequency of the magnetic field. The digitized sensor values are coded together with the identification number, status information of the sensor transponder and check sum to a data packet to be transmitted. For this transmission the method of absorption modulation is used, which is frequently used in transponder systems [4]. The field damping of absorption modulation is evaluated by the reader. If the check sum of the transferred data is valid, pressure value processing will be continued.

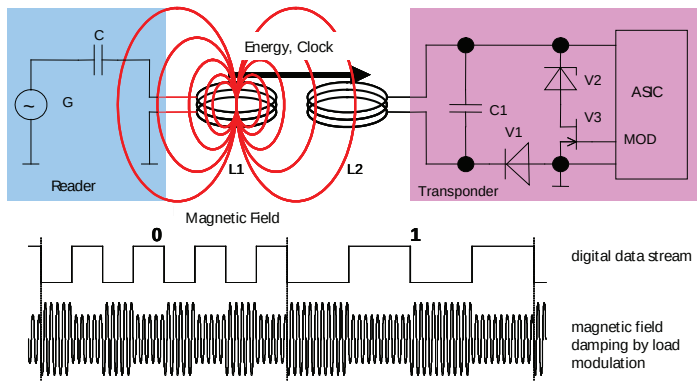


Fig. 2 Principle of inductive coupling for energy transfer. Field damping is additionally applied for data transfer.

3.2 Embedding of Sensor Transponders in VIP

For the direct measurement of pressure and temperature inside the panel the sensor has to be placed inside the enclosure. The actual size of the sensor transponder is about four millimeters in thickness and about 25 millimeters in diameter. So it is advised to form a cavity of this size into the VIPs core board and to insert the sensor transponder in this place. This establishes a fixed mounting position and avoids shifting during handling and evacuation process.

Figure 3 shows the principle of embedding the sensor transponder inside the panel: The left photograph shows a cutted core board with an inserted transponder, while on the middle photograph

the surface of an evacuated panel is seen. In this configuration a reading range of up to 50 centimeters is possible, depending on reader parameters. The drawing on the right side of figure 3 shows a cross section of an embedded sensor transponder. For reliable behaviour the sensor chip is encapsulated in a stable housing. This keeps mechanical stress away from the encapsulation such as forces from foil and core as well as bending effects. In future versions the thickness of the sensor transponder will be reduced to about two millimeters.

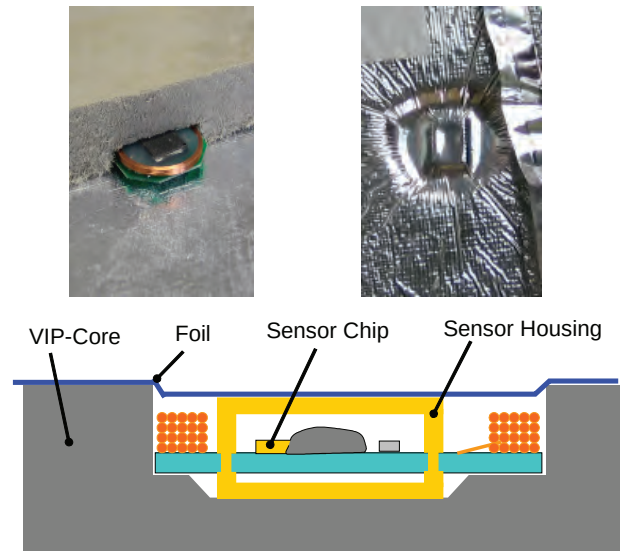


Fig. 3 Embedded sensor transponder in VIP

The transmission of energy and data has to take place through the layers of the enclosure foil. This foil typically consists of several layers with one or more aluminum layers for a better impermeability. Usually the thickness of the aluminum layer is far below one micrometer and therefore it has a low impact of transmission properties. Using foils with relatively thick aluminum layers of several micrometers shows an attenuation of the electromagnetic field and a mistuning of antennas. The result is a limited reading range or even impossible readout.

3.3 Microelectronic Circuit with Surface Micromachined Pressure Sensor

Micromachined capacitive pressure sensor is a mature technology that is well-known [5]. Thin diaphragms which deflect under pressure are appropriate basic structures for the detection hereof. A deflected plate shows specific stress and strain states proportional to the deflection and hence proportional to the pressure. For strain based sensors the distance change between the deflected plate and another fixed plate can be used to detect a change in the capacitance, provided both plates are conducting, as illustrated in figure 4. Known for its ideal elastic behavior silicon is an excellent material for the creation of a diaphragm.

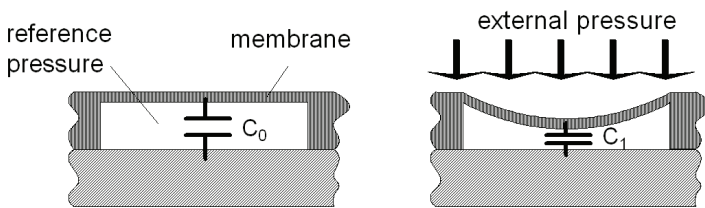


Fig. 4 Principle of a capacitive pressure transducer

A simple way to fabricate a micro plate capacitor is to apply surface micromachining. Figure 5 shows SEM images (scanning electron microscope) of a fabricated pressure sensor array. The basic steps of the process flow used for the fabrication of the device are as follows: The bottom electrode is an implanted n+-area in a p-type silicon wafer. With the p+-implantation a pn-junction is formed for electrical isolation of the n+-electrode from the substrate. A dielectric layer is deposited to electrically isolate the bottom electrode from the later formed top plate. The pattern of the spacer oxide and channel oxide defines the cavity between the two electrodes. Now the pressure sensitive polysilicon diaphragm as the top electrode is deposited and patterned leaving the etch channel accessible to the hydrofluoric acid. The etchant removes selectively the oxide resulting in a cavity which then is sealed under vacuum condition, resulting in an absolute pressure sensor cell. After metallization and passivation the passivation layer is locally removed from the polysilicon diaphragm of the pressure sensitive elements.

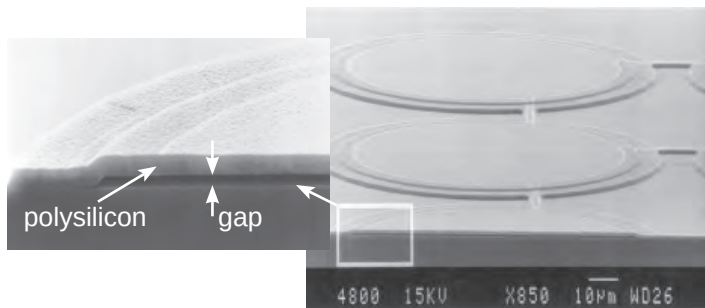


Fig. 5 Micro plate capacitor for pressure sensing

The pressure range is design controlled by adjusting the diameter of the sensor diaphragm, keeping the thickness to be fixed. This allows the fabrication of various sensors for low (0.1 bar to 0.5 bar e.g. for VIPs with pyrogenic silica) up to high (350 bar max.) pressure ranges on a same wafer or even on a same device. For low and atmospheric pressure the diaphragm diameter is about 100 µm. A close up view of a sensor cell reveals the extreme aspect ratio of the diaphragm diameter and the cavity height considering that the diameter is in the range of some tens up to a hundred micrometer. The small cavity height (< 1 µm) limits the deflection of the diaphragm automatically, once the top plate touches the bulky bottom substrate.

In order to readout the small capacitance of the pressure sensor cell only very small current is needed to charge or discharge the capacitor. Combining this with CMOS circuits allows the realization of low power consuming systems.

Since the surface micromachining technique is a planar technology similar to a CMOS process the pressure sensor process module can be integrated. A co-integration of pressure sensor and CMOS process has been implemented. A high voltage option and EEPROMs are also available. Figure 6 shows an example of a tiny integrated pressure sensor chip.

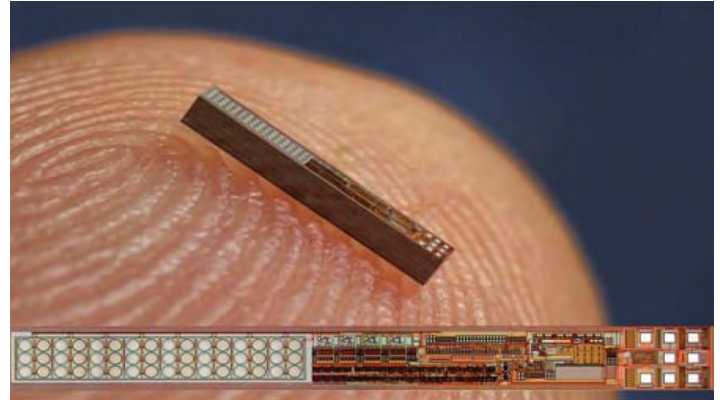


Fig. 6 Integrated pressure sensor chip on finger tip

3.4 Calibration

From the production process the sensors have a spreading in raw values as well as a non-linear behaviour in pressure and temperature. However, a precise measurement is possible using an appropriate calibration and correction algorithm. After readout of the sensors specific equations have to be computed in the reader using the raw values and additional calibration coefficients to get the real values. For the calculation of pressure a 2nd order polynomial and for temperature a 1st order polynomial have to be computed. The coefficients for the polynomials are generated in the calibration process and stored in the memory of the sensor transponder.

The calibration process is performed after the assembly of the sensor transponders and before the insertion into VIPs. The sensor transponders are placed inside a vacuum chamber where temperature and pressure can be applied controlled by a computer, and the raw data of the sensors is taken for further calculation steps. The calibration process is executed in the following steps:

1. Setting temperature and pressure, wait settling time,
2. Gathering raw data from sensors by wired interface,
3. Repeat step one and two for two temperature points and three pressure points,

4. Calculate calibration coefficients for each sensor according to the “best fit” algorithm,
5. Store calibration coefficients in memory of each sensor and
6. Final inspection of each sensor.

4. Experimental Results

The first step of characterization of the sensor transponders was the measurement of the pressure gradient over the pressure range from near vacuum up to ambient pressure. Figure 7 shows typical curves from the measured „raw” data ZP of the sensor transponders up to 500 mbar. The applied temperature was set to 0 °C, 25 °C and 50 °C. The pressure resolution is 0.1 mbar at a fix temperature which is a very acceptable value. The pressure shift due to temperature variation results in about 1.0 mbar per Kelvin without compensation. The calibration procedure comprises also the temperature compensation so that the expected overall pressure shift due to temperature variation results in about 1.0 mbar per 50 Kelvin. The overall accuracy can be estimated with ± 2.0 mbar within the temperature range of 0 °C to 50 °C.



Fig. 7 Typical pressure characteristics
(Pist: applied pressure, ZP: raw values)

A subsequent test took place using sensor transponders embedded in VIPs. During manufacturing several transponders were assembled in panels with different “starting” pressures. The panels under test were stored in a climatic chamber at 50 °C and 60 % humidity. In irregular intervals the panels were temporarily removed and measurements were taken. The results compared to ambient pressure are shown in figure 8.

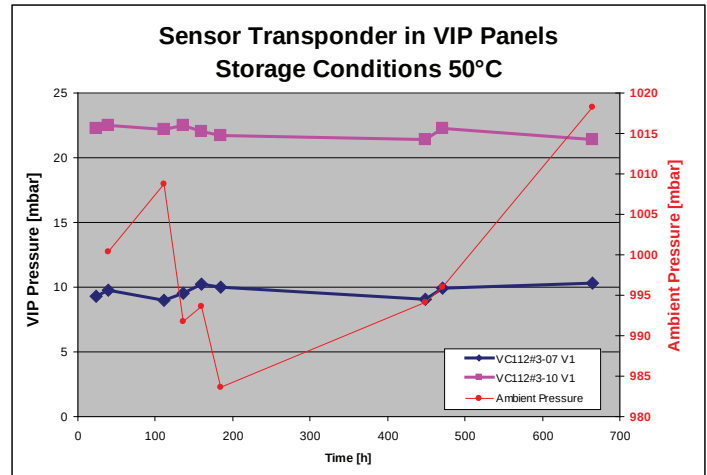


Fig. 8 Long term measurement of embedded sensor transponders

5. Summary and Outlook

Measurement of the absolute pressure inside the panel down to some few mbar with an accuracy (1 sigma) of better than 1 mbar is achieved. The wireless transmission can even be achieved through the gas-tight enclosure including a thin metallic coating. The results demonstrate that the pressure sensor transponders presented here are as tiny as necessary for the integration into a thin vacuum insulation panel. It has also been verified that the power consumption of the system is as low as required for an inductive transmission of power and data without the need to incorporate a battery into the vacuum insulation panel. This wireless monitoring technique of the intra-panel pressure will allow a safe and more reliable use of vacuum insulation panels.

In next steps the long term measurements and environmental tests will be completed, evaluated and documented. These tests are executed in cooperation with partners in research and VIP manufacturers. It is planned to equip buildings with “smart” VIPs, which means VIPs with built-in sensor transponders, in the near future.

In a current research project the use of sensor transponders for the estimation of energy efficiency aspects is evaluated. In this approach sensor transponders are used not only for the monitoring of VIPs, but also in specific places within the building envelope. By measuring temperatures it is possible to determine the heat flow and to derive exact thermal transfer coefficients. This allows a comparison with data from the planning process. Figure 9 shows a screen shot of a kiosk software supporting the calculation of the thermal transfer coefficients in facades.

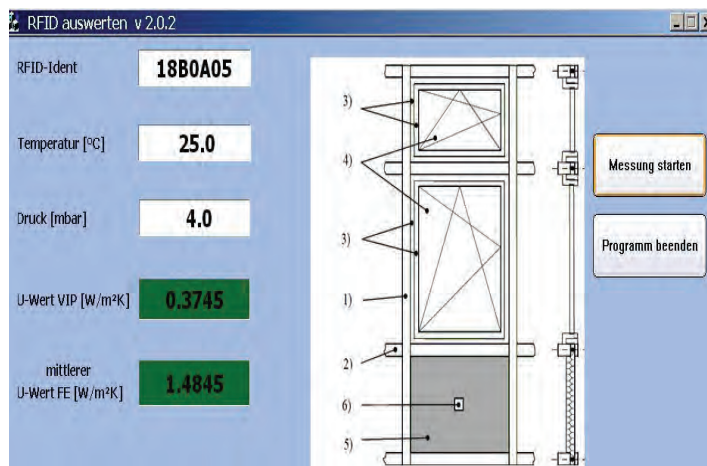


Fig. 9 Outlook: Monitoring with VIP Transponder in facades: Evaluation of characteristics from measurements for the building envelope

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Technical Session 2

Application of VIPs in Construction –I

*(Session Chair – Dr. M. Kumar Kumaran,
NRC-IRC, Canada)*

Experimental and Numerical Investigations of Polystyrene Encapsulated Vacuum Insulation Panels - Heat Transfer Results

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Abstract

As the energy consumption in buildings is gaining ever more focus, the building regulation requirements are becoming stricter with respect to energy efficiency. Thus, high performance thermal insulation materials and solutions such as vacuum insulation panels (VIP) with thermal conductivities as low as 4 mW/(mK) may be applied to obtain a satisfactory high thermal resistance with an acceptable building envelope thickness. However, the fragility of the barrier foil, risk for puncturing and nonadaptability at the building site with respect to physical dimensions, may hamper VIP-applications.

To improve the building site adaptability and robustness, encapsulated or protected VIPs may gain more interest, where some examples are already available on the market. These VIPs have a thermal insulation layer of e.g. expanded polystyrene (EPS) around the VIP, where part of the EPS layer may be cut away for final adjustments at the building site. A disadvantage of such EPS protected VIPs is the reduced thermal resistance at the edges, as EPS has much higher thermal conductivity than a VIP. Another drawback is that it may be more difficult to immediately see if a VIP has been perforated or not, i.e. loss of vacuum or not, when the VIP is covered by EPS.

In this work, laboratory experiments with EPS covered VIPs have been carried out in a guarded hot box. The EPS covered VIPs consisted of a special twolayer system reducing the overall heat flow as the twolayer system comprised alternating layers

of VIPs and EPS. Experimental heat transfer results have been compared with numerical simulations. Overall, there is good agreement between the experimental and numerical results. The calculations according to the standard ISO 6946 also compare well with experimental and numerical results.

1. Introduction

Global warming and climate crisis increased the focus on how to reduce the CO₂-emissions from buildings. One of the most cost-effective measures to reduce the CO₂-emissions is by adding more thermal insulation to existing buildings as well as in new buildings [1].

Several insulation products may be used to increase the thermal resistance of buildings. New materials and solutions have also reached the market, such as aerogel [2], gas filled panels [3] and vacuum insulation panels (VIPs) [4]. Aerogels and VIPs have the advantage of having a higher thermal resistance per insulation thickness, i.e. a lower conductivity. Thinner building assemblies may therefore be constructed, that have a higher thermal resistance than similar walls with traditional insulation. One of the most used new building insulation materials, VIPs, are however fragile to perforation, and systems have been suggested that may increase their robustness. These may be adapted at the building site, and are also protected by their surrounding material. The heat transfer in such systems is however quite complex as the

difference in thermal conductivity between VIP and surrounding material, makes it three-dimensional.

In this work we examine the thermal performance of an encapsulated vacuum insulation system in detail. Experimental investigations are performed in a hot box and compared with calculations according to the standard ISO 6946 [5] and numerical 2D and 3D simulations.

2. The LockPlate system

The building insulation system examined is the Weber LockPlate system, that applies VIPs embedded in an expanded polystyrene (EPS) envelope. The applied VIP is a Porextherm Vacupor PS-B2-S VIP with standard dimensions 0.4 m x 0.9 m, thickness 0.03 m and thermal conductivity of 0.005 W/(mK)[†] [6]. The EPS used for encapsulating the VIPs has a thermal conductivity of 0.035 W/(mK) [7]. The LockPlate system consists of a special two-layer system of alternating layers of VIPs and EPS using three different boards of EPS covered VIPs: the standard plates (1.0 m x 0.5 m), a half-sized standard plate (0.5 m x 0.5 m) and the LockPlate (0.25 m x 1.0 m). At the edges of each standard and half-sized standard plate there is an EPS 'cutting'-zone of 0.04 m. This allows an adjustment in the plate dimension of maximum 0.08 m.

A base layer of embedded VIPs is formed with standard plates. In our experiments the plates are horizontally arranged. On the top of each standard plate some additional EPS forms a horizontal opening in which a second layer of embedded VIPs is placed, the so-called LockPlates (see Figure 1). The vertical opening created between two Standard plates is filled with a homogenous insulation board. For the experiments, EPS with thermal conductivity of 0.035 W/(mK) is applied as gap filling material. The total system thickness is 0.09 m.

3. Experimental setup

A guarded hot box in accordance with the international standard NS-EN ISO 8990 [8] was used to evaluate the thermal insulation system. A LockPlate test field was placed between a hot and a cold chamber. For a given temperature difference between both chambers, the total amount of heat through the specimen from the hot side to the cold side, ϕ_{sp} was measured.

[†] Thermal conductivity at 1 mbar, measured at 22.5°C mean temperature.

3.1 Description of the Test Field

To perform the experiment, the test field shown in Figure 1 was selected, since it constitutes a representative part of the insulation system. The test field has dimensions 1.0 m x 1.0 m and consists of two standard plates sealed with a LockPlate. EPS boards are used as a homogenous gap filling material. The EPS boards applied on the top and bottom will be a linear thermal bridge that also may be present in a real plate distribution, however, its influence here is larger because of the rather small total size of the test field. The thermal transmittance retrieved from the measurements will therefore be slightly overestimated. A three-dimensional illustration of the test field is shown in Figure 2.

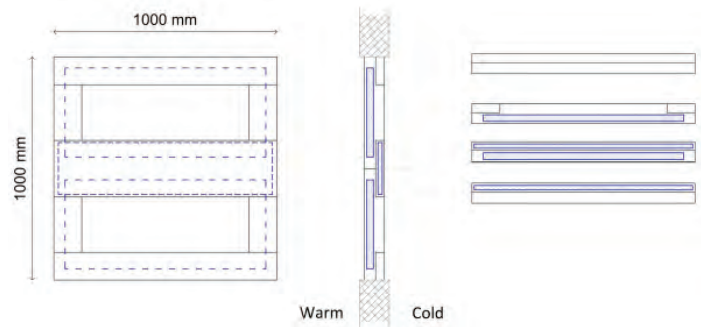


Figure 1. Left: Plane view of test field with VIP contours in dot-line. Middle: Vertical cross-section of the test field, mounted in the frame. Right: Horizontal cross-sections.

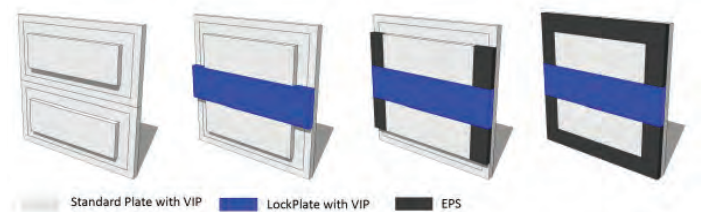


Figure 2. Three-dimensional build-up of the test field.

A hot box template with an aperture area of 1.22 m x 1.22 m was adjusted with additional EPS to meet the dimensions of the test field. After the test field was mounted and placed between the two chambers, the joints between the specimen and the surround panel were sealed with tape on both sides. Then, 17 thermocouples and 6 heat flow meters (HFMs) were taped on the surface.

3.2 Measurement Procedure

The measurements were performed at steady-state state conditions of air and surface temperatures. For each test, the temperature on the hot side, T_h , was set to 20°C, while the temperature on the cold side, T_c , was set to 0°C, i.e. a temperature

difference ΔT of 20°C. In one of the experiments T_c was also set to -20°C in order to estimate the influence of the temperature difference. The measured U-values were standardized for a total surface heat resistance of 0.17 m²K/W. To obtain sufficiently accurate results, each test was performed over a time period of 24 hours. The measured U-value is thus the mean value of 24 hourly measurements.

4. Numerical simulations

4.1 Calculations According to ISO 6946

As a second method, the thermal transmittance of the hot box test field is calculated according to the international standard EN ISO 6946 [5]. The calculation method was also applied with internal and external surface resistances, R_{si} and R_{se} , of 0.13 (m²K)/W and 0.04 (m²K)/W respectively. The U-value was calculated for the three equivalent thermal conductivities of the VIP-element as given in Table 1. The method is only valid when the ratio of upper and lower limit of thermal conductivity does not exceed 1.5, which is the case for our calculations.

4.2 2D and 3D numerical Simulations

Heat transfer simulations were also performed. The hot box test field was simulated in TRISCO [9], a thermal analysis program for steady-state heat conduction transfer in three-dimensions. The simulated U-values can be compared with the measured results, while the graphic output, the heat flux and temperature plots, provide insight in the importance of the thermal bridges. To reduce the calculation time for the U-value simulation, only one quarter of the test field was simulated, which is sufficient due to the symmetry of the test field. The right bottom corner was implemented in TRISCO, as depicted in Figure 3.

In addition, two-dimensional simulations were performed in THERM [10]. Figure 4 shows the cross-section of the LockPlate assembly that was simulated. It is important to note that the thermal resistance in the THERM simulations values is overestimated with regard to the hot box measurements, because the thermal bridges on the sides, caused by the gap filling with EPS, are not included in the two-dimensional simulation. Therefore it is difficult to compare these results with the measured values.

Both simulations were carried out with internal and external surface resistances, R_{si} and R_{se} , 0.13 (m²K)/W and 0.04 (m²K)/W respectively, i.e. a total surface resistance of 0.17 (m²K)/W. To develop a simplified model, the VIP-elements were simulated as

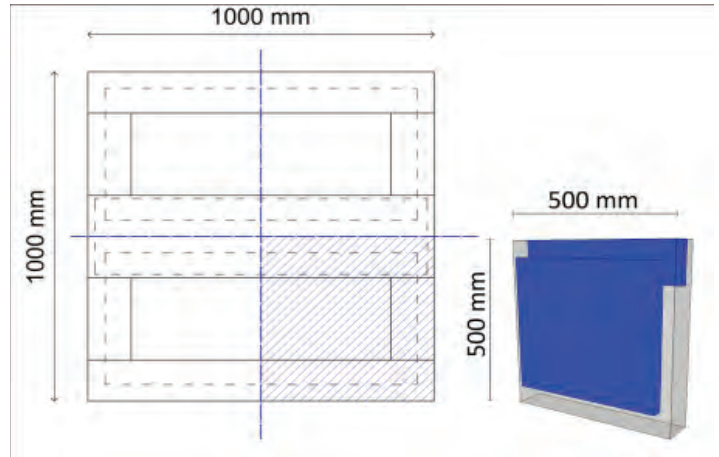


Figure 3. The right bottom quarter of the test field was simulated in TRISCO.

one material layer with an equivalent thermal conductivity, λ_{eq} , rather than simulating both silica core and barrier foil separately. The reason for this simplified approach is the focus of this work on the thermal bridge effect of the EPS surrounding the VIP's, rather than the foil surrounding the porous core of the VIP. More details on the justification of this assumption can be found in Van Den Bergh (2011) [11].

For λ_{eq} , the design thermal conductivity described by Porextherm was applied, i.e. a λ_{eq} of 0.007 W/(mK) [6]. This value is recommended for verification calculations and includes the thermal bridge effect of panel edges with aluminized film and the effect of some ageing, i.e. the raising of internal pressure with time [12]. Secondly, a simulation is performed with a λ_{eq} for punctured VIP-elements. A thermal conductivity for the punctured VIP's of 0.020 W/(mK) is recommended by the manufacturer [6]. The different thermal conductivities for which the simulations were run are summarized in Table 1.

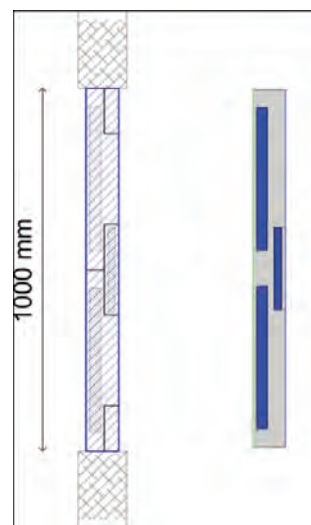


Figure 4. A two-dimensional cross-section of the test field simulated in THERM. The panel edges are implemented as adiabatic boundaries.

Table 1. Thermal conductivities of VIP for numerical simulations and calculations.

$\lambda_{VIP} = 0.007 \text{ W/(mK)}$	$\lambda_{VIP} = 0.020 \text{ W/(mK)}$
Includes thermal bridging due to the barrier foil and the effect of ageing	Punctured VIP's

5. Results

The results are summarized in Table 2. More detailed results can be found in Van Den Bergh (2011) [11]. For the hot box experiments the following test configurations are listed:

- (1) the test field with taped joint between the standard plates on the warm side and a temperature difference ΔT of successively 20°C and 40°C;
- (2) the test field with taped joints on both sides and a temperature difference of 20°C;
- (3) the test field with a taped joint on the warm side, of which all VIP elements were punctured and for a temperature difference of 20°C.

The standard deviation of the measurements is also included in Table 2. The thermal transmittance simulated with respectively

TRISCO and THERM are also listed in Table 2 for different λ_{eq} . In TRISCO, the grid was sufficiently refined to obtain accurate results. The “maximum heat flow divergence for any node” was set to 1 %. Variations in dimensions of the VIP panel[‡] are taken into account by performing the simulation for the largest of the possible dimension variations, and the influence on the simulated U-value are included in Table 2. The “percent error energy norm” in THERM did not exceed 5%, which also implies that the mesh was sufficiently refined to provide reliable U-values. Graphical output from TRISCO and THERM is presented in Figure 5 for a λ_{eq} of 0.007 W/(mK). The error estimation for the analytical calculation according to the standard varied between 1.3 and 11.6%.

6. Discusson

6.1 Hot Box Results

With regard to the hot box results, it should be stressed that the measured U-values are slightly higher compared to a normal LockPlate configuration due to the thermal bridge effect at the top and bottom of the test field.

To study the effect of air infiltration through the LockPlate system on the thermal performance, measurements were performed where the joints between the standard plates were successively

Table 2. Results from the hot box measurements, numerical simulations and calculations.

Measurements		Configuration (1)		Configuration (2)		Configuration (3)	
	ΔT	20.05 °C	39.06 °C	19.91 °C		19.91 °C	
	U	0.210 W/(m²K)	0.188 W/(m²K)	0.213 W/(m²K)	0.333	W/(m²K)	
	s	± 0.008	± 0.003	± 0.004		± 0.005	
Calculations		$\lambda_{VIP} = 0.007 \text{ W/(mK)}$		$\lambda_{VIP} = 0.020 \text{ W/(mK)}$			
TRISCO (3D)	U	0.214 W/(m²K)		0.310 W/(m²K)			
	s	± 0.003		± 0.002			
THERM (2D)	U	0.188 W/(m²K)		0.302 W/(m²K)			
Calculated (ISO 6946)	U	0.219 W/(m²K)		0.310 W/(m²K)			

[‡] Thickness tolerances of ± 1.0 mm are listed for a panel thickness of 20 mm, and + 1.0 and – 2.0 mm are listed for a panel thickness up to 30 mm [6].

un-taped and taped. The measurements aimed at quantifying the effect on the total U-value. However, the configuration without tape produced very variable results. The test field was considered insufficiently airtight to perform reliable hot box measurements and therefore, quantifying the effect of air flow from the data was not possible. Airflow through a construction layer occurs when a pressure difference is present between the two environments separated by this layer. The pressure difference between the two chambers of the hot box was not measured and it is recommended for future measurements to provide additional pressure difference equipment in the hot box. Results are therefore presented where one or both sides of the system joints were taped. It should however be mentioned that when the LockPlate system is applied in a real wall construction, air-circulation can also be prevented by the airtightness of the construction, provided by wind and/or vapor barriers, in which case taping becomes unnecessary.

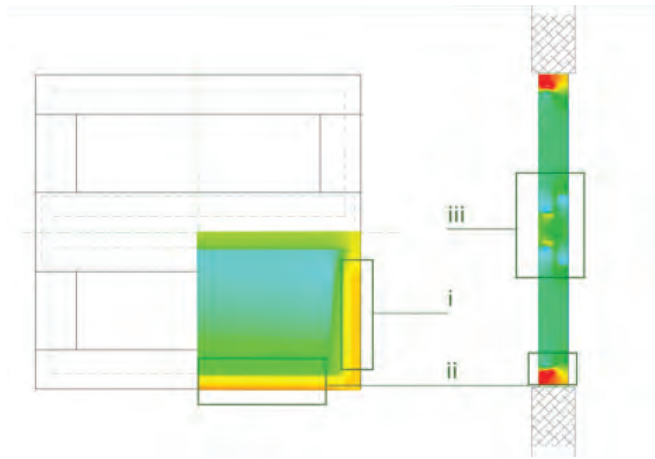


Figure 5. Left: Plane view of the test field with heat flux plot from TRISCO. Right: Cross-section of the test field with heat flux plot from THERM. The thermal bridges are numbered (i) to (iii).

Comparing the U-value where taping is applied on only the warm side to the U-value where both sides are taped, a relative increase of 1.4% in measured U-value is noted. This increase can be considered as statistically insignificant, since the uncertainty intervals for both configurations overlap. With taped joints, the remaining airflow is due to the air flow through the EPS encapsulating the VIP. Further studies could be performed to investigate the effect by providing e.g. a wind barrier on one or both sides of the insulation layer.

A relative decrease in measured U-value of 10.5% is noted for an increasing temperature difference from 20°C to 40°C. This effect could be explained by the decrease in the thermal conductivity of both the EPS and the VIPs. The conversion for temperature dependency of the EPS can be calculated according to ISO 10456 [13]. The change in temperature difference leads to a change in the thermal conductivity of EPS from 0.035 to 0.034 W/(mK). A similar effect may be found for the encapsulated VIP panel. The dependency on temperature of the VIP can be divided in a

dependency of solid thermal conductivity of the core material and the thermal conductivity of air. The latter is not calculated here, in the simplified assumption that the core consists of complete vacuum. The dependency on temperature of the evacuated specimen is proposed as a linear equation (1), which takes into account the effect of solid conductivity and the radiation [14].

$$\lambda_{\text{evac,dry}}(T) = (0.0124 T + 0.0808) \cdot 10^{-3} \quad (1)$$

If the core temperature of the VIP is considered constant over its thickness, equal to the average of the surface temperatures of the VIP, the temperature dependency can be determined using the VIP surface temperatures derived from TRISCO. However, the temperature of the VIP in the LockPlate is dependent on the thermal conductivity of the VIP in the Standard plate and therefore, the temperature dependency of the two VIPs is obtained in two iteration steps. A decrease in $\lambda_{\text{evac,dry}}$ of 3.1 % is found for the VIPs in the Standard plates and 4.9 % for the VIP in the LockPlate. Combining the conversion in thermal conductivity of the EPS and the VIPs, however, only explains part of the measured decrease in U-value with increasing temperature difference.

6.2 Numerical Results

From Table 2 we see that the 3D simulations and the ISO 6946 procedures compare quite well for the geometry studied here. The THERM U-values are, as expected, lower since EPS sections are omitted in these simulations.

6.3 Comparison of Measured and Simulated U-values

The measured U-values of configuration (1) and (2) for a ΔT of 20°C (0.210 W/(m²K) and 0.213 W/(m²K) respectively) correspond quite well with the numerically calculated value in TRISCO for a λ_{eq} of 0.007 W/(mK) (0.214 W/(m²K)).

The puncturing of the panels increases the measured U-value with approximately 60% with respect to the value with intact VIPs. An increase of 45% is noted for the numerically calculated U-value for a λ_{eq} of 0.007 W/(mK)). For this configuration, the measured values do not correspond with the calculated U-values within the uncertainty interval. This could presumably be explained by the dependency of the VIPs on the moisture content of the core. Experiments on this dependency on water content [15] showed a significant increase of heat transfer with increasing water content. The VIPs were punctured from the cold side of the hot box, where a water basin was present to make it possible to reach very low temperatures. By puncturing the panels, the hygroscopic core could gradually absorb moisture, which influences the heat transfer.

7. Conclusions and Further Work

This paper describes experiments and numerical simulations carried out to investigate the thermal performance of an encapsulated vacuum insulation panel system. The results show that 3D simulations and ISO 6946 calculations compare quite well to the experimental hot box results. The results also show that the ISO 6046 procedures are able to estimate the thermal transmittance of the encapsulated VIP system quite well, even though the insulation system is very inhomogeneous and three-dimensional.

Further studies will be carried out to study the thermal bridge effects and the hygrothermal performance of the encapsulated vacuum insulation system, used for adding insulation to existing buildings.

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Heat And Moisture Conditions In Walls With Vacuum Insulation Panels

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Materials and construction of vacuum insulation panel VIP

Keywords: VIP panel, thermal bridge, moisture, condensation risk, refurbishment.

Abstract

Vacuum insulation panels provide unprecedented possibilities for bringing the existing building stock up to date in terms of thermal losses through the building envelope. This study is focused on the implementation of VIP panels in energy retrofit projects with rendered outer walls. Particular emphasis is put on reducing the thermal bridges that may arise due to mechanical fasteners and at the joints of the panels. These have been evaluated using 3D FEM simulations software. Furthermore, the moisture conditions in the construction are studied. The dynamic moisture behaviour of a wall construction has been modelled with one dimensional numerical methods. The long term effects are investigated in terms of accumulated moisture and the risk of condensation. The possibilities of the drying out of surplus water are also discussed. The simulations are based on a possible technical solution for the refurbishment of a building that is typical for the great Swedish building program of the 1970s.

1. Introduction

The transmission losses through the climatic envelope represent about half of the energy used for space heating, and a substantial share of the total energy use in Sweden. A reduction of the heat losses through the walls, floors and roofs of the buildings must therefore be a part of the strive towards reducing the energy use, in benefit of environment and economy. If conventional insulation materials are to be used the result will be a significant increase in the thickness of the climatic envelope. A house in Sweden, that is to meet the passive house standards, for instance, would have to have an insulation thickness of more than 330 mm in the wall in order to meet a U-value of $0.10 \text{ W}\cdot\text{m}^{-2}\text{K}^{-1}$. Consequently, significant living space area may be lost and restrictions are put on architectural possibilities. In terms of refurbishing, there is often

too little space available on the inside of the building and the application of external insulation may threaten the architectural values of the facades and pose problems in terms of detailing.

The unique insulations properties of VIPs may, however, provide new opportunities since only a fraction of the insulation thickness is required.

The application of Vacuum insulation has been limited to a fairly small number of buildings. An account of their use can, for instance, be found in the report of the International Energy Agency [1], Ghazi Wakili et al. [2] and Binz and Steinke [3].

1.2 VIPs and Thermal bridges

The in situ performance of VIP panels depends on the properties of the panels and the manner in which they are applied. The joints at which the panels meet give rise to thermal bridges that increase the heat loss through the building envelope. Analytical models for high barrier laminates around VIPs are to be found in the work of Tenpierik and Cauberg [4] while Thorsell and Källebrink [5] looked at the effects of applying a serpentine edge on a metal panel. Others have investigated the different thermal bridges that arise when VIPs are applied in constructions and building details [6], [2], [7] and [8]. Our previous parametric studies show that the thermal edge loss can be compensated with an adjacent layer of thermal conductivity in the range of traditional insulation materials [9].

1.2 Moisture conditions

Excessive moisture is arguably the greatest single threat to the durability of buildings. The implementation of a new building technology must therefore await a thorough analysis of the moisture performance of the construction, including an evaluation of the risk of condensation and high relative humidity.

* corresponding author

Brunner and Simmler [10] did an in situ performance assessment of VIPs in a flat roof construction, with measurement above and below the panels as well as at the joints. Johansson [11] did an assessment of a timber wall construction from the 1930s, retrofitted with exterior vacuum insulation panels, concluding that the moisture content of the wall is expected to decrease after retrofitting and Sveipe et al. [12] did investigations of improving thermal insulation of timber frame walls by retrofitting with vacuum insulation panels, finding that exterior VIPs may at certain conditions cause condensation in the wall. Buxbaum et al. [13] studied the hygrothermal performance of external masonry walls with inside insulation systems made of VIP sandwich panels.

2. The implementation of VIPs in a retrofit project

Due to its vast capacity, the current building stock in Sweden must be included in the effort to reduce the energy used for heating. The Million Unit Program in Sweden is of special interest. The Million Unit Program is a common name for about one million housing units that were built in a 10 year period around the 1970s, many of which are now in dire need of retrofitting, not at least in terms of thermal insulation. With a high degree of repeatability, it may be argued that the Program has a high potential to gain from thorough studies and development of technical solutions for refurbishment.



FIG 1. Hovsjö, an example of a housing project in the Million Unit Program [14].

The area of Hovsjö, south of Stockholm, is a typical representative of the Program, with 2200 apartments in mostly 3 to 8 storey buildings. With an outer wall construction of light aggregate concrete blocks, the thermal insulation is far below today's requirements.

This study investigates the possibilities of using VIPs for improving the thermal insulation of the wall construction while addressing the issue of thermal bridges at the joints at which the panels meet as well as due to mechanical fasteners. Of particular interest is a solution with an insulation material adjacent to the VIPs on the outside, that may limit the thermal bridges while protecting the panels and providing a carrier for the rendering of the façade.

The aim is to investigate how the heat flux through the construction is affected by the thermal conductivity of the material in the gap where the panels meet and furthermore how the heat flux is influenced by the thermal conductivity of the adjacent insulation and the thermal conductivity of the fasteners. The moisture distribution in the walls is also studied and compared to the saturated vapour content.

2.1 A description of the construction

The retrofit solution, shown in fig. 2, consists of an existing light aggregate concrete wall with an added outer insulation of vacuum insulation panels on top of which there is an insulation layer that serves to protect the VIPs and provides a foundation for the rendering of the wall. The joint at which the panels meet is filled with insulation material. A mechanical fastener, at the corners where the panels meet, keeps the adjacent insulation in place.

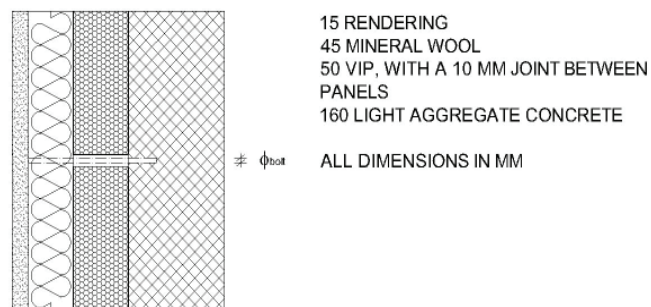


FIG 2. A cross section of the construction.

The thermal and hygric properties of the different materials are shown in table 1. The table shows the default values of the study while we want to investigate the potential gains of altering both dimensions and thermal properties. The thermal calculations have been carried out with one equivalent layer in the envelope with a total thickness equal to the sum of the thicknesses of the aluminium layers in a multilayer foil.

TABLE 1. Material layers, thermal conductivity and water vapour permeability.

	Thickness, mm	Thermal conductivity, W·m ⁻¹ ·K ⁻¹	Water vapour permeability, ·10 ⁶ m ² ·s ⁻¹
Rendering	15	1.0	1
Mineral wool	45	0.04	20
VIP core	50	0.005	20
VIP envelope	0.0003	200	1.1·10 ⁻⁵
Material at the joint of panels	50	0.1	-
Light aggregate concrete	160	0.14	4
Stainless steel bolt	5 mm diameter	20	-

The water vapour permeability is an equivalent value for an arbitrary modelling thickness of 1mm derived from the values of the Water Vapour Transmission Rate presented in the literature [15].

Parameter	Range
Thermal conductivity of bolt	5 - 200 W·m ⁻¹ ·K ⁻¹
Thermal conductivity of joint	0.02 - 0.1 W·m ⁻¹ ·K ⁻¹
Thermal conductivity of adjacent mineral wool	0.02 - 0.04 W·m ⁻¹ ·K ⁻¹

TABLE 2. Parameters and the range of study.

Linear approximations are used to describe the sorption curves of the light aggregate concrete and the fumed silica core. Based on data found in the literature, the light aggregate concrete was estimated to have a moisture content of 37 kg·m⁻³ at 100% relative humidity [16] while the value for the fumed silica of the core is estimated to be 32.4 kg·m⁻³ [15].

2.2 Calculation models

Thermal calculations were carried out with a stationary 3-dimensional FEM model with Comsol Multiphysics®. The thermal model assumes indoor and outdoor temperatures of 20°C and 10°C respectively. The panels have a dimension of 40 by 40 cm while the boundaries are placed at the line of symmetry at the middle of the panels.

The moisture distribution was calculated with a transient one dimensional diffusion model assuming a steady indoor temperature and relative humidity of 20°C and 40% while -10°C and 90% out of doors. The initial vapour content in the different materials was assumed to correspond to that of the exterior, except for the vacuum insulation panel, the initial moisture content of which was assumed to be zero. The simulations were carried out for a period of one year.

3. Results

The following results are to be measured against the performance of a construction with no thermal bridges. For a construction with no thermal bridges other than the edges of the panels the calculated resulting U-value is 0.09 W·m⁻²·K⁻¹. The results are shown below, starting with the diagram of fig. 3 that shows how the thermal conductivity of the fasteners affects the resulting U-value of the wall construction. The red solid line shows that the influence of the bolts is almost negligible in the case of a light aggregate concrete wall, in contrast to the results for a massive concrete wall as illustrated by the blue dotted line. It is also of interest to study the influence of the material of the joint. As shown in fig. 4 the effect of using a joint material with low thermal conductivity has a significant effect on lowering the heat loss through the material. Going from a value of 0.10 W·m⁻¹·K⁻¹ to a value of 0.02 W·m⁻¹·K⁻¹ will give a reduction that amounts to about 30 per cent of the total heat loss.

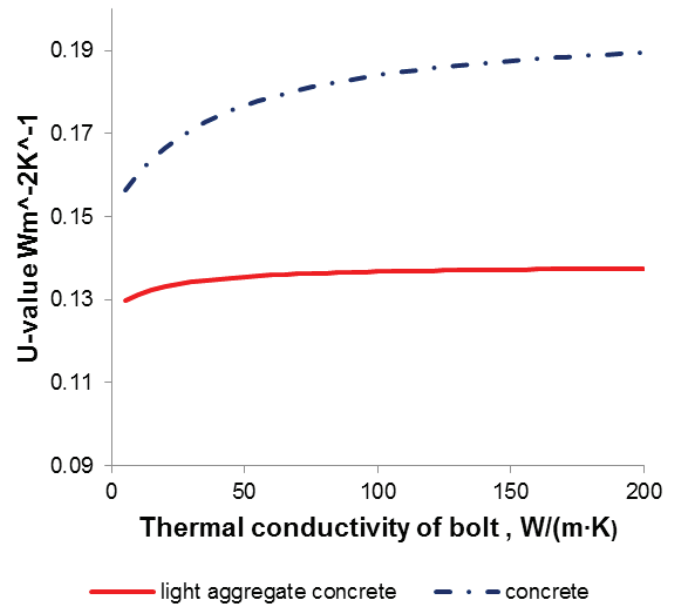


FIG 3. The resulting U-value of the section as a function of the thermal conductivity of the bolt.

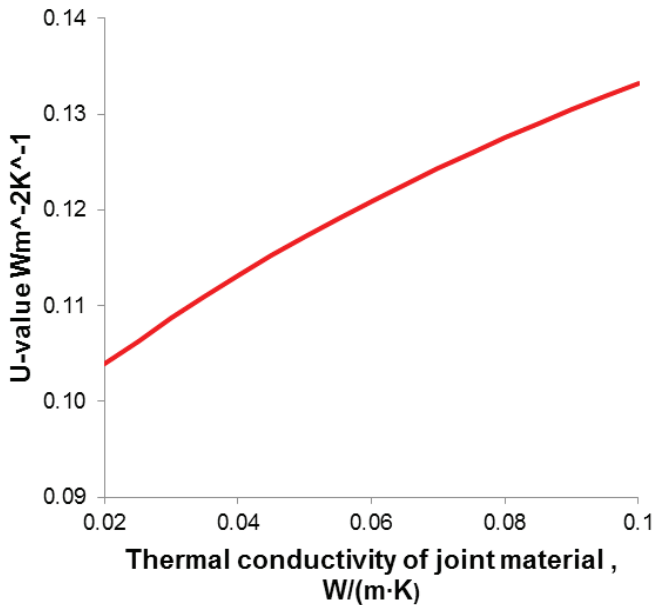


FIG 4. The resulting U-value of the section as a function of the thermal conductivity of the joint material.

The insulation layer on the outside of the VIPs provides protection for the panels and serves as a substrate for the rendering. As shown in fig. 5 the influence of improving the outer insulation layer has a significant effect on the heat flux, although somewhat less than the effect of lowering the thermal conductivity of the joint.

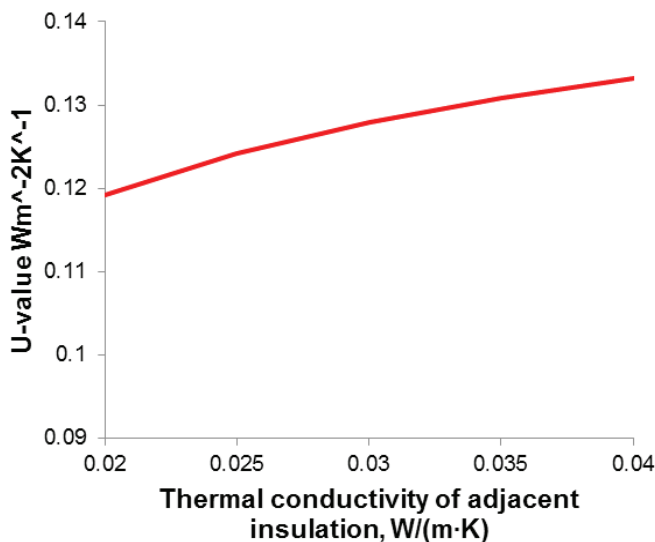


FIG 5. The resulting U-value of the section as a function of the thermal conductivity of the adjacent insulation.

The results of the transient moisture simulation are shown in fig. 6. With a concentration gradient that climbs from zero within the panel towards the ambient on both sides and with a foil that has a moisture resistance of several magnitudes greater than that of the other materials, it is clear that the vapour content of both inside and outside of the panel will reach the vapour content of

the immediate surroundings. The diagram does also show the saturated vapour content that is a function of the temperature. The superior thermal properties of the VIP ensure that the temperature throughout the light aggregate concrete on the inside will be in the vicinity of the indoor temperature and consequently the relative humidity on the inside of the panel will be very close to the relative humidity of the indoor air. By a similar argument it may be concluded that the relative humidity of the on the outside of the panel will be close to the relative humidity of the outdoors. The temperature at the joints on the inside of the panels was also investigated. With a stainless steel bolt the temperature was found to be around 12°C while 15 °C without a bolt at the joint, in both instances well above the dew point for the actual vapour content.

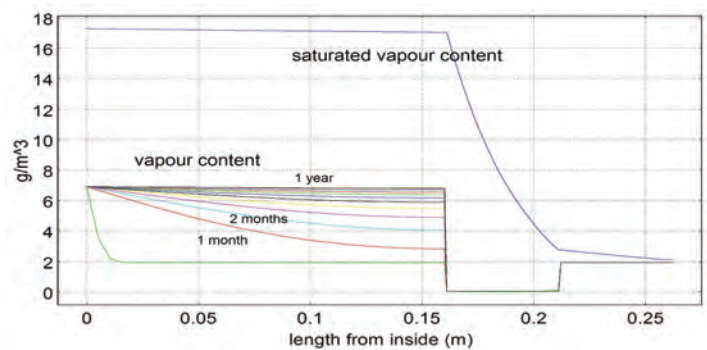


FIG 6. Moisture distribution in the wall construction.

A simulation with an internal VIP gave comparable results, with the layers on the inside and outside of the VIP attaining a vapour content of the indoor and outdoor air, respectively. The light aggregate concrete will in this case be subject to high relative humidity. The main source of excessive moisture will, however, most probably be that of rainwater. The rendering and the light aggregate concrete must therefore be able to withstand high moisture content at sub-zero temperatures. It is also obvious that the moisture resistance of the foil of the VIPs will not allow for any drying out through the panels.

4. Conclusions

This study is concerned with the thermal performance of a refurbished outer wall of light aggregate concrete with exterior vacuum insulation panels. One option of particular interest is that of rendering on an insulation layer on the exterior of the VIPs. The simulations show that, while the VIPs have superior insulation properties, the detailing must be given a careful consideration. Using a material of relatively low thermal conductivity at the joints at which the panels meet has a significant effect on the resulting U-value of the construction. The thermal conductivity

of the adjacent insulation layer has a notable effect on the heat flux, but the choice of material for the fasteners does not have a noteworthy effect on the resulting U-value.

The moisture performance of the construction was evaluated with a transient diffusion model that shows how the materials on both sides of the VIPs will reach the vapour content of the surroundings. A calculation of the relative humidity illustrates that the placement of the vacuum insulation on the outside of the wall does not pose an immediate moisture problem to the construction with the materials. The model does not take into account the penetration of rainwater and leakage through the joints of the panels and further work must take this aspect into consideration.

5. Acknowledgements

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Evaluation on the Energy Performance of the Highly Efficient Material Using Vacuum Technology

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1. Introduction

The developed nations, which have focused on cross-border energy issues caused by the global warming, have promoted the intensive building-energy policies since 1990. European nations, including Germany, are building and supplying the ultra energy-saving houses such as Passive House which makes heating energy reduced by 90% through enhancing the insulation performance of construction structure. In addition, all the nations in EU plan to make mandatory the energy-zero for all the new buildings by 2020.

Now the energy consumed at building sector in Korea accounts for 23% of the total energy and the 54% of that is consumed at residential buildings. With regard to the energy consumption, the government plans to make the reduction of heating/cooling energy compulsory: the low-energy house level of 50% reduction in 2012; the Passive House level of over 90% reduction in 2017; and the zero-energy house level in 2025.

In order to achieve these goals, the development of advanced insulation technology differentiated from the existing insulation system is needed so that windows and walls can be composed of high-insulation materials and the energy loss minimized.

Accordingly, this Study reviewed the technology development situation in terms of vacuum glazed glass and vacuum insulator applying the vacuum technology with excellent insulation performance through blocking heat loss caused by convection, and tried to assess the insulation performance of the vacuum glazed glass and the vacuum insulator under the development in this Institute.

2. Vacuum Technology Overview

2.1 Vacuum glass

The vacuum glass makes vacuum the interval between 2 panels, so it makes minimized the heat loss caused by transfer, convection

and radiation occurring by air or gas inside glass. Accordingly, it has the better insulation performance than general double-layer glass and blocks the dew condensation on glass and cooling draft on window, so it's effective in reducing the heat loss. In case the inside of double-layer glass remains vacuum, there is a big pressure difference between the internal vacuum situation and the external air pressure, so several fine pillars should be installed inside the double-layer glass. In addition, in order to make vacuum the inside of double-layer glass, the edge parts are required to be welded in airtight.

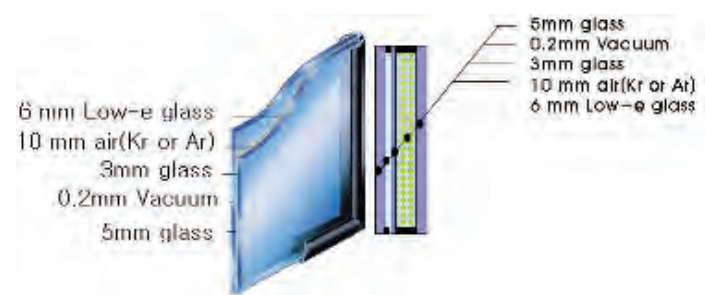


Fig. 1: An example of vacuum glass model

2.2 Vacuum insulation materials

Because the high-efficiency outer-cover structure basically needs the high-insulation materials to minimize heat loss caused by transfer, the insulation materials using vacuum for blocking the transfer heat of outer-cover are actively being developed. The vacuum insulation materials are largely composed of 3 elements: heartwood to keep the form of insulation material; getter to keep the internal vacuum; and outer-cover material to block the gas movement inside/outside insulation materials. Damp proof film composing of polymer film and aluminum foil can be applied to the outer-cover and various materials, including fiberglass, SiO₂ powder, Aerogel, PE foam, PU foam and PS foam, can be applied to the heartwood.

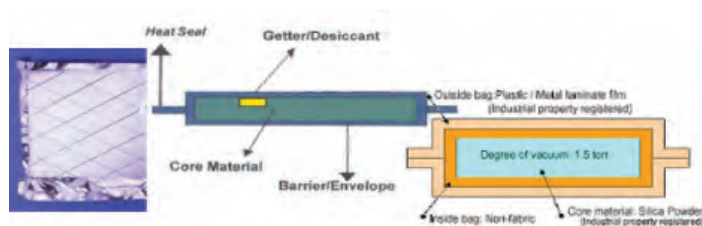


Fig. 2: Vacuum insulation material composition

In addition, in case the vacuum insulation material, which has the excellent insulation performance about 10 times than the existing common-used materials, is applied to buildings, it would be very advantageous in terms of construction-structural space utilization through reducing the volume of building components and very effective to the enhancement of building energy efficiency.

3. Development Status of Technology Using Vacuum Materials

3.1 Home/abroad development status of vacuum glass technology

3.1.1 Abroad development status

Europe presented an EnEV (Energie-Einsparverordnung) regulation to reduce the energy cost of buildings centering on Europe by 30% in order to lower the global warming and CO₂ emissions. Under the effective EnEV regulation, German is required to lower the heat transfer rate of glass at 0.5W/m²K level and to apply the vacuum glass in order to meet the insulation performance standard under the circumstance that it is now using low emissivity glass fully like the below diagram, so ProVIG Project to develop vacuum glass through reflecting the current situation is under the active progress.

Japan has usually applied vacuum single-panels to remodeling market including house, apartment and hospital and exported them to Europe. And China has usually applied them to domestic market including high-class villa and public facilities and to public organizations including China's government. And it has applied the vacuum glass to a curtain wall of 26-storey building for the first time in the world and to Tsinghua University, a representative building in terms of low-energy loss, as well.

TianHeng Building('05)	Tsinghua University ('05)
• Applied to curtain wall (26-storey building) for the first time in the world • Area applying vacuum double-layer (20mm) - Glass Curtain wall: 7,000 m² - The others: 2,500 m² - Production period of 4 months required • Mixed-use of triple glass and double glass	• Model building of low-energy loss (4-storey) • Photovoltaic applied • Mixed-use of triple glass and double glass

Table 1: Case of vacuum glass applied in Asia

3.1.2 Domestic development status

In the nation, recently Korea Institute of Construction Technology and one window-related company developed together the prototype of vacuum glazing glass to keep the internal vacuum level at 10E⁻⁴ or less. In order to develop the slim-type vacuum glass with the heat transfer rate of 0.8W/m²K or less, the air layer is vacuumed at the thickness of 0.25mm and the low-melting lead-free sealing materials with the melting point of 480 °C or less are developed to secure the safety of sealing material quality and to optimize the melting bond conditions. In addition, in order to manufacture the glass at the size of 2,400x1, 800mm, the mass production facilities for large-sized vacuum glass were built and the safety for enhancing the line productivity is under the progress. The development status of domestic vacuum glass is shown at Table 2.

Table 2: Development status of domestic vacuum glass

		'97	'04	'10
Vacuum glass structure	Vacuum layer thickness (mm)	0.2	0.12	0.25
	Pillar interval (mm)	20	28	30
	Pillar number (units/m ²)	2,500	1,250	1,024
The largest product size (mm)		2,400x1,350	2,400x1,200	2,400x1,800
Vacuum glazing glass's heat transfer rate (W/m ² K)		1.4	1.2	0.8
Projected ventilation device height (mm)		5~6	6~7	0.3~0.5
Ventilation pipe		Common glass ventilation pipe used	Common glass ventilation pipe used	Low-melting point glass ventilation pipe used
1) Glass composition : 5mm transparent glass + vacuum + 5mm low-emissivity glass				

3.2 Home/abroad development status of vacuum insulator technology

3.2.1 Abroad development status

It is Germany and Switzerland that started R&D to apply the vacuum insulation materials to buildings internationally. The two nations started R&D with the subject of Annex39 High Performance Thermal Insulation as a part of ECBCS (Energy Conservation in Building & Community Systems) program under International Energy Agency (IEA). Institutes, manufacturers and universities, including ZAE-Bayern and Fraunhofer IVV in Germany, EMPA in Switzerland, NRC in Canada, CSTB in France, TU Delft in Netherlands and Stockholm KTH in Sweden, have participated and developed the possibility to apply them to VIP buildings through analyzing the existing vacuum insulation materials. So, the developed nations, including Germany and Japan, developed the vacuum insulation materials with the heat conductivity below 0.0035W/mK and the durability of 10-30 years and their markets, including building floor, wall and ceiling, are gradually expanded.

Table 3: Status of the application of vacuum insulation materials to buildings

Country	Application status
Germany	Commercialization stage of various construction fields including floor insulation, balcony insulation, wall insulation, inside-insulation panel design and construction and outside-insulation system development
Switzerland	Vacuum insulation materials and aluminum panel used but sandwich panel for construction developed
Netherlands	High-duration vacuum insulation panel for construction developed and applied
United Kingdom	Vacuum insulation material- applied cladding system developed and applied
USA	Active vacuum insulation panel developed and applied

3.2.2 Domestic development status

In this nation, the existing vacuum insulation materials are been manufactured as small-sized products below 0.5 m² and they have been applied to home appliance insulation including refrigerator and freezer. Through building the pilot plants to manufacture the vacuum insulation materials to apply them to construction, recently the various shapes of construction vacuum insulation

module products are being developed. And through applying the vacuum insulation materials to the inside of entrance door or fire door, in addition to applying them to construction wall, the high-performance ultra-insulation doors were also developed.

4. Assessment on Insulation Performance of Technology Using Vacuum Materials

The objective, quantitative insulation performance assessment was tried through a mock-up test on the ultra-insulation doors applying vacuum glazing glass and vacuum insulation materials; a passive technology developed through using vacuum materials as a part of commercialized technology development for saving the building energy.

4.1 Assessment on insulation performance of vacuum glass

4.1.1 Overview on insulation performance assessment

The value of heat transmission rate to represent the insulation performance of windows follows “KS F 2278:2008 Window Insulation Test Method”, so the insulation performance on vacuum glazing glass was evaluated though applying the test method. The performance standard value evaluates the heat transmission rate under the condition of the indoor temperature of 20 °C, the relative humidity of 50% and the ambient temperature of 0 °C.

The test device was sealed with silicon after being installed with glass to heat opening (2,000mm x 2,000mm), the framework attached to test specimen, and after being filled with urethane foam to the interval between the test device-attached framework and the test device. In addition, the test specimen was equally divided into 9 parts for installing the sensor to measure the surface temperature of the specimen and then the temperature was measured through attaching T type thermocouple to the total of central 9 points. Laboratory is composed of two chambers: a low-temperature chamber to realize the outer weather conditions and a constant temperature and humidity chamber to control the indoor environment conditions. A specimen installment scene and a cross-section diagram are follows:

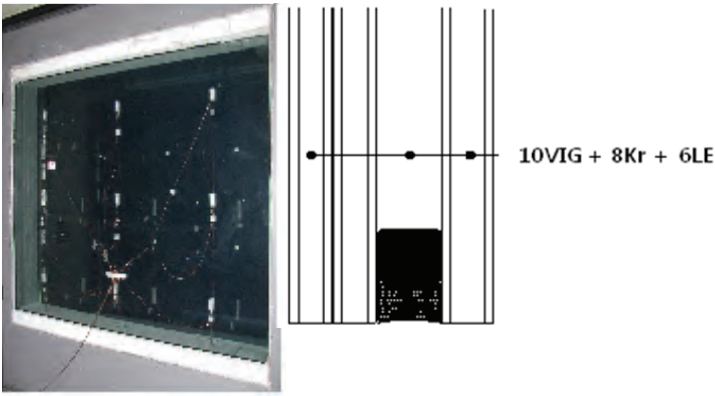


Fig. 5: Test device (10VIG 24mm-vacuum glazing glass) installment and cross-section diagram

4.1.2 Insulation performance assessment and results

According to the test results originated from KS F 2278:2008 'Widow Insulation Test Method' for testing the insulation performance of vacuum glazing glass, the insulation performance of 24mm vacuum glazing glass (10VIG + 8Kr + 6LE) was found to be $0.83 \text{ W}/(\text{m}^2\text{K})$. As a result, given the domestic widow's heat transmission rate standard of $2.1 \text{ W}/(\text{m}^2\text{K})$ level, the insulation performance was found to be very excellent; the significant reduction of heat loss.

Table 4: Test results of 10VIG 24mm vacuum glazing glass

Test item	Unit	Ug value	Specification
Heat transmission rate	$\text{W}/\text{m}^2\text{K}$	0.83	24mm vacuum low-emissivity glazing glass (10mm vacuum glass + 8mm Kr + 6mm low-emissivity glass)



Fig. 6: Infra-red camera measurement photo

4.2 Insulation performance assessment on vacuum insulation materials

4.2.1 Overview on insulation performance assessment of vacuum insulation materials

Both the heat conductivity test and the heat transmission rate test on construction wall applying the vacuum insulation materials were conducted at the same time in order to measure the insulation performance of vacuum insulation materials. The heat conductivity rate of vacuum insulation materials according to "KS L 9016:2005 Heat Conductivity Rate Measurement Method on Thermal Insulator" using a flat-board heat flow meter was measured and a test method was applied according to "KS F 2277:2002 Insulation Performance Measurement Method on Construction Components – Calibrated Hot Box Method and Guarded Hot Box Method", and then the heat transmission rate on the construction wall applying the vacuum insulation materials was measured.

The insulation performance assessment was conducted under the conditions of the indoor temperature of 20°C , the relative humidity of 50% and the ambient temperature of 0°C . The size of test specimen was $1.0\text{m}(\text{H}) \times 1.0\text{m}(\text{W}) \times 0.3\text{m}(\text{D})$ and the surface temperature of the specimen was measured with attaching T type thermocouple to the total of 9 points. The specimen installment scene for assessing the insulation performance, the surface temperature-measured point and the cross-section components of construction wall applying the vacuum insulation materials are shown at the following figure:

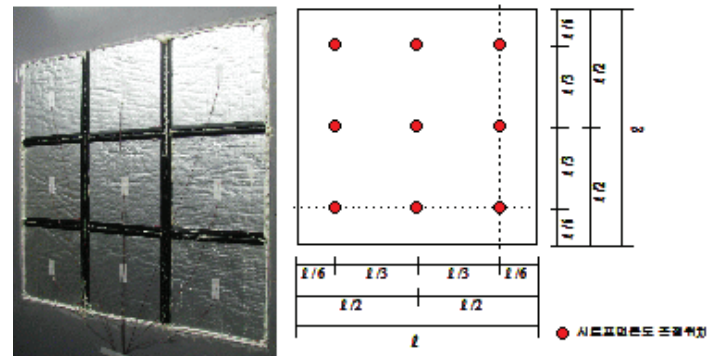


Fig.7: Specimen installment scene and surface temperature-measured points

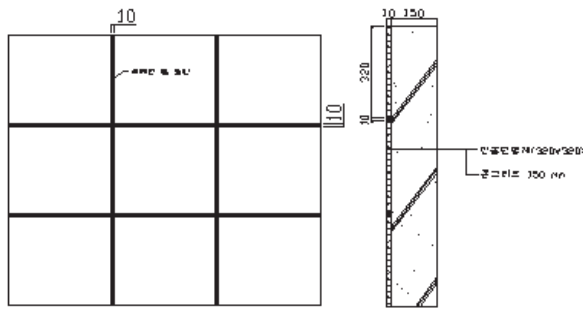


Fig. 8: Cross-section composition of construction wall applying vacuum insulation materials

4.2.2 Results of insulation performance assessment on vacuum insulation materials

According to the test result through 'KS L 9016:2005 Heat Conductivity Rate Measurement Method on Thermal Insulator' in order to measure the heat conductivity of vacuum insulation materials, the heat conductivity rate of vacuum insulation material with the density of 374.5kg/m^3 and the thickness of 8.7mm was found to be 0.005W/mK . And according to the test result of insulation performance of the construction wall applying vacuum insulation material though 'KS F 2277:2002 Insulation Performance Measurement Method on Construction Components – Calibrated Hot Box Method and Guarded Hot Box Method', the insulation performance was found to be $0.90\text{W/m}^2\text{K}$. The performance was found to be enhanced a little compared to the existing domestic insulation material with the heat conductivity of 0.04W/mK level, but it was found to be far behind to the developed nations until now.

Table 5: Assessment result on insulation performance of vacuum insulation materials

Test item	Unit	Value	Specification
Thermal conductivity	W/mK	0.005	Density 374.5kg/m^3 , thickness 8.7mm
Heat transmission rate	$\text{W/m}^2\text{K}$	0.90	Vacuum insulation material 10mm + concrete 150mm

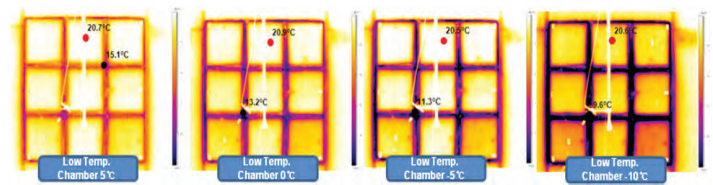


Fig. 9: Indoor surface temperature change through the infrared light heat image measurement on vacuum insulation materials

4.3 Assessment on the insulation performance of ultra-insulation doors applying vacuum insulation materials

The insulation performance was evaluated on the ultra-insulation door applying the vacuum insulation materials in order to expand the application boundary of vacuum insulation materials to buildings. The composition and prototype shape of the ultra-insulation doors applying the vacuum insulation materials are follows:



Fig. 9: Prototype of insulation door applying the vacuum insulation materials

Table 6: Composition of ultra-insulation doors applying the vacuum insulation materials

Section	Composition
Doorframe	Glass wool
Door leaf	Glass wool + ultra-insulation composite insulator (VIP)
Size	Door manufactured at $990\text{mm} \times 2,200\text{mm}$ Doorframe width 120mm

According to the measurement and test result of thermal transmission rate through applying the glass wool and the vacuum insulation materials inside the ultra-insulation door, the thermal transmission rate was measured to be $0.75\text{W}/\text{m}^2\text{K}$.

5. Conclusion

This Study reviewed the technology development situation in terms of vacuum glazing glass and vacuum insulator applying the vacuum technology with excellent insulation performance through blocking heat loss caused by convection, and tried to identify the insulation performance of the double-layer vacuum glass and the vacuum insulator under the development in this Institute.

The results are as follows:

- (1) The thermal transmission rate of vacuum glazing glass was measured to be $0.83\text{W}/\text{m}^2\text{K}$;
- (2) The heat conductivity and thermal transmission rate were measured to be $0.005\text{W}/\text{m}$ and K , $0.90\text{W}/\text{m}^2\text{K}$ respectively; and
- (3) The thermal transmission rate of ultra-insulation door applying vacuum insulation materials was measured to be $0.83\text{W}/\text{m}^2\text{K}$.

The above Study purposed to push up the commercialization period through applying the vacuum glass and vacuum insulation materials to real construction. The vacuum glass is very excellent in terms of heat insulation but very hard to manufacture, so in order to successfully commercialize it, the design of vacuum window should be conducted in combination with economic feasibility and basic frame. In addition, the construction method development and the comprehensive performance assessment to apply the vacuum insulation materials to building in conformity to domestic conditions should be continually performed.

References

- [1] Korea Standards Association (2008). KS F 2278:Method of testing the thermal insulation of windows 2008

Incorporation of Vacuum Insulation Panels in a Wood Frame Net Zero Energy Home

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Introduction

This paper discusses the design, construction and preliminary performance of an exterior wood frame wall assembly that utilizes vacuum insulation panels (VIPs). The home in which this wall assembly is used is referred to as the Harmony House Project. This project is being constructed under the Canada Mortgage and Housing Corporation EQuilibrium Initiative, a national program dedicated to facilitating the construction of net zero energy single and multifamily homes across Canada. Our interest in using VIPs is to produce a durable wall assembly that can achieve a very high level of thermal performance at an acceptable cost while at the same time having the physical dimensions of a conventional wood frame exterior wall assembly. By meeting these criteria this type of assembly could contribute to the acceptance of net zero energy construction by the design and building communities. Habitat Design + Consulting (HD+C) and other members of the design team have designed the wall assembly and modeled its hygrothermal performance. HD+C with the support and guidance of Natural Resources Canada has documented the construction process and have begun monitoring the actual hygrothermal performance of the assembly.

Net Zero Energy Housing

Net zero energy (NZE) houses on an annual basis produce as much energy as they consume. This is typically achieved by significantly reducing heating, cooling, lighting and appliance loads and supplying the energy needs of the building through onsite passive and active renewable energy systems. In order to reduce space heating and cooling loads to a level where onsite renewable energy systems can supply all the energy requirements the building envelope is typically highly insulated and airtight. For low rise residential buildings (3 stories or less) in Canadian climates this requires insulation values in the range of RSI 3.5 (R 20, K 0.284) for basement or crawlspace floor slabs, RSI 5.28 to RSI 7.04 (R 30 to R 40, K 0.189 to K 0.142) for below grade and

above grade walls and RSI 10.57 to RSI 14.09 (R 60 to R 80, K 0.95 to K 0.071) for ceilings. To achieve these insulation levels in walls and ceilings using conventional insulations very thick assemblies in the range of 406mm to 610 mm (16 inches to 24 inches) are required. Using these types of assemblies also leads to the following:

- Reduced total useable interior floor area for a given floor space ratio
- Reduced ground floor area for a given footprint area
- Reduced ceiling heights due to maximum building height regulations
- Additional flashings and other detailing around doors and windows if they are set to the inside face of exterior walls
- Additional mouldings and interior wall finishes if the windows and doors are set to the outside face of the exterior wall
- Additional framing to accommodate thicker insulations
- High costs of construction
- Higher costs per square meter of liveable floor area

One or more of these conditions will impede the adoption of NZE housing and also the construction of what are referred to as net zero ready (NZR) housing. NZR housing is housing that is insulated to the same levels as NZE housing and in which provision has been made for future use of onsite renewable energy systems when the costs of renewable energy systems becomes cost competitive. At the present time a future version of the British Columbia Building Code will be requiring NZR construction by 2020. Similar standards are being called for by 2020 or earlier in the EU and UK and possibly other jurisdictions in North America.

Harmony House Wall Assembly

The above grade wall assembly developed for the Harmony House was designed to meet the following goals:

- A wall no thicker than currently used by the housing industry in Canada. At this time the most common exterior wall system used in Canada and the northern USA is based on 38mm x 140mm (2x6) framing. Builders and sub trades are used to working with this dimension of lumber and windows and doors are manufactured for walls of this thickness. The move from the previous standard for exterior walls of 38mm x 89mm (2x4) framing took about 30 years.
- A composite RSI (R, K) value in the range of 7.04 (40, 0.142)
- A durable wall assembly that will not be affected by moisture accumulation from rain penetration or condensation formation due to exterior or interior moisture
- A wall assembly that will protect the VIP during and after construction
- A very airtight wall assembly
- A wall assembly that will not lead to moisture accumulation in the event of a VIP failure
- A wall assembly that can use off the shelf VIPs

These criteria were addressed by the wall design shown below; the wall is constructed in the following manner:

- The exterior cladding is supported on vertical preservative treated 19mm x 89mm (1x4) strapping which provides a vented rain screen cavity allowing for both drainage and drying by natural convection.
- A layer of commercial grade spun bonded polyolefin building wrap (water resistive barrier) is stapled to the exterior face of the 12.7mm (1/2") thick plywood wall sheathing. This prevents wetting of the wall sheathing while also allowing for drying. In the hygrothermal analysis discussed below moisture accumulation in the north wall sheathing was predicted so all north wall sheathing is treated with a preservative.
- 2x6 studs are spaced at 610mm (24") on centre and framing details used that minimize lumber in the wall assembly such as two stud corner and single top plates.

- a 50mm (2") layer of foil faced isocyanurate foam board is placed behind the exterior plywood wall sheathing, this provides an RSI of 2.1 (R12, K0.47) which in Vancouver's climate ensures in the case of VIP failure that the interior face of the VIP will be kept above the indoor air dew point temperature.
- a 15mm (9/16") thick VIP panel with a insulation value of RSI 6.59 (R 37.4, K 0.152)¹ is then placed with double sided tape on the inside the foam board and sealed to the sides of the studs and to the wall top and bottom plates with urethane foam, this secures the VIP and helps contribute to the wall assembly airtightness. Placing the VIP near the center of the wall cavity depth provides the most protection possible from nails and screws during and after construction.
- the inner layer of insulation consists of a castor bean oil based low density spray foam insulation which both insulates and air seals
- The interior finish consists of 12.7mm (1/2") thick gypsum wall board which is air sealed to the wall framing using low density closed cell foam tape, screws and sealants using a technique called airtight drywall.

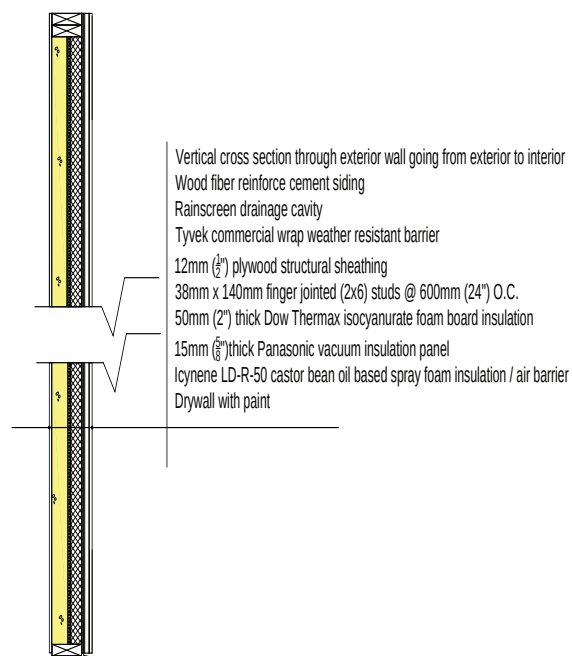


Figure 1: Vertical section through the Harmony House above grade exterior wall assembly

¹Based on test results according to ASTM C 518-04 produced by National Research Council of Canada on an 8mm thick vacuum insulation panel submitted by Panasonic Canada.

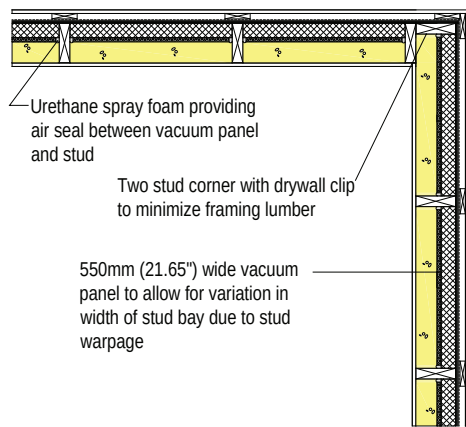


Figure 2: Plan section through the Harmony House above grade exterior wall assembly showing an exterior corner

Hygrothermal Modeling

The hygrothermal performance of the wall was modeled by RDH Building Engineering using both Therm 5.2 and WUFI 4.0. The effective R-value for this wall assembly was assessed using THERM for the materials of the wall assembly from the drywall to the exterior water resistive barrier. The air-space and cladding were not accounted in the thermal assessment since the rainscreen air-space is ventilated to the outdoors. Interior and exterior air-film coefficients are included in the assessment. Material properties were provided by the manufacturers or taken from the THERM material database. Spruce, pine or fir wood studs were assumed to have an average thermal conductivity of $0.14 \text{ W/m}\cdot\text{K}$ ($R\text{-}1.0/\text{inch}$). Because the VIPs are only 550 mm within a 572 mm stud cavity, the remaining 11 mm on each end are filled with closed-cell spray foam 0.041 RSI/mm ($R\text{-}6/\text{inch}$). Figure 3 presents the modeled materials, temperature isotherms, and heat flux isotherms for the typical assembly.

Temperature and heat-flux isotherms show that the majority of heat flow occurs through the wood framing members. As the VIP has the highest thermal resistance, the largest thermal gradient occurs across the panel. The interior surface of the VIP panel would be expected to have a minimum surface temperature of 15.6°C when the exterior temperature is at -7°C , well above normal indoor dew point temperatures of approximately 10°C during the wintertime. The nominal insulation only thermal resistance of the wall assembly is $\text{RSI-}11.07$ ($R\text{-}62.9$) conductivity of $\text{K } 0.09$, however when the studs are accounted for, the effective thermal resistance of the wall assembly is $\text{RSI-}6.78$ ($R\text{-}38.5$) or a conductivity of $\text{K } 0.147$ using ASHRAE design boundary conditions (39°C , 70°F temperature difference). The modeled effective thermal resistance at Vancouver wintertime design

conditions are also similar (28°C , 50°F difference). This thermal resistance value does not take into account additional thermal bridging associated with the extra framing around windows, doors, sill or top-plates.

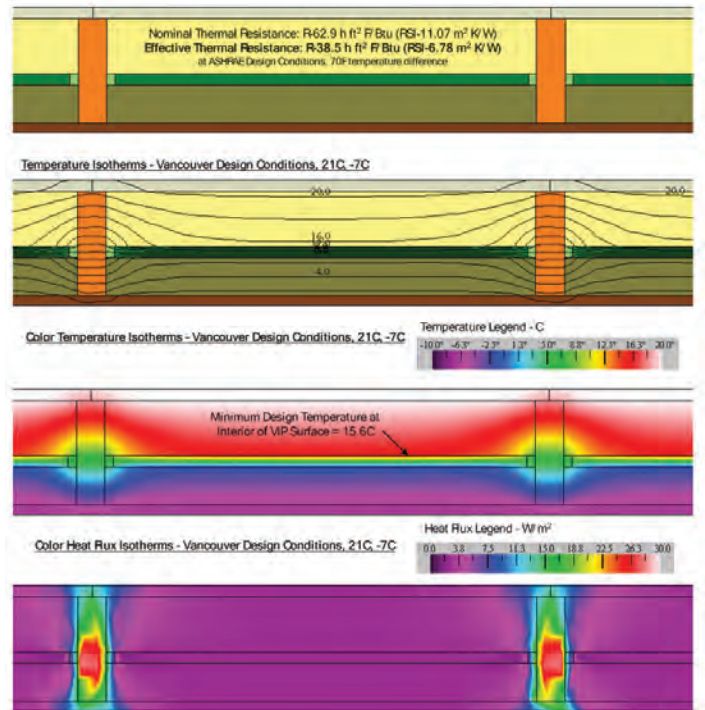


Figure 3 : Temperature isotherms, and heat flux isotherms for the typical assembly

A hygrothermal analysis of the Harmony House wall assembly was performed using WUFI 4.2. WUFI is a one-dimensional hygrothermal analysis program used to simulate the performance of building enclosure assemblies under real climatic loads and interior conditions. The program outputs assist in evaluating the expected long-term durability and appropriateness of a wall assembly built within a specific climate. The purpose of this analysis is to assess the performance of the proposed wall assembly and compare to a typical wall assembly for reference. Vancouver cold- and warm-year climate data for a wall facing each cardinal direction was modeled. The warm-year is representative of a wet warmer winter, while the cold-year is representative of a colder drier winter.

Driving rain was modeled, however has only a small effect on the overall performance of the wall due to the nature of the ventilated cladding. The indoor RH conditions were assumed to vary based on the outdoor conditions. Normal and high indoor RH cases were simulated, representing average wintertime RH levels of 40 and 50% respectively. The indoor RH levels only affect the RH and potential for condensation on the interior surface of the vacuum insulation panel.

To assess the wall assembly, the temperature and RH at the interior surface of the vacuum insulation panel/open-cell spray foam interface and the moisture content of the plywood sheathing is used as indicators of performance. The proposed wall assembly is compared to a typical fiberglass batt insulated wood-frame wall assembly for reference. Two year simulations were performed, with data from a typical year presented in the figures here.

Figure 4 plots the temperature and relative humidity at the interior surface of the impermeable vacuum insulation panel for a worst case cold-year. This is the potential interface within the wall assembly where condensation could occur due to air-leakage or vapour diffusion from the interior. The ratio to the exterior/interior at this interface controls this temperature. If the temperature drops below the indoor dewpoint temperature there is a risk for air-leakage related condensation (i.e. through electrical outlets and other interfaces) or by vapour diffusion.

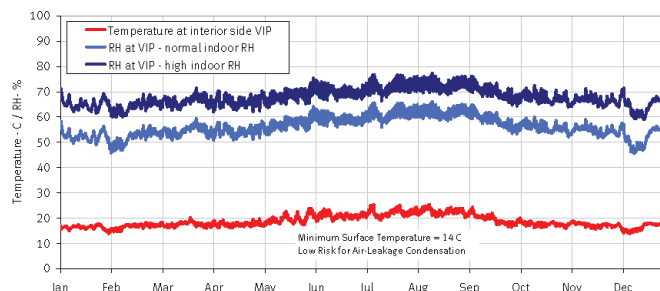


Figure 4: Temperature and relative humidity at the interior surface of the impermeable vacuum insulation panel for a worst case cold-year

As shown, even under the higher indoor RH case, the risk for condensation or moisture accumulation at the VIP/open-cell SPF interface is low, largely due to the high temperature maintained by the inner face of the RSI 6.59 (R-37.4) VIP. Wintertime RH levels at the panel are on average 54% for the low RH case and 66% for the high RH case, both within safe limits. Figure 5 plots the moisture content of the plywood sheathing for a north and south facing wall using the WUFI cold- and warm-year climate files. The plywood moisture content is largely a function of the outdoor RH, cladding moisture content, cavity ventilation rate, and wall orientation.

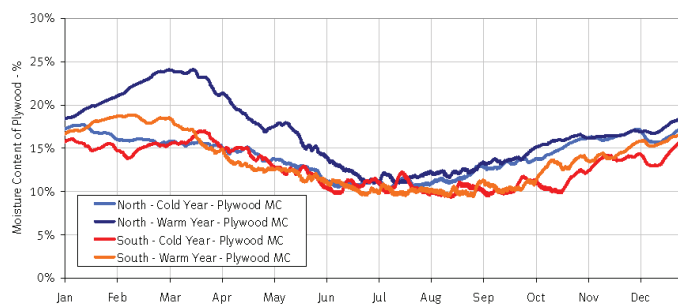


Figure 5: Plywood Sheathing Moisture Content – Harmony House North/South Walls for Warm/Cold Weather Years

The moisture content of the plywood follows typical trends for a wood-frame rainscreen wall in Vancouver. However, because this wall is so well insulated, heat-loss which usually helps dry the sheathing is minimal and wintertime moisture levels do reach 24% for a few months on the north facing walls. While during a colder year (lower outdoor RH), or on a more solar exposed elevation (i.e. south or even east/wet) the wall remain warmer and drier. In all cases, the wall assembly dries to relatively low moisture contents in the spring and summer. The foil-faced polyisocyanurate insulation also prevents drying towards the interior of the stud cavity, which can occur when vapour-open insulation such as fiberglass is used. This finding is consistent with field research on other highly-insulated walls with closed-cell spray foam cavity insulation and minimal interior drying capacity. The behaviour reinforces the importance of ventilation behind the cladding in super-insulated wall assemblies, particularly in Vancouver's climate.

The performance of the proposed super-insulated wall is compared to a wall with nominal R-20 fiberglass batt within the stud cavity. The performance of this typical rainscreen wall assembly has been measured in several field applications and monitored field data has been calibrated to WUFI results with good accuracy.

Figure 5 plots the moisture content of the plywood sheathing within the proposed wall assembly on a north elevation along with a traditional rainscreen wall using the WUFI cold- and warm-year climate files.

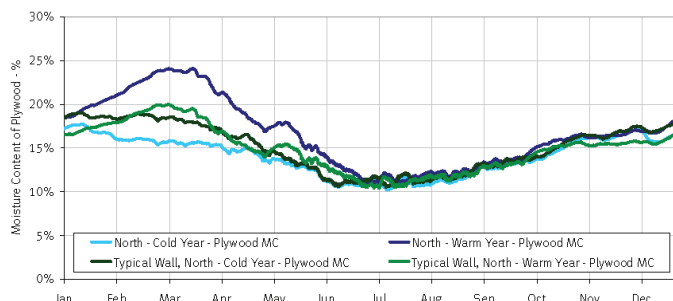


Figure 5: Plywood Sheathing Moisture Content of Harmony House and Traditional Rainscreen Wall Assembly – North Walls, Cold/Warm Weather Years

As shown, the proposed wall assembly performs slightly worse during the warm-wet year than the traditionally insulated stud wall, however this result is expected due to the increased insulation levels and impermeable insulation directly behind the sheathing (reducing inward drying). During the cold year, the proposed Harmony House wall is slightly drier than the traditionally insulated stud wall. On average the proposed assembly is expected to perform similarly to a traditional stud-cavity insulated wall when exposed to the same conditions.

The proposed wall relies on cladding ventilation for drying of the exterior sheathing. Detailing of this ventilation is therefore an important design consideration. In addition, the cement board cladding should be back primed and painted (in addition to factory priming) to reduce water absorption, and all penetrations flashed to the exterior to reduce the amount of moisture within the ventilation cavity.

Construction Sequencing

The 50mm (2") thick foil faced isocyanurate foam board is installed behind the wall sheathing upon completion of framing and installation of the building wrap and a waterproof membrane on the roof. In order to minimize the possibility of damage all electrical, plumbing and heating and ventilation services are installed before the VIPs. All wiring in exterior walls is for electrical receptacles only this allows the wiring to be kept low and makes for easy installation of the VIPs. All light switches, daylight sensors and occupancy sensors in the home are wireless and therefore can be surface mounted later on the finished drywall and therefore do not interfere with the installation of the VIPs.



Figure 6: Harmony House initial exterior wall construction showing VIP in lower portion of wall with foil faced isocyanurate foam board behind.

Monitoring

Monitoring of the hygrothermal performance of the wall will take place over the coming year using wireless sensors that can provide RH, wood moisture content and temperature readings every 5 minutes. The data is transmitted to the manufacturer's web site via an internet gateway. Readings will be taken at the outside face of the plywood sheathing, at the outside face of the VIP, the inside face of the VIP and behind the gypsum wall board. These readings will be taken at mid wall height as well as at the bottom wall plate.

Conclusions

Based on preliminary experience with the construction of this assembly and the modeled performance of the wall it appears it has the following benefits and drawbacks.

Wall Assembly Benefits

- Conventional 38mm x 140mm (2x6) wall thickness
- 610 mm (24") O.C. spacing and other advanced framing techniques reduce lumber content of wall thereby reducing thermal bridging
- Finger jointed studs minimize warpage
- 12mm (1/2") gap maintained between sides of VIP and studs to allow for in inaccuracies in framing and warpage
- VIP protected within wall assembly
- VIP functioning as air barrier and vapour barrier as well as insulation
- If VIP fails enough thermal resistance is outboard to prevent interstitial moisture accumulation in climates in southern Canada.
- Composite insulation value between RSI 6.78 (R 38.5) and RSI 7.4 (R 42) depending on wall height

Wall Assembly Drawbacks

- A rigid 610mm (24") on centre stud spacing must be adhered too
- Window sill heights dictated by VIP dimensions
- Where point loads occur and additional studs or columns are required the VIP may not be able to be included in stud bay
- Thermal bridging occurs through studs reducing the nominal thermal resistance by 39%

Application of VIP: Evaluation of Winter and Summer Energy Performance of External Walls with VIP in Buildings located in Middle Latitudes

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Abstract

This study intends to analyze the potentiality of the use of Vacuum Insulation Panels (VIP) in office buildings located in middle latitudes. Static and dynamic thermal performance of some external walls with VIP, and thermo-dynamic simulations of a virtual test-room (located in 3 different Italian cities), have demonstrated that external walls with VIP (even with a low superficial mass) can determine an annual energy saving: not only in wintertime but also in summertime.

1. Introduction

The application of Vacuum Insulation Panels (VIP) in building envelope systems generally aims at reducing the heat loss in winter, thus saving heating energy. This research intends to demonstrate that an appropriate use of VIP in external walls of buildings located in middle latitudes (e.g. in Italy) effects, in addition to saving energy for heating purposes, even a reduction in energy demand for summer cooling with a good level of indoor thermal comfort.

Conforming to Italian regulations this study analyzes static and dynamic performance of 5 external walls containing VIP. The investigated thermal performance parameters are: U thermal transmittance [$\text{W}/\text{m}^2\text{K}$], M_s superficial mass [kg/m^2], φ time shift [hours], F_a decrement factor [dimensionless] and Y_{mn} periodic thermal transmittance [$\text{W}/\text{m}^2\text{K}$].

In addition to the above mentioned thermal analysis, this research provides thermo-dynamic simulations of the energetic behavior of the 5 selected walls in a virtual test-room localized in different Italian cities. These simulations evaluate the winter and summer energy demand of the test-room, with respect to a good level of winter and summer indoor thermal comfort. The thermal performance of the external walls with VIP has been compared with that of an Italian common massive building envelope, characterized by a high superficial mass.

1. Case Studies: Static and Dynamic Thermal Performance

In order to verify the potential application of external walls with VIP in middle latitudes, where VIP haven't yet been applied, 5 buildings have been selected (4 new and 1 energy retrofit). These selected buildings (Fig.1-5), located in North Europe, show different applications of VIP panels (Tab.1-5).

The parameter values of the wall materials have been taken from the Italian laws UNI 10351:1994 and UNI 6946:2008. The missing values from these standards have been taken from product data sheets. The thermal performance values for each external wall have been calculated according to European law UNI EN ISO 13786 by means of a software [1].



Figure 1: Case study 1: ZAE Bayern's laboratory and experimental building in Würzburg (Germany), 1999. Design by Michael Volz. Image by: Dieter Leistner.

Table 1: Technical data of the external wall type 1.

	s [m]	λ [W/mK]	ρ [kg/m ³]	R [m ² k/W]	C [J/kgK]
h_e				0.040	
toughened safety glass	0.005	1.000	2500	0.005	850
beaverboard	0.015	0.150	660	0.100	2700
EPS	0.003	0.040	30	0.075	1400
VIP	0.020	0.005	200	4.000	930
VIP	0.020	0.005	200	4.000	930
EPS	0.003	0.040	30	0.075	1400
vapor barrier	0.000	0.400	940	0.001	1800
beaverboard	0.015	0.150	660	0.100	2700
h_i				0.130	



Figure 2: Case study 2: Single family house in Neumarkt (Germany), 2004. Design by Martin Forstner. Image by: Variotec.

Table 2: Technical data of the external wall type 2.

	s [m]	λ [W/mK]	ρ [kg/m ³]	R [m ² k/W]	C [J/kgK]
h_e				0.040	
plywood panel	0.033	0.130	450	0.254	1610
sandwich panel with VIP	0.051	0.010	200	5.100	1050
CLT panel	0.094	0.130	500	0.723	1610
gypsum panel	0.015	0.350	1200	0.043	1010
h_i				0.130	



Table 3: Technical data of the external wall type 3.

	s [m]	λ [W/mK]	ρ [kg/m ³]	R [m ² k/W]	C [J/kgK]
h_e				0.040	
toughened safety glass	0.004	1.000	850	0.004	2500
VIP	0.020	0.004	200	5.000	930
toughened safety glass	0.004	1.000	850	0.004	2500
h_i				0.130	



Figure 4: Case study 4 Single Family House for Solar Decathlon, Washington, 2007. Design by: Team Germany TU Darmstadt Manfred Hegger. Image by: TU Darmstadt.

Table 4: Technical data of the external wall type 4.

	s [m]	λ [W/mK]	ρ [kg/m ³]	R [m ² k/W]	C [J/kgK]
h_e				0.040	
wood panel	0.013	0.120	450	0.108	2700
air space	0.050	-	1	0.180	1000
VIP	0.030	0.008	200	3.750	930
VIP	0.030	0.008	200	3.750	930
OSB board	0.019	0.130	650	0.146	1700
rock wool insulation	0.100	0.042	40	2.381	840
air space	0.020	-	1	0.175	1000
gypsum panel	0.015	0.350	1200	0.043	1010
h_i				0.130	



Figure 5: Case study 5: Energy retrofit of a building in Munich, 2004. Design by: Martin Pool, Pool Architekten. Image by: Va-q-tec.

Table 5: Technical data of the external wall type 5.

	s [m]	λ [W/mK]	ρ [kg/m ³]	R [m ² k/W]	C [J/kgK]
h_e				0.040	
plaster	0.015	0.900	1800	0.017	910
EPS	0.080	0.028	30	2.857	1400
VIP	0.020	0.008	200	2.500	930
concrete wall	0.250	0.570	2000	0.439	1250
plaster	0.015	0.900	1800	0.017	910
h_i				0.130	

The selected external walls have been evaluated with respect to the current Italian design regulations, that (conforming to the European Directive 2002/91/EC [2]) define wintertime and summertime minimum thermal performance.

Generally, the climate conditions in Italy follow the pattern of traditional European climates, similar to other countries that open onto the Mediterranean sea and which are also influenced by Alpine terrain.

Thus the Italian regulation D.lgs 311/2006 [3] divides Italy in 6 climate zones (from A the hottest one to F the coldest one). Each climate zone is characterized by different law limit values for winter and summer thermal parameters.

The winter thermal parameter is the *thermal transmittance* [U in W/m^2K] and it has to be lower than $0.62 W/m^2K$ for a building in climate zone A and lower than $0.33 W/m^2K$ for buildings in the climate zone F.

Instead, in order to reduce the excessive high temperature indoor and the use of air conditioning systems in summer, the regulation D.lgs 311/2006 imposes (for the climate zones from A to E) a minimum value of *superficial mass* [M_s in kg/m^2] for the external walls. The M_s -value has to exceed $230 kg/m^2$. In case the M_s -value falls below this limit, it is necessary to prove that the thermal inertia is equivalent to that of an external wall with a M_s -value $> 230 kg/m^2$. The thermal inertia of a wall can be verified with some performance parameters such as *time shift* [ϕ in hours] and *decrement factor* [F_a , dimensionless].

The ϕ is the period of time between the maximum amplitude of a cause and the maximum amplitude of a response to it. The F_a is the reduction of the amplitude of the heat transmission. In the Italian law D.M. 26/6/2009 [4] five levels of evaluation are defined according to both the time shift and the decrement factor values (Tab.6).

Table 6: Evaluation of the values of ϕ and F_a on the basis of the Italian regulation (D.M.26/6/2009).

Time shift [h]	Decrement factor [-]	Evaluation
$\phi > 12$	$F_a < 0.15$	excellent
$12 \geq \phi > 10$	$0.15 \leq F_a < 0.30$	good
$10 \geq \phi > 8$	$0.30 \leq F_a < 0.40$	medium
$8 \geq \phi > 6$	$0.40 \leq F_a < 0.60$	average
$\phi \geq 6$	$F_a \leq 0.60$	bad

The regulation D.P.R. 59/2009 [5] introduces a dynamic parameter, the *periodic thermal transmittance* [Y_{mn} in W/m^2K] in order to evaluate in a more correct way the behaviour of the thermal inertia of a wall, during the summer period.

Y_{mn} is a complex quantity defined as the complex amplitude of the density of the heat flow rate through the surface of the component adjacent to zone m , divided by the complex amplitude of the temperature in zone n when the temperature in zone m is held constant.

The DPR 59/2009 imposes also that (in the climate zones from A to E) for external walls with M_s lower than $230 kg/m^2$ the Y_{mn} -value has to be lower than $0.12 W/m^2K$. Table 7 shows that the selected external walls have a high level of *winter performance* (U) and *summer performance* (ϕ , F_a , Y_{mn}) too. Indeed, the walls from 1 to 4 - even if they have a $M_s < 230 kg/m^2$ - are characterized by a Y_{mn} -value $< 0.20 W/m^2K$, i.e. a high thermal inertia. The wall type 5, example of an energy retrofit, has a high M_s -value and a Y_{mn} -value $< 0.20 W/m^2K$ (Tab.7).

Table 7: Thermal performance of the selected external walls compared with the minimum or maximum values, as defined by the Italian regulations.

	s [m]	U [W/m^2K]	Ms [kg/m^2]	F_a [-]	ϕ [h]	Y_{mn} [J/kgK]
Wall type 1	0.081	0.12	32	0.822	5.06	0.096
Wall type 2	0.193	0.16	90	0.313	10.62	0.050
Wall type 3	0.028	0.19	11	0.984	2.32	0.190
Wall type 4	0.277	0.09	52	0.199	10.49	0.019
Wall type 5	0.380	0.19	560	0.037	16.04	0.007
Italian regulation		Max 0.33	Min 230	0.60 average value non mandatory	6 average value non mandatory	Max 0.20 (if $M_s < 230$)

2. Thermo-dynamic Simulations: Methodology

This study intends also to test the *thermal performance in use* of the selected external walls by means of thermodynamic simulations using the software package *Energy Plus* applied to a virtual test-room located in three Italian cities characterized by a different climate: Milano (MI, climate zone E), Ancona (AN, climate zone D) and Catania (CT, climate zone B). The room has been simulated as an office space, because this type of building (due to high internal thermal loads) generally has a high energy demand for cooling in summer. The Table 8 summarizes the characteristics of input and output data of the simulations.

Table 8: Information about the simulation methodology: input and output.

DIMENSIONAL DATA OF THE TEST-ROOMS			
Dimensions	5.00 x 4.50 m, h = 3.00 m		
Characteristics	the room envelope (walls, floor and roof) is adiabatic, except one wall, that is the test-wall.		
Orientation of the test-wall	South		
Window size of the test-wall	3.00 x 1.35 m _ 30% of the test-wall		
Solar shading system	not exist		
LOCATIONS OF THE TEST-ROOMS			
	MILANO	ANCONA	CATANIA
Latitude	45°27' E	43°36' E	37°30' E
Longitude	9°11' N	16°30'N	10°05' N
Altitude above sea level	122 m	16 m	7 m
Average max temp. in summer	29 °C	30.1 °C	33.6 °C

Average min temp. in winter	-2 °C	1 °C	5 °C
INTERNAL HEAT LOADS			
2 people + 2 computers + 1 lamp	180W + 150W + 50W		
Schedules	9:00 am -1:00 p.m. and 3:00-7:00 p.m. (Mo.- Fr. except holidays)		
VENTILATIONS			
Natural ventilation rate in air changes	0.6 h ⁻¹		
Mechanical ventilation	not exist		
HEATING SYSTEM			
Fuel	Gas		
Temperature set point of heating device	< 20°C		
Heating period	Milano: October 15th – April 15th		
(conforming to the Italian regulations)	Napoli: November 1st – April 15th		
	Catania: December 1st – March 15th		
Schedules	9:00 am -1:00 p.m. and 3:00-7:00 p.m. (Mo.- Fr. except holidays)		
HEATING SYSTEM			
Energy source	Electric power		
Temperature set point of cooling device	> 26°C		
Cooling period	Milano - Napoli – Catania		
(conforming to the Italian regulations)	May 1st – September 30th		
Schedules	9:00 am -1:00 p.m. and 3:00-7:00 p.m. (Mo.- Fr. except holidays)		
OUTPUT OF THE SIMULATIONS			
Outdoor temperature [°C]	20 Time steps per hour for 1 year		
Indoor temperature [°C]	20 Time steps per hour for 1 year		
Indoor operative temperature [°C]	20 Time steps per hour for 1 year		
Heating Energy demand [kWh, €, kg of CO ₂]		month / year	
Cooling Energy demand [kWh, €, kg of CO ₂]		month / year	
Year Energy demand: heating + cooling [kWh, €, kg of CO ₂]		month / year	

The annual energy demand to ensure the internal comfort (20°C in winter and 26°C in summer) has been calculated assuming a gas-powered heating system and an electric-powered cooling system. The annual energy demand is expressed in terms of kWh, € and produced kg of CO₂ (Tab. 9).

Table 9: Method of calculating costs and produced CO₂

HEATING SYSTEM	
efficiency of the heating system	90 %
price of natural gas (first quarter 2011 data [6])	0.076 €/kWh
CO ₂ emissions produced	0.20 kg of CO ₂ /kWh
1 kWh for heating with gas	0.08 € = 0.20 kg of CO ₂
COOLING SYSTEM	
EER: Energy Efficiency Ratio	3.3 W/W
price of electric energy (first quarter 2011 Italian data [7])	0.16 €/kWh
CO ₂ emissions produced	0.58 kg of CO ₂ /kWh
1 kWh for cooling with electricity	0.05 € = 0.16 kg of CO ₂

The results of the simulations of the virtual test-room with the 5 different test-walls have been compared with those of the virtual test-room with a reference external wall with a $M_s > 230\text{kg/m}^2$. This wall is commonly used in Italian buildings (Tab.10-11).

Table 10: Technical data of the reference external wall.

	s [m]	λ [W/mK]	ρ [kg/m ³]	R [m ² K/W]	C [J/kgK]
h_e				0.040	
plaster	0.015	0.900	1800	0.016	910
big honeycomb brick	0.120	0.500	800	0.240	840
plaster	0.015	0.900	1800	0.016	910
insulation panel	0.070	0.030	100	2.300	670
small honeycomb brick	0.080	0.250	700	0.320	840
plaster	0.015	0.350	1200	0.042	1010
h_i				0.130	

Table 11: Performance of the reference wall.

	s [m]	U [W/m ² K]	M_s [kg/m ²]	F_a [-]	ϕ [h]	Y_{mn} [J/kgK]
Reference wall	0.315	0.31	231	0.425	9.05	0.135

3. Thermo-dynamic Simulations: Sensitivity Analysis and Results

In order to better understand the thermal performance in use of the tested external wall, some sensitivity analyses have been carried out:

- variation of orientation towards 4 cardinal points (N, E, S, W);
- variation of the window-to-wall ratio in the test-wall (20%, 30% and 50%, corresponding to dimensions of 2.00 x 1.35 m, 3.00 x 1.35 m and 4.10 x 1.56 m).

The sensitivity analysis has demonstrated that the variation of orientation (Fig.6) and window-to-wall ratio (Fig.7) of the external walls influence considerably the value of the annual energy demand. The different walls with VIP have a similar energy performance in use, while the reference external wall has the worst performance.

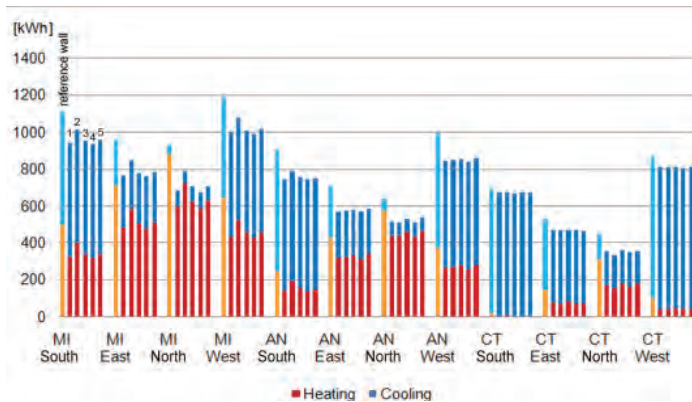


Figure 6: Annual energy demand for the different Italian cities and different orientation. The sequence of the virtual room wall types, left to right: reference external wall; wall type 1; wall type 2; wall type 3; wall type 4; wall type 5 – energy retrofit.

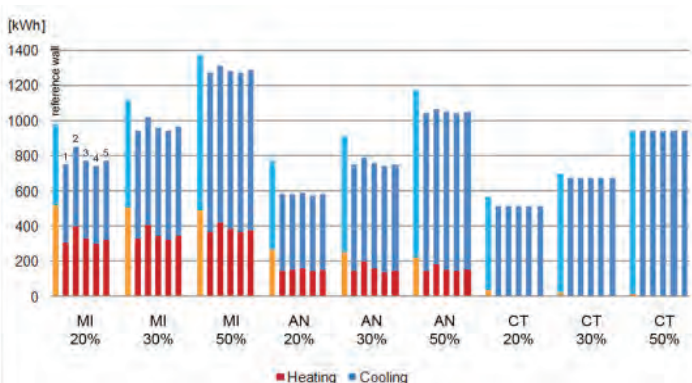


Figure 7: Annual energy demand for the different Italian cities and different window-to-wall-ratio. The sequence of the virtual room wall type is the same of Figure 6.

In particular Figure 8 and Figure 9 show the energy saving potential for the 5 tested external walls and the reference wall in the office test-room (22,5 m², South orientated, 30% window to wall ratio, without solar shading system) located in Ancona. The calculated values of energy demand, expressed in kWh, take into account only the behaviour of the building envelope. Instead, when the energy demand is expressed in € and kg of CO₂, also the efficiency of heating and cooling systems are taken into account (Tab.12). Furthermore Table 12 shows that the use of external walls with VIP determines a greater energy saving than the reference wall.

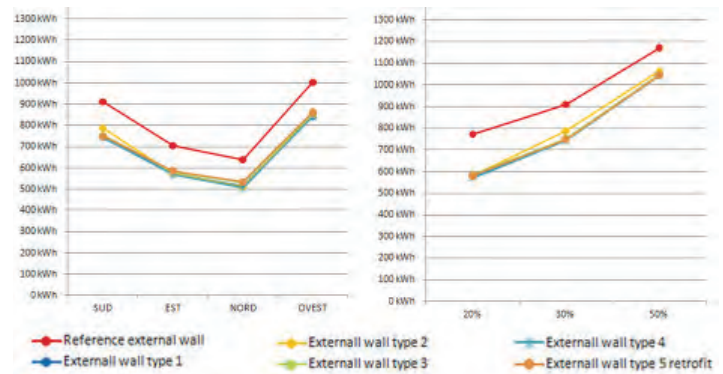


Figure 8: Results of the sensitivity analysis for the test-room located in Ancona. The diagram shows the annual energy demand (cooling and heating) in kWh/year.

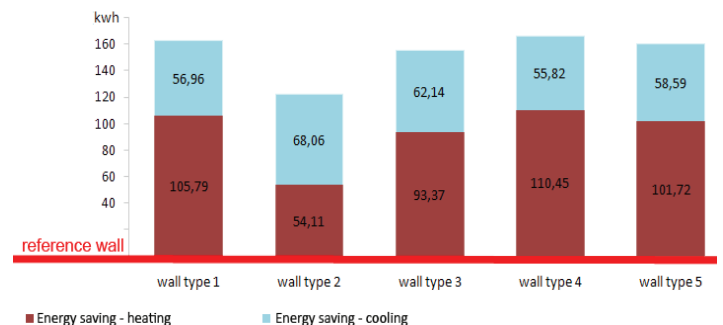


Figure 9: Energy saving potential [kWh/year] for the tested external walls with VIP in comparison with the reference external wall: test-room located in Ancona.

Energy demand reference wall / year	kWh	€	kg of CO ₂	%
Heating	247.05	16.90	54.90	100
Cooling	662.69	32.13	116.95	100
Heating and Cooling	909.75	49.03	171.85	100
Energy saving for heating / year	kWh	€	kg of CO ₂	%
Wall type 1	105.79	8.46	21.16	43
Wall type 2	54.11	4.33	10.82	22
Wall type 3	93.37	7.47	18.67	38
Wall type 4	110.45	8.84	22.09	45
Wall type 5 – energy retrofit	101.72	8.14	20.34	41
Energy saving for cooling / year	kWh	€	kg of CO ₂	%
Wall type 1	56.96	2.85	9.11	9
Wall type 2	68.06	3.40	10.89	10
Wall type 3	62.14	3.11	9.94	9
Wall type 4	55.82	2.79	8.93	8
Wall type 5 – energy retrofit	58.59	2.93	9.37	9
Energy saving for H and C /year	kWh	€	kg of CO ₂	%
Wall type 1	162.76	11.31	30.27	23
Wall type 2	122.18	7.73	21.71	17
Wall type 3	155.52	10.58	28.61	22
Wall type 4	166.28	11.63	31.02	24
Wall type 5 – energy retrofit	160.32	11.07	29.72	23

Table 12: Energy saving potential (heating and cooling) for the tested external walls with VIP in comparison with the reference external wall: test-room located in Ancona.

4. Conclusion

The evaluation of the static and dynamic performance and the thermo-dynamic simulations have demonstrated that walls with VIP (even with a low superficial mass), in comparison to a traditional heavy wall with a high inertia (reference wall), can result in buildings located in middle latitudes (e.g. Italy) a high energy saving: about 40% energy saving for the winter, 9% for the summer and approximately 22% for the total annual energy demand. However the sensitivity analyses have shown that some design choices (orientation and window-to-wall ratio) influence the energy demand more than the characteristics (materials, layers and construction systems) of the external walls. In conclusion in building design it is very important to combine the use of high performance walls (e.g. with VIP) with appropriate design choices.

- [1] The software created by Andrea Ursini Casalena is free available at: <http://www.mygreenbuildings.org>
- [2] European Directive 2002/91/EC
- [3] DECRETO LEGISLATIVO 29/12/2006, n.311
- [4] DECRETO MINISTERIALE 26/06/2009
- [5] DECRETO PRESIDENTE DELLA REPUBBLICA 02/04/2009 n. 59
- [6] <http://www.autorita.energia.it/it/dati/g3.htm>
- [7] <http://www.autorita.energia.it/it/dati/ees5.htm>

Technical Session 3

Application of VIPs in Construction –II

*(Session Chair – Robin Sinha,
Natural Resources Canada, Canada)*

Vacuum Insulation Panels (VIPs) Arrive in Northern Canada: Institutional Building Pilot Retrofit in Yukon

Doug MacLean¹, Juergen Korn², Phalguni Mukhopadhyaya³

Abstract

Yukon is known for its sub-arctic weather, and because of its climate, thermal insulation plays an important role in residential, commercial, and institutional building construction in this region. Use of high performance, lightweight and thin (12 mm (0.5 inch)) vacuum insulation panels (VIPs) in northern buildings is potentially an attractive option for the construction industry because of its high insulation value per unit of thickness, and low material volume.

Regional stakeholders and researchers collaborated to retrofit a portion of an institutional building in Yukon with vacuum insulation panels (VIPs). This paper outlines the construction details, challenges, and instrumentation for long-term performance monitoring of this VIP wall system.

Selected preliminary thermal performance data is included in this paper. It is hoped that successful adaptation of VIPs in this project will lead the way to eventual mass application of VIPs and enhanced energy efficiency in northern buildings.

Introduction

Heating costs in Yukon have always been high relative to the rest of Canada, due largely to its remote northern location, relatively low population base, and sub-arctic climate. Heating oil is the most common building heating fuel, although some buildings are heated with propane, electricity and wood. Recent escalations in world oil prices⁴, declining world oil production⁵, and high local prices for heating fuel⁶ are resulting in increasing interest in

insulation retrofits to reduce energy costs. Given Yukon's colder climate and higher transportation and labour costs, insulation that has a high insulation value per unit of thickness, and per unit of weight, is more likely to be seen as an attractive choice. Local contractors and potential clients alike have expressed interest in bringing such insulation to the Yukon as soon as it is commercially available. There was thus interest in piloting vacuum insulation panels to determine what local adaptations may be needed to use this product in the northern-most regions of Canada.

Design

Economic Insulation Level and Contractor Acceptance

The existing wall selected for retrofitting with VIP insulation was made of 50 mm x 150 mm (2" x 6") stud construction with fiberglass batt insulation and a concrete block exterior with a nominal total insulation value of RSI 3.5 (R20). The insulation goal for this wall after retrofit was based on previous studies which showed that the economic wall insulation level in northern locations was in the order of RSI 8.8 – 10.5 (R50 to R60)⁷, with higher values in attic areas. Thus it was originally proposed to install two layers of VIPs with a total nominal RSI value of 10.5 (R60).

In order to obtain meaningful data on the savings, it was initially proposed to insulate an entire building. Due to lack of experience with this product however, cost estimates were high and contractor reaction was understandably hesitant.

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⁴ See http://en.wikipedia.org/wiki/Price_of_petroleum for a graph showing world oil prices over time.

⁵ See http://en.wikipedia.org/wiki/Peak_oil for graphs showing world oil production over time and predicted future production levels.

⁶ See http://www.housing.yk.ca/pdf/13_Graph.pdf for a graph showing heating costs in the Yukon over time.

⁷ See <http://www.cchrc.org/docs/sns/Dumont.pdf> for a paper by Rob Dumont showing the optimum house insulation levels found in previous studies in northern locations.

The decision was made to install only one layer of VIPs on a small section of wall on an institutional building in order to simplify the installation, test the design, and build contractor confidence in the product and associated construction methods.

Condensation

Condensation issues are referred to in the literature⁸. The existing wall insulation level is adequate to prevent condensation problems in the building. A continuous 0.15 mm (6 mil) polyethylene air vapour barrier was installed on the exterior of the existing block wall, so there is little likelihood of there being any condensation within the additional wall insulation. The amount of insulation added outside the new vapour barrier also conformed to the insulation ratio requirements in the Canadian 2010 National Building Code⁹.

Any condensation on the exterior side of the vacuum insulation panels has the potential to result in deterioration of the insulation cover, and possible mechanical damage. In order to reduce the potential for this happening, the vacuum insulation panels were covered on the outside with a layer of foam board insulation. This raises the temperature of the exterior VIP surface, and minimizes the amount of moisture that is in contact with the insulation.

The foam insulation board insulation thickness was based on previous laboratory and field experience that indicated that placing foam next to the VIPs would move the condensation surface to the exterior of the foam insulation, and also help prevent condensation in the building in the event of a VIP failure. Monitoring and inspections during the testing phase were planned to determine if the amount of insulation on the exterior of the VIPs was adequate to eliminate condensation concerns.

Mechanical Rubbing

The potential for mechanical rubbing of the VIPs against the rough surface of adjacent material was identified as a possible issue¹⁰. The mechanical rubbing can occur due to thermal expansion and contraction in response to changes in the ambient outdoor temperature, and due to building shifting. The need to prevent or mitigate mechanical rubbing between each VIP and any adjacent surface influenced the design.

The VIPs were glued directly to a layer of 25 mm (1") polystyrene foam board which ensured that the bottom surface of each VIP was attached to a smooth surface and protected from abrasion. A layer of 6 mm (1/4") soft foam (Domfoam 1095) was placed over the exterior surface of the VIPs to help prevent mechanical rubbing of the outside surface of each VIP against the 25 mm (1") polystyrene foam board placed on top of it.

Given the potential vulnerability of these vacuum insulation panels, the design used was such that VIPs could be relatively easily replaced if a problem occurred. The steel siding could be removed over the area affected. The 25 mm (1") foam board and 6 mm (1/4") Domfoam could be removed, and the VIP replaced. The Domfoam, foam board and steel siding could then be reinstalled.

Adhesive Selection

Two concerns with using spray (or other) adhesives were the possibility that they become a source of abrasion, and the possibility that the glue may attack the cover of the VIP, causing gradual structural failure over time, and subsequent loss of vacuum. Two approaches were used to deal with this. First, it was agreed by the contractor that he would try to minimize the use of spray adhesive if it was not needed. Second, various adhesives were tested before use.

⁸ See Binz, Armin et. al., Vacuum Insulation in the Building Sector: Systems and Applications (http://www.ecbcs.org/docs/Annex_39_Report_Subtask-B.pdf) for a discussion of condensation issues.

⁹ See Canadian Commission on Building and Fire Codes, National Research Council, National Building Code, Vol. 1, Section A-9.26.1.1.(2), Table A-9.25.5.2.

¹⁰ See, for example, Binz, Armin et. al., *ibid.*, page 5, paragraph 3.

¹¹ See, for example, Maxwell, A.S., Broughton, W.R., Dean, G. and Sims, G.D., "Review of Accelerated Ageing Methods and Lifetime Prediction Techniques for Polymeric Materials", NPL Report DEPC MPR 016, 2005, appendices 2 and 3, for comprehensive lists of the International Organization for Standardization (ISO) and American Society for Testing and Materials (ASTM) standards for the accelerated ageing of plastics, rubbers, composites and adhesives. See also: <http://www.adhesivestoolkit.com/Docs/test/Environmental%20Conditioning%20and%20Testing%20-%20Test%20Methods%20and%20References.xtp> (Accessed July 18, 2011)

One way to test spray adhesives to predict premature failure is to do a “thermal stress test”¹¹ or “thermally accelerated life-cycle test”. Such a test helps to predict if any of the adhesives being considered for use would cause premature failure of the aluminum composite cover on the VIPs. Four spray-on adhesives were tested by applying them to one side of the cover of two VIPs. The glues were allowed to dry for 30 minutes. One glue did not adhere well to the VIP and was eliminated from further testing. One VIP with three different adhesives on it was put into an oven that had been preheated to 76 °C (170 °F). The glues and the VIPs then were heated for two days. The insulation was observed after 5 days to see if there was any visible damage to the aluminum composite cover, and none was observed.

The adhesives were also sprayed onto sample pieces of 0.15 mm (6 mil) polyethylene, polystyrene, and Domfoam 1095. One glue was rejected for use with polystyrene as it tended to dissolve the polystyrene. Another was rejected for use with polyethylene, polystyrene and VIPs because it did not stick to any of these products.

Final Design

The cross-section of the design is shown in figure 1 below. A 0.15 mm (6 mil) polyethylene air-vapour-moisture barrier was installed first on the existing concrete block wall, held in place with spray adhesive. 25 mm (1") polystyrene board was glued to the polyethylene to provide a smooth surface on which to mount the VIPs. 50 mm x 75 mm (2" x 3") studs were mounted

on the polystyrene board and attached to the concrete wall with anchors (HPS-1 from Hilti). The VIPs (with a “peel and stick” adhesive on one side) were mounted between the 50 mm x 75 mm (2" x 3") studs. The VIPs were covered with 6 mm (1/4" nominal) Domfoam 1095 foam material held in place with sheathing tape, instead of adhesive spray as originally planned. 1" polystyrene board was placed on the outside of the VIPs to prevent condensation and to protect the VIPs from mechanical damage during and after construction. The layout of the VIPs is shown in figure 2.

Polystyrene insulation board was selected instead of polyisocyanurate. The later product is sandwiched between two layers of metal foil which were considered likely to interfere with the infrared measurements that would be needed during monitoring of the project.

Monitoring

Temperature sensors were installed to monitor the effectiveness of the insulation in this application. Temperature sensors for this purpose were located as shown on in figure 3 below.

A cluster of four sensors (thermistors) were placed approximately 2 meters (6') from the south edge of the wall, and 1 meter from the top of the wall. They were placed to measure the temperature on the existing wall surface, on the exterior of the first polystyrene layer, on the exterior surface of the VIPs, and on the exterior surface of the second polystyrene layer.

The purpose of these sensors was to monitor the temperature on the surface of each layer of insulation to determine if it was performing as expected.

Three sensors were placed on the existing wall approximately 2 meters (6') from the north edge of the wall retrofitted area. One sensor was located approximately 1 meter from the top of the wall. The others were placed approximately 2 and 3 meters (6' and 9') from the top of the wall. The purpose of these sensors was to monitor for thermal gradients from the top to the bottom of the wall.

As an initial step, a thermal image of the wall was taken at the site and is shown, along with a picture of the wall, in figures 4 and 5.

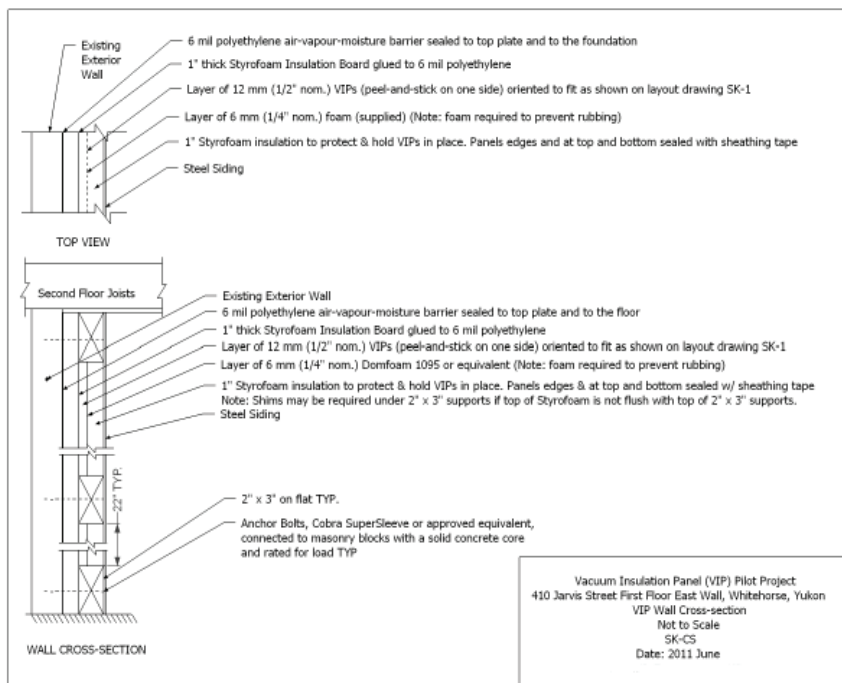


Figure 1. Vacuum Insulation Panel Wall Cross-section.

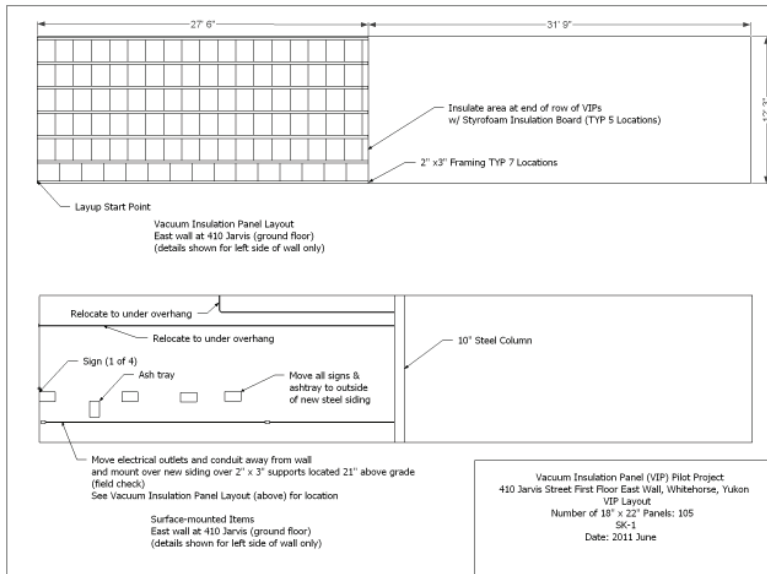


Fig. 2. Vacuum Insulation Panel Layout

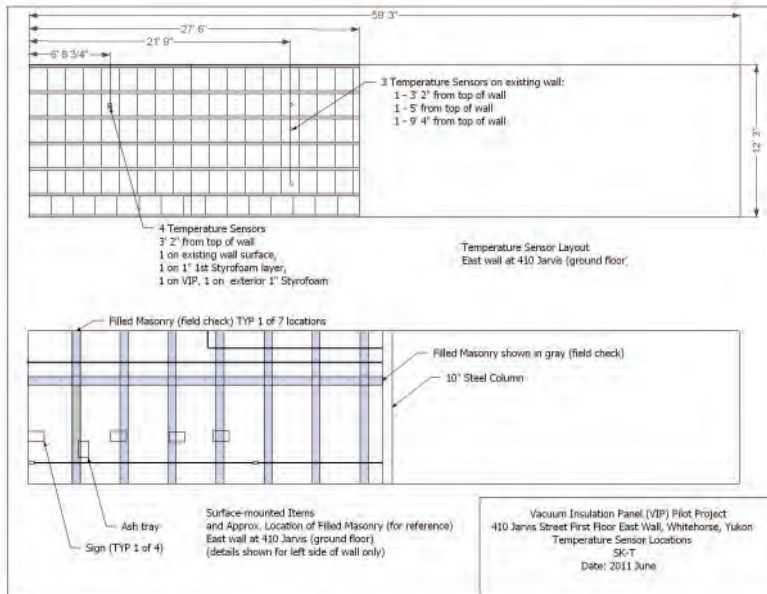


Fig. 3. Temperature Sensor Locations

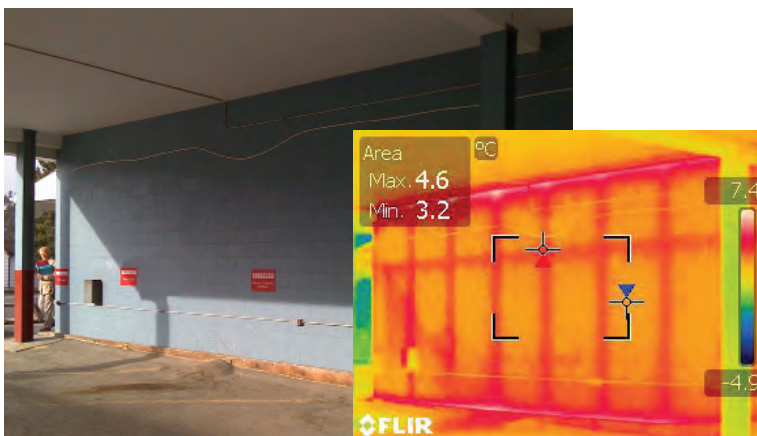


Fig. 4. Wall selected for VIP pilot.



Fig. 5. Infrared Image of the wall selected for the VIP pilot.

Construction Experience

Construction was based on a scope of work similar to the generic scope shown in Appendix 1. During construction, experience with installation of the VIPs was more positive than originally anticipated. Only one minor installation problem was encountered, and it was related to the use of anchors in masonry walls rather than installation of the VIPs.



Fig. 6. Installation of the air/vapour/moisture barrier.

Installation of the air/vapour/moisture barrier (figure 6) proceeded smoothly as was expected. Similarly, installation of the 25 mm (1") polystyrene foam board layer over the air/vapour/ moisture barrier also proceeded without incident. The spray adhesive used to hold the polystyrene in place was effective, meaning that no rework or significant adjustments were required.

Installation of the 50 mm x 75 mm (2" x 3") horizontal support members (figure 7) was started at the top of the wall. A jig was made from a piece of 50 mm x 75 mm (2" x 3") wood exactly the same length as that of the VIPs plus a small 3 mm (1/8") clearance. The jig was used to ensure that the supports were spaced apart so that the VIPs would fit in between over the full length of the wall. This strategy was effective. None of the supports had to be moved as all the VIPs fit properly.



Fig. 7. Installation of the horizontal support members over the polystyrene layer.

Standard anchors (HPS-1 from Hilti) were used. These anchors are designed for use with hollow concrete block walls and were spaced to carry the wall load. Some difficulties were encountered during construction in that some anchors did not appear to grip properly. This was resolved by installing a second anchor adjacent to any anchor that did not appear to be firmly set. Installation instructions were checked and more care was taken as well. Installing an additional anchor, when judged prudent, and taking care installing them resolved the concern.



Fig. 8. Installation of the vacuum insulation panels (VIPs).

Installation of the VIPs proceeded quickly (figure 8). Because there is a mild adhesive on the back of each VIP, installation was analogous to installing “peel and stick” floor tile. A protective wax paper cover over the adhesive backing is removed just before putting each VIP in place on the foam board. The concern that the adhesive on the back of the VIPs would not be strong enough proved to be unfounded. Once put in place, the VIPs did not move. VIPs did occasionally need to be repositioned however, and it was found that the panels could be removed without difficulty if the panels were detached slowly from the foam board. When repositioned they adhered well.

The 6 mm (1/4") foam layer over the VIPs was cut to width using a straight edge and a knife so as to fit between the 50 mm x 75 mm (2" x 3") horizontal support members. This approach proved to be both fast and satisfactory. The width was accurate and little to no re-cutting was needed. Installation was simpler than expected as the foam was easily held in place using standard sheathing tape (Canadian Technical Tape Ltd, 205-02 60 mm). A photo is shown in figure 9.

Using sheathing tape to hold the foam in place meant that no adhesive was in contact with the aluminum cover of the VIPs. This change from the original design meant that the risk of friction caused by dried adhesive was eliminated. The tape was not attached to the VIPs, with one or two exceptions. This meant



Fig. 9. Installation of 6 mm (1/4") foam layer over the vacuum insulation panels.

that both surfaces of the foam were free to move, reducing the potential for mechanical rubbing on the VIP surface beyond that expected with the original design.

Installation of the second layer of 1" foam board also proceeded smoothly (figure 10). Pieces were cut to size and a slight friction fit between the foam board and support members proved to be reliable for holding the polystyrene in place until the vertical steel siding could be installed. The steel siding was installed as construction proceeded in order to protect the VIPs installed each day. Plywood sheets screwed to the framing were used to protect the work that was not complete at the end of each day.



Fig. 10. Installation of the second layer of polystyrene. Plywood was used to cover unfinished work overnight.

During construction, thermistors were installed in order to monitor the performance of the wall compared to a portion of the wall that was not insulated. The wiring was inset in a shallow handsaw cut in the insulation to protect it and prevent contact with the VIPs. The location of the thermistors on the insulated wall is as shown in figure 3.

No exterior air/weather barrier was needed to meet code requirements in this location, but normally would be installed before installing the steel siding. Leaving out an exterior air/weather barrier also may facilitate taking infrared temperature measurements. It was expected that it would be necessary to remove a portion of the steel siding to take infrared measurements from the outside, as any air gap in the wall can interfere with infrared temperature readings. However, there was no air space beneath the steel siding, except at the ribs, and the initial infrared temperature readings looked good. See, for example, figure 12 on the next page.

Because the location of the 50 mm x 75 mm (2" x 3") support members was accurate, it was possible to pre-drill the vertical siding at all locations where screw fasteners were required. The siding was stacked. The location for each hole was marked on the top piece of siding. After checking the dimensions to each hole, all pieces of siding were drilled at once.

Because all holes for fasteners were drilled before the siding was put on the wall, it was possible to visually check that all fastening points were directly over the support members. This was done by looking through the pre-drilled holes to see the wooden support member underneath. This step virtually guaranteed that none of the adjacent VIPs would be damaged due to misalignment of the siding. In fact, no VIPs were damaged during the construction process, to the best of our knowledge. There was concern that because the polystyrene was slightly higher than the supports the VIPs underneath could be compressed causing a failure of the vacuum seal. Care was taken with installation to avoid overstressing the VIPs. During the monitoring period, the condition of the VIPs will be checked to confirm whether or not shims under the supports are required.

As a final step, electrical and water lines, signs, etc. in the area were reinstalled. The siding, nearly complete is shown in figure 11. An infrared image of the wall with the vacuum insulation panels installed is shown in figure 12. Although the ambient temperature is higher than it was when the first infrared image was taken before adding insulation, it is clear that the area with the greatest heat loss is over the 50 mm x 75 mm (2" x 3") support members which are not covered with VIPs.

Summary

The increases in heating fuel costs over the last few years and desirable features of vacuum insulation panels were factors behind obtaining the financial support needed to complete this pilot and demonstration project.

Although a minor problem was encountered installing anchors, the contractor found that the Vacuum Insulation Panels (VIPs) proved to be straight-forward to install. As a result, the installation was completed under budget. The labour cost to install VIPs could be lower than for completing alternatives due to its relatively light weight and thinness.

The experience during construction made us more optimistic that this product may well be suited for application in the north, depending on the overall material and labour costs, and availability of suitable shapes in future.

Thermistors were placed at various locations in order to monitor the thermal performance of the wall.

While temperature monitoring will provide us with objective data, initial indications are positive for application of this building insulation product in northern and colder climates.

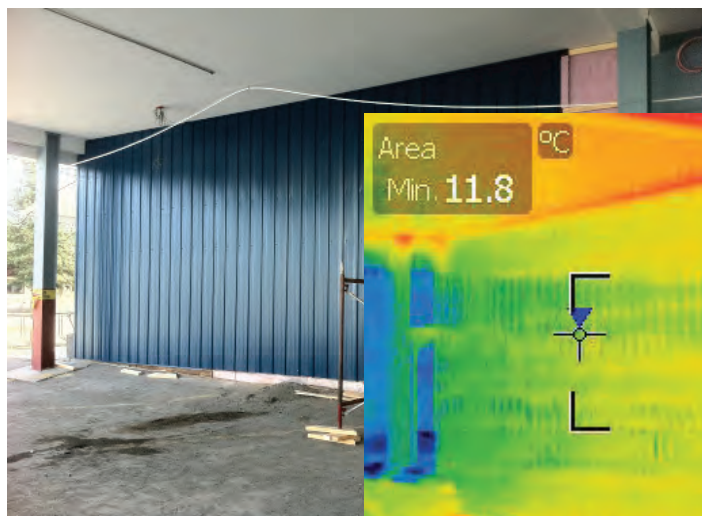


Fig. 11. Insulation and siding.

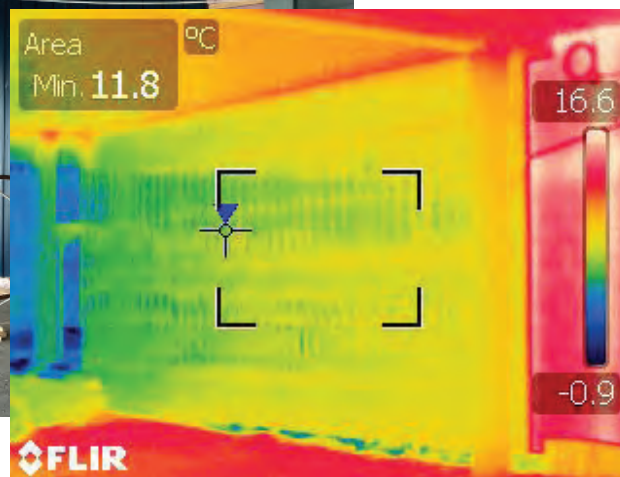


Fig. 12. Infrared image of the wall with vacuum insulation panels installed.

Acknowledgements

We are very appreciative of the support of Panasonic Canada Inc., and Panasonic Corporation for supplying the vacuum insulation panels used in this pilot project, and for their technical expertise and support. We would like to thank Yukon Housing Corporation for allowing us to use a wall of one of their buildings for this pilot project, and for providing monitoring equipment. The financial help and technical contributions provided by Yukon College are also highly appreciated.

Appendix 1. Sample Scope of Work:

Installation of Vacuum Insulated Panels (VIPs)

Initial Preparation

1. Contact the project manager and visit the site with him or her to ensure that all project requirements are clearly understood. For any questions during the project contact the project manager.
2. Provide a schedule of work for the project.
3. Provide and maintain on site at [address], in clean and orderly condition, locked weatherproof storage facilities for all tools, equipment and materials.
4. Store the vacuum insulation panels (VIPs) and siding in the locked weatherproof sea container provided on site. This sea container shall be kept locked at all times. Ensure that there is no damage to the VIPs before beginning construction. Materials other than the VIPs may be stored in the sea container if there is room.
5. Ensure that all required materials are in storage on site, or at a nearby secure location if not needed for construction immediately, so that each area of VIPs that is installed can be protected with 25 mm (1") polystyrene board insulation and siding the same day that it is installed.
6. Protect the VIPs and other construction materials from weather, damage and theft at all times.
7. Train all staff working on the project on how to install the VIPs and the reasons for taking care to ensure that none of the panels are damaged in any way. These panels are currently expensive and difficult to replace. Any damage to a VIP can cause a vacuum leak which will reduce the insulation value from approximately RSI 10 (R 58 per inch) to approximately RSI 0.88 (R 5 per inch).
8. Use screws only for installation of all framing, framing components, siding and flashing as needed, in order to reduce the risk of damage to the VIP insulation. Once the VIPs are covered with the 25 mm (1") polystyrene board insulation, only screws shall be used for installing metal siding, trim, flashing, and other components.
9. Purchase and deliver to the site all materials needed for the project, including the vacuum insulation panels (VIPs), the 6 mm (1/4" nom.) thick foam (Domfoam 1095 medium density foam, or approved equivalent),

framing, and siding, etc.

10. The siding [brand, or equivalent] used shall be pre-painted steel siding. The colour shall match the existing adjacent siding.
11. Coordinate the work with the installation of temperature sensors, monitoring and data logging at this site, and any other work by other contractors (none expected), as necessary. Working with the project manager, provide a 12.5 mm (½") hole through the wall at a location near the top of the insulation above the monitoring sensors so that data loggers

can be installed indoors (2 locations). See drawing SK-T for details. It is expected that the sensors will be installed before, during and after the insulation work is finished. See paragraph 26 on measures to ensure easy access to the sensors.
12. Move out all existing electric outlets, water connections, piping and tubing supports, etc. so that the insulation can be installed. Once the insulation has been installed, fasten existing surface-mounted electric outlets, etc. to the 50 mm x 75 mm (2" x 3") framing used to hold the insulation in place. See drawings SK-1 and SK-CS for more information.

Preparation for VIP Installation

13. Organize the insulation work so that before the end of each work day the VIPs installed that day are covered with a protective layer of 25 mm (1") polystyrene board insulation, held in place between the 50 mm x 75 mm (2" x 3") framing, and covered with siding. Shims under the 50 mm x 75 mm (2" x 3") framing shall be installed if needed to ensure that the exterior (top) layer of polystyrene is flush with the exterior (top) surface of the 50 mm x 75 mm (2" x 3") framing. A temporary plywood cover shall be installed if the siding cannot be installed the same day as the insulation is installed.
14. Begin work by preparing the existing masonry block wall surface where necessary by chiselling or grinding down any rough surfaces to help prevent damage to the air-vapour barrier or the VIPs. Grinding shall be done with a HEPA filter on the grinder to minimize the amount of dust produced. Minimal chiselling or grinding should be needed.
15. Install a 0.15 mm (6 mil) polyethylene air-vapour barrier on the existing masonry wall using a compatible sealant spread over the entire wall surface to be insulated and seal it at the top of the first floor wall, at the foundation, and around any openings with sealant or sheathing tape, Tuck 20502 Contractor's Sheathing Tape, or approved equivalent. Proper air sealing of the building envelope

is key to preventing heat loss due to air leakage and to prevent moisture concerns.

16. Glue a layer of 25 mm (1") polystyrene board insulation over the 0.15 mm (6 mil) polyethylene air-vapour barrier. Glue the foam board in place using a compatible contact cement. Enough one-inch polystyrene board can be installed for the day's work, or the whole wall area to be insulated can be covered at once. See drawing SK-1 for more details.

VIP Installation

17. Field check the VIP wall layout shown on drawing SK-1. Install the 50 mm x 75 mm (2" x 3") framing as shown in drawing SK-1. A jig shall be used to ensure that the spacing between the 50 mm x 75 mm (2" x 3") framing members is correct so that the VIPs fit between them. Field check spacing between the 50 mm x 75 mm (2" x 3") framing to ensure that the VIPs will fit. Attach the 50 mm x 75 mm (2" x 3") framing with anchor bolts, [brand and model] or approved equivalent connected to the masonry block wall and rated for the load that they will need to carry.
18. Before installing each VIP, examine the VIP to ensure that it is not damaged. Extreme care should be taken at each stage to ensure that the VIPs are not damaged in any way. See item 7 "Train all staff..." in this scope of work for more information.
19. The VIP layout is as shown in the layout drawing SK-1. Install each VIP by removing its protective wax paper backing to expose the adhesive surface and placing the VIP in position as shown in the layout drawings. Ensure that the VIP is firmly attached to the one inch polystyrene board insulation before installing an adjacent VIP and then continue until all the VIPs are installed in the selected area for that day's work. Fill in the insulation gaps in the spaces not covered with VIPs with polystyrene board insulation.
20. Replace any damaged panels as needed using the extra panels provided.
21. Call the project manager for an inspection of installed VIPs in the selected area for that day's work. Organize the work and installation method such that any deficiencies identified by the project manager can be corrected with minimal delay to completion of the project.
22. In the area being insulated, apply a layer of 6 mm (1/4" nom.) thick foam (Domfoam 1095 medium density foam, or approved equivalent) over the VIPs. Hold the 6 mm (1/4") foam in place between the 2' x 3" horizontal support members with sheathing tape attached to the support members. The 6 mm (1/4" nom.) foam is required to prevent rubbing of the VIPs against the polystyrene placed over the 6 mm (1/4" nom.) foam and the

VIPs. Staples shall not be used to hold the 6 mm (1/4" nom.) foam in place.

23. Ensure that the exterior (top) surface of the 6 mm (1/4" nom.) foam is smooth and flat after installation. Check the VIP panels, and replace any damaged panels as needed using the extra panels provided.
24. Call the project manager for an inspection of the completed work and complete the inspection prior to beginning installation of the exterior (top) layer of 25 mm (1") polystyrene.
25. Cover the completed area of VIPs and 6 mm (1/4" nom.) foam with a layer of 25 mm (1") polystyrene board insulation. The polystyrene shall be attached with sheathing tape to adjacent polystyrene and the adjacent 50 mm x 75 mm (2" x 3") framing to hold it in place, and to reduce air infiltration.
26. Once the VIP insulation and exterior (top) layer of 25 mm (1") polystyrene is installed in the area selected for the day's work, cover the insulation with siding and flashing as needed to provide protection from the weather. When the siding is put over the area where the monitoring sensors are located, take care to ensure that polystyrene insulation and the

siding installed is readily removable in order to access the monitoring sensors, and to complete infrared testing. When installing flashing take care to ensure that the VIPs are not damaged. See paragraph 10 for the siding to be used.
27. A temporary 12 mm (1/2") plywood cover, screwed in place in such a way as to avoid damage to the VIPs, shall be used if necessary to provide overnight or temporary protection for unfinished areas so that all installed VIPs are never left uncovered for more than eight hours during the day, and are never left uncovered overnight.
28. Collect all the waste debris from the site, and repurpose, recycle, or dispose of it properly in a landfill.
29. Ensure that all required work is substantially complete and then complete an application for a *Certificate of Substantial Performance* and give it to the project manager.
30. Once the work is complete, make a written application for a *Certificate of Total Performance*. See the *General Instructions* in the specifications for more information. Ask the project manager for a final inspection of the completed work. Complete the final inspection prior to demobilizing and leaving the site so that any deficiencies identified can be corrected while still on-site.

Referenced Specifications, Standards and Drawings

31. The following standards and references shall be followed for the work in this project:
 1. *National Building Code of Canada, 2010*
 2. Drawings:
 1. *SK-1 Vacuum Insulation Panel (VIP) Pilot Project - VIP Wall Layout*
 2. *SK-CS Vacuum Insulation Panel (VIP) Pilot Project - VIP Wall Cross-section*
 3. *SK-T Vacuum Insulation Panel (VIP) Pilot Project - Temperature Sensor Locations*
 3. Owner's Specifications:
 1. *Exterior Retrofit – General Instructions*
 2. *Exterior Retrofit – General Carpentry*
 3. *Exterior Retrofit – Finish Carpentry*
 4. *Exterior Retrofit – Metal Flashing and Trim*

Energy Performance of Highly Insulated Wood-Frame Wall Systems Using a VIP

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Abstract

Despite recent advances in highly performing envelopes that are technically feasible and can reduce heat loss by about one half, most current construction still just meets the provincial building code minimum of 2" x 6" constructions with conventional batt insulation. This project addresses several barriers to the adaptation of new envelope systems, including issues of buildability, incremental cost of labour, materials, and wall system energy performance assessment.

The National Research Council of Canada's Institute for Research in Construction (NRC-IRC) is a partner in the PERD (Program on Energy Research and Development) Project with NRCan and PWGSC on "Next Generation Building Envelope Building Systems". This project deals with thermal performance of eco-friendly advanced thermal insulation materials integrated into wall assemblies that are adapted for Canadian wood frame construction. The current project is looking at laboratory, field testing and modeling of highly insulated wall assemblies. The work consists of evaluating the thermal performance of different High-R-value wall systems as well as different retrofit strategies by adding innovative thermal insulation on the exterior such as Vacuum Insulated Panels (VIP). The objective of this project is to develop recommended construction specifications and guidelines for assembling next generation building envelope systems with the ultimate goal of encouraging their use in Canadian wood frame construction.

1. Introduction

The energy crisis in the 70's had major effect on our building technology related to energy efficiency. Thermal insulation of buildings became the key element to minimize heat losses and to improve energy performance. Much more thermal insulation was placed in exterior walls, and the need for a corresponding increase in airtightness had started to get recognition.

Achieving better airtightness, high levels of envelope insulation will certainly be required, with wall R-values of more than 3.33 m².K /W and roof R-values of more than 5.0 m².K /W.

The drive to the reduction in energy use in new buildings is led by new regulations in Europe for example [1]. To achieve these new levels of energy performance with existing wall systems and materials, the wall systems could be considerably thicker and this may not be acceptable to consumers. In addition, this will lead to loss of usable floor area, greater weight, increase costs such as transport and time of construction, as well as new challenges on the structures.

To overcome those hurdles, a promising recent innovations in building technology is being investigated within the context of application in Canada - , the vacuum panel insulating systems. Due to their very high R-values, their potential is considered to be a promising way of insulating the building envelope to very high levels of thermal resistance while maintaining reasonable envelope thickness. The Vacuum Insulating Panel (VIP) is of interest owing to its exceptional insulating R-value, up to R-60 per inch or even higher [2].

1. This concept is starting to gain interest by architects and building scientists and mainly for two reasons [3]:
2. To reduce the thickness of the insulating material, thus the wall assembly. With VIP, the insulation thickness can be reduced by a factor of 5 to 10 compared to conventional materials-with the same thermal insulation value.

To increase or enable insulation in critical constructions area (i.e. retrofit of exterior walls)

Despite their insulating values, VIPs have been slow to make inroads into construction because of three drawbacks: cost, the need to protect them against puncturing, and the absence of long-term performance data or procedure to predict their long-term performance.

Up till recently, Canadian and European research efforts have been mainly focused on the VIPs themselves [4, 5, 6 and 7]. However, subsequent research started to investigate how to implement a VIP panel in building construction in such a way that the thermal advantages are fully used. This has been published in the IEA Annex 39 on High Performance Thermal Insulation [8] and [7 and 9]. It is important to study the interaction between the thermal insulation layer and the building component in which it is integrated into.

The VIP panel can be used in the retrofit of the existing house either at the interior or at the exterior [10]. It can also be used in new construction such as wood-frame construction in the double stud walls [11].

Most of the VIP activity in Canada is still in the R&D phase with some demonstration projects planned. Germany and Switzerland are the two first countries where a market in its early stage has been established and have introduced VIP-Technology to building construction sector, through research efforts such as the IEA Annex 39 [8] as well as other R&D efforts [1, 12, 13 and 14]

In 2005 [1], VIP was used in cladding systems within new building envelopes in the industrial and commercial sector. Applications exist in at least three categories:

1. Mainstream industrial cladding systems where in terms of cost and performance systems must be competitive with conventional technology, and where the thickness of the panels is not a decisive advantage.
2. Commercial building cladding where 'thin wall technology' can moderate the increase the net gross area of the building and consequently deliver higher rental yields.
3. Architectural applications where performance and appearance of the panels is advantageous, such as used in conjunction with structural glazing systems (i.e. curtain walls).

Since VIP technology is presently considerably more costly than established technology, improved production capacity and efficient manufacturing techniques are likely to be essential such as looking to alternative and less expensive core material of the VIP [4] thereby making the VIP a more cost-effective material for building envelope.

Based on research efforts of NRC-IRC and others, it appears that VIPs hold great promise for use in building construction in a way that could substantially reduce energy consumption [8].

Several prototype projects have been completed or being carried out in Europe using VIP technology [8,].

Canada, a country with very cold climate, was in forefront of cold-climate insulating technology and renowned leader of research and development activities at that time. However, further technology developments in the area of insulation technology and recent global concerns about the climate change phenomena showed that there is room and need for improvement in the insulation technology for building envelopes. Hence, NRC-IRC and others organizations and laboratories around the world have established research programs and studies that focused on the applicability of high performance vacuum insulation panels (VIP) in building envelope construction.

2. Objectives and Scope

The main objective of this project is to develop recommended construction specifications and guidelines for assembling next generation building envelope systems with the ultimate goal of encouraging their use in Canadian construction, especially in wood-frame construction.

The scope of the project includes: 1) constructing wall samples insulated with poly-wrapped and sealed (glass fiber batts), as reference wall, and different types of VIPs; 2) performing thermal and air leakage tests on wall samples and 3) developing experimental details and recommended specifications for highly insulated walls using VIPs such as double stud walls for new construction and different pre-fabricated concepts panels for energy retrofit by adding insulation for example at the exterior of the sheathing board.

The challenge for this type of construction using VIP is to maximize their protection from nails, screws and fasteners during assembly and as well after assembly from fasteners from exterior, nails and other penetrations for hanging shelving, frames, and other decorations on the interior finish.

Finally, the ultimate goal is to show the buildability using Canadian wood frame construction techniques in order to assess as-built performance.

3. Concept Development and Experimental Task

Through a series of consultations with project partners and industry stakeholders, a number of workable concepts were developed for wall constructions that feature one or two protected layers of VIPs and conventional wood framing techniques used for the load-bearing portion of the walls. Some of these concepts are presented below.

In the experimental task, laboratory testing is performed on each wall sample to determine: air leakage and thermal transmission coefficient (R-value). In addition, separate VIP material sample are prepared to conduct material characterization according to established standards. In some cases, the air leakage rate and R-value tests are performed before and after sample conditioning, as will be explained later.

3.1 Wall Description

In this paper two types of VIPs from different manufacturers were used to demonstrate the process of installation. Table 1 shows the different configurations and type of walls that were used in this series of experiments. The first wall tested as shown in Table 1 as a reference wall (REF) was constructed using conventional 2" by 6" wood stud frame, and insulated with: Poly-lapped and sealed (glass fiber batts). The overall dimension of the wall is 2.4 m by 2.4 m (as a standard size to fit the NRC-IRC Guarded Hot Box (GHB) apparatus). In all remaining walls, VIP panels were inserted between the double stud wall assemblies i.e. 2"x4" exterior and 2"x3" interior. Differences between configurations listed in Table 1 were in the details of wood-stud cavity some of which were insulated and some not. Table 1 also provides full description of the ten walls samples reported in this paper.

The Guarded Hot Box apparatus was used to perform tests on those different wall assemblies to measure their thermal performance R-values before and after performing the Air Leakage Test in accordance with CCMC Air Barrier Technical Guide 07272 [15]. Note that all tested walls were opaque walls with no penetrations, nor windows.

Figure 1 shows a schematic vertical cross section for concept 1 of double stud wall with VIP Type 1 with uninsulated (Glass fiber batts) wood stud cavities.

CONCEPT 1A – Double Stud Wall

The first concept that we developed is double stud walls. The VIPs are held in the middle of a double-stud wall. This concept could be tested with and without fibreglass batts in the exterior stud cavity.

Advantages:

- Central location of VIPs is less likely to be pierced by nails
- Interior stud cavity can be left empty, to allow for ease of wiring

- Disadvantages:
- Difficult to replace damaged VIPs
- Labour and material intensive – like building two walls
- Thicker wall - approximately 250 mm, but relatively thin for the delivered R-value.

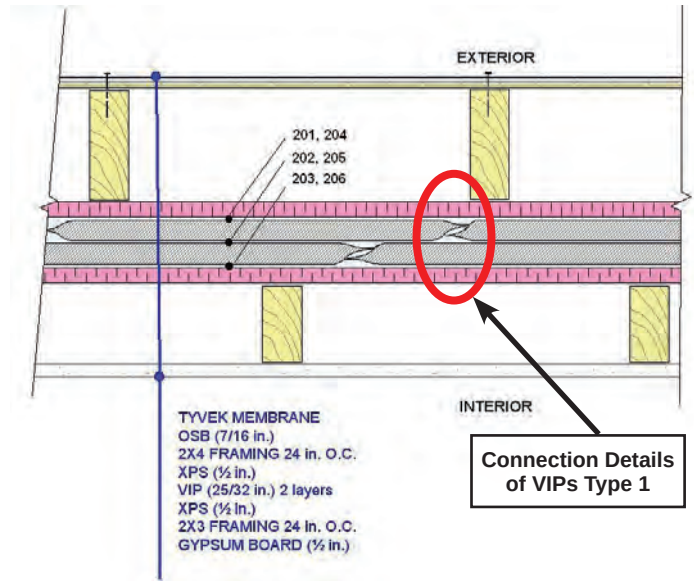


Figure 1: Concept 1A Wall Configuration (9 3/4" double stud; 3.5" batts both cavities)

Figure 2 shows a schematic vertical cross section concept 1 of double stud wall with VIP Type 2 with insulated (Glass fiber batts) wood stud cavities.

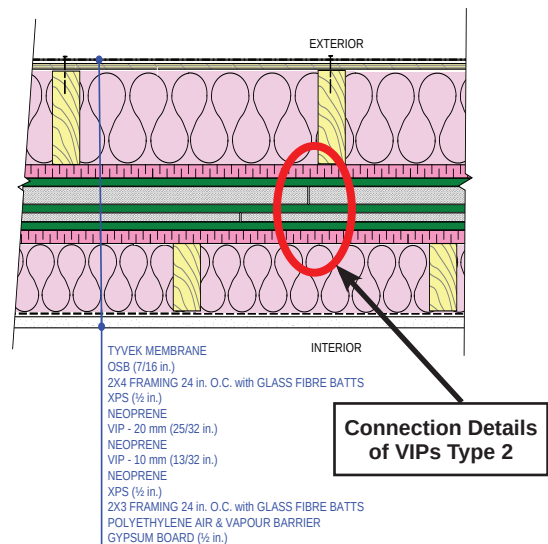


Figure 2: Concept 1G Wall Configuration (9 3/4" double stud; 3.5" batts both cavities)

Table 1 Summary of wall description

Wall Specimen (2.44m x 2.44m)	VIP Type	Test	Procedure	Specifications
REF	1	R-VALUE	2 temperature settings (-35, -20 °C)	Wall specimen with Glass Fibre, 2"x 6" construction
VIP-1A				Wall specimen with VIP panels only
VIP-1B				Wall specimen with VIP panels & Glass Fibre in 2"x 4" exterior cavity
VIP-1C				Wall specimen with VIP panels & Glass Fibre in 2" x 4" exterior and 2"x 3" interior cavities <i>Test specimen with Polyethylene</i>
VIP-1D				Wall specimen with VIP panels & Glass Fibre in exterior and interior cavities. Repeat of VIP-1C after the wall specimen was opened and VIP panels fixed, <i>Test specimen with Polyethylene</i>
VIP-1D		ALT	Air leakage before conditioning, 1000 cycles @ + & -800 pa, 1 burst @ + & -1200 pa. Air leakage after conditioning	Wall specimen with VIP panels & Glass Fibre in exterior and interior cavities. Repeat of VIP-1C after the wall specimen was opened and VIP panels fixed, <i>Test specimen with Polyethylene</i>
VIP-1D_c				Wall specimen with VIP panels & Glass Fibre in exterior and interior cavities <i>Test specimen with Polyethylene, CONDITIONED</i>
VIP-1EE	2	R-VALUE	1 temperature setting (-35 °C)	Wall specimen with VIP panels only (new type, square edges)
VIP-1FF				Wall specimen with VIP panels (new type, square edges) & Glass Fibre in 2"x 4" exterior cavity
VIP-1G				Wall specimen with VIP panels (new type, square edges) & Glass Fibre in 2"x 4" exterior and 2"x 3" interior cavities <i>Test specimen with Polyethylene</i>
VIP-1G		ALT	Air leakage before conditioning, 1000 cycles @ + & -800 pa, 1 burst @ + & -1200 pa. Air leakage after conditioning	Wall specimen with VIP panels (new type, square edges) & Glass Fibre in 2"x 4" exterior and 2"x 3" interior cavities <i>Test specimen with Polyethylene</i>
VIP-1G_c		R-VALUE	1 temperature setting (-35 °C)	Wall specimen with VIP panels (new type, square edges) & Glass Fibre in 2"x 4" exterior and 2"x 3" interior cavities. <i>Test specimen with Polyethylene, CONDITIONED</i>

3.3 Wall Sample Preparation

Figure 3 shows the installation of the first layer of VIP Type 2-Rounded edges (see Table 1). Figure 4 shows the installation of the staggered second layer of VIP Type 2-square edges.

The big challenges in this kind of installation (New Construction) were:

1. Samples that were provided by manufacturers were in different sizes and not optimized and normalized for typical North American wall type construction.
2. In laying out those VIP panels so that they could cover the whole surface of the wall (8'x8') and,
3. In reducing or eliminating the air leakage by sealing edges and connections.

Through trial and error, with feedback from each experiment, new techniques were investigated to achieve superior performance at each stage. For example, VIPs with square edge insulation sandwiched first in thin neoprene layers (Figure 4) and then extruded polystyrene layers seemed to be the favourable

approach to protect the VIPs during fabrication. Using caulking around the edges of the VIPs (see Figure 5) also led to stability of the VIP pieces during assembly and good resultant air tightness and overall thermal performance.



Figure 3: Installation of the first layer of VIP Type 2-rounded edges



Figure 4: installation of the staggered second layer of VIP Type 2-Rounded edges



Figure 5: Sealing edges with silicone



Figure 6: Polyethylene Air & Vapour Barrier sealed on perimeter

Figure 6 shows how to seal the poly-lapped Air/Vapour Barrier meeting the requirement of part 9 of the National Building Code (NBC) [16] and how we insure the continuity of the designated Air Barrier (i.e. 6-mil Polyethylene).

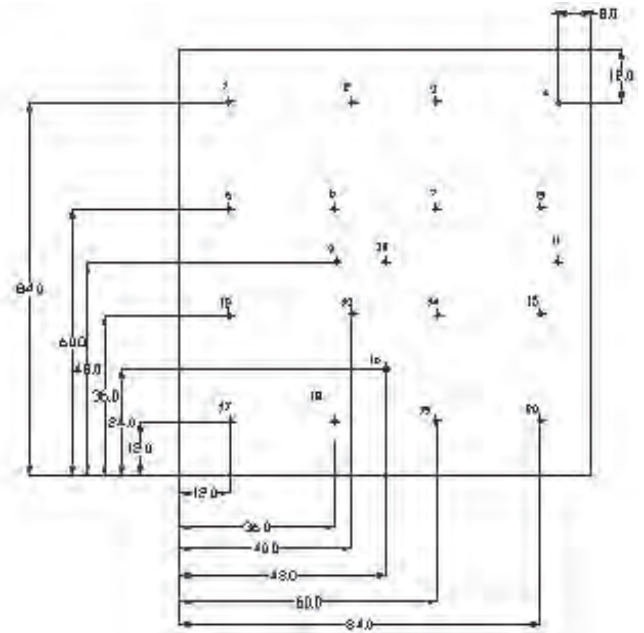


Figure 7 - Surface thermocouples locations (dimensions are in inch).

3.4 Instrumentation of Wall Assembly

Each wall is furnished with an array of thermocouples on interior and exterior surfaces in order to measure Surface-to-Surface R-value Standard Test that was performed in the GHB. Some interstitial thermocouples are also installed to measure the surface temperature of VIPs for future modeling purposes. Figure 7 shows the thermocouples mounted on the wall surface.

3.5 Test Sequence

Each wall sample is subjected to a series of tests. This included:

- Air leakage test before conditioning,
- Sample conditioning,
- Air leakage test after conditioning and,
- Thermal resistance test after conditioning.

It was decided not to measure the R-value before conditioning due to the insignificant impact of conditioning on the R-value for other types of walls [19].

3.6 Sample Conditioning

Each wall is conditioned (after initial air leakage) according to the CCMC guide 07272. Figure 8 illustrates the conditioning pressure cycles.

The wall sample is subjected to cycles of positive and negative pressure as follows (See Figure 8):

- A positive pressure rise from 0 to +800 Pa in 1 second remains constant for 3 seconds, down to 0 Pa in one second and remains at 0 Pa for 3 seconds. This cycle is repeated 800 times
- A negative pressure is applied from 0 to – 800 Pa in one second, remains at – 800 Pa for 3 seconds, increases to 0 Pa in 1 second, and remains at 0 Pa for 3 seconds. This cycle is repeated 800 times.
- Gust wind: two cycles from 0 to + 1200 Pa (and another to – 1200 Pa) in a similar cycle.

Pressure Cycle for Sample Conditioning

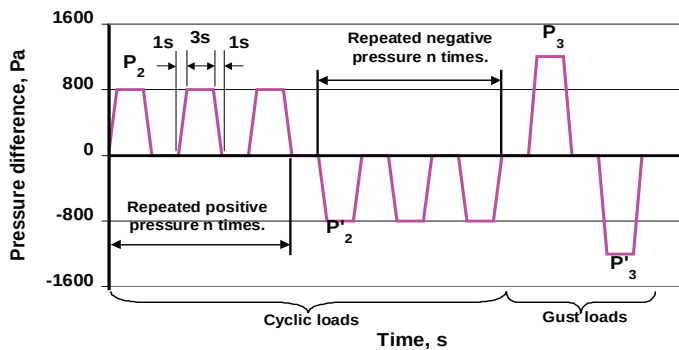


Figure 8: A schematic of the pressure cycle during sample conditioning.

3.7 Material Characterization

The material characterization was performed using heat flow meter according to ASTM C-518-98 standard (ASTM 2004) [18] on all VIPs used in this project. The test specimens were placed horizontally in a 60 cm x 60 cm Heat Flow Meter apparatus. Heat flowed vertically upwards through the specimens during the tests. The thermal conductivity was determined at mean temperature of around $24 \pm 1^\circ\text{C}$. Table 2 provides a summary of the results of VIPs used in different wall assemblies.

VIP Type	$T_{\text{mean}} (^\circ\text{C})$	Thermal Conductivity λ (W/m.K)
Type 1	24.0	0.0032
Type 2	24.1	0.00494

The thermal conductivity of the VIP is an average value of 5 samples.

3.8 Air Leakage Test Results

All wall samples are tested to determine their air leakage performance at different pressure differential [19]. Figure 9 shows a wall mounted in the air leakage tester. Also, the same test facility is used for the sample conditioning.

Following the mounting of the wall sample, the extraneous air leakage (system air leakage) is determined. Ideally, the extraneous air leakage should be less than 10% of the expected air leakage rate (as per the ASTM standard). After many modifications, the system now has zero extraneous air leakage.

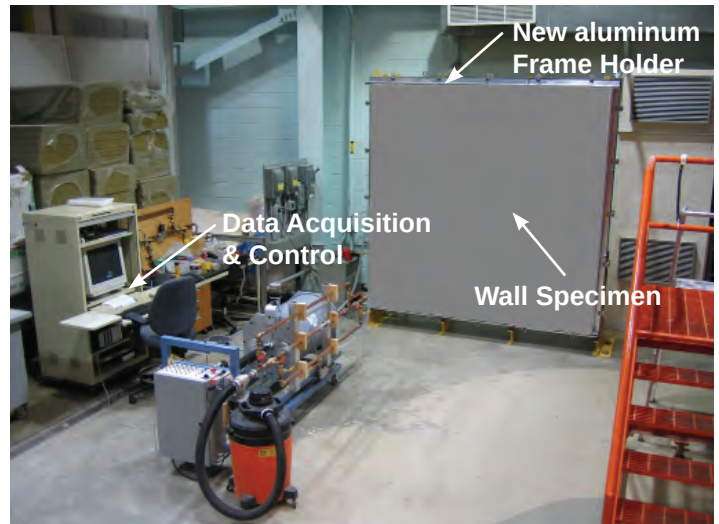


Figure 9: A Wall Sample Mounted in the Air Leakage Tester

Figure 10 shows the air leakage characteristic of the wall VIP-1G after conditioning (see Table 1). The wall sample was subjected to a pressure difference that varied between 0 and ~150 Pa, and determine the air leakage rate. The CCMC Air Barrier Guide sets the maximum allowable air leakage rate for the product to be labeled as “air barrier”. This limit is set to $0.05 \text{ l}/(\text{m}^2.\text{s})$ at $\Delta P = 75 \text{ Pa}$. The results showed that the wall assembly is airtight and well below the CCMC limit @ 75 Pa.

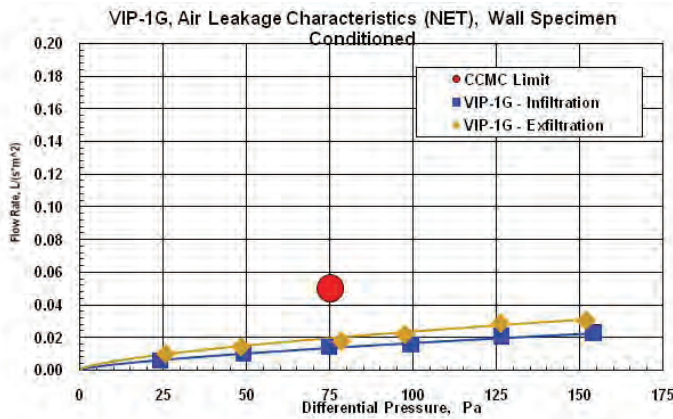


Figure 10: Air Leakage Test Results for Wall VIP-1G after Conditioning

3.9 R-value Test Results

The R-values of all walls are determined in the NRC-IRC guarded hot box facility [20 and 21]. Figure 11 shows a picture of a wall mounted in the mask wall of the guarded hot box.

As indicated earlier, the R-value of some walls was determined after sample conditioning, since there was not a significant change in the R-value after conditioning compared to the values before conditioning. Also, the R-values were determined at a warm side temperature of $20 \pm 1^\circ\text{C}$ while the cold side was maintained at $-20 \pm 1^\circ\text{C}$ and $-35 \pm 1^\circ\text{C}$. Figure 12 is a bar chart showing the R-values (in $\text{ft}^2 \text{ hr } ^\circ\text{F}/\text{BTU}$) of the ten walls at one set of temperature difference. Note that the uncertainty in the measured R-values in the GHB is within $\pm 6\%$ GHB [22].

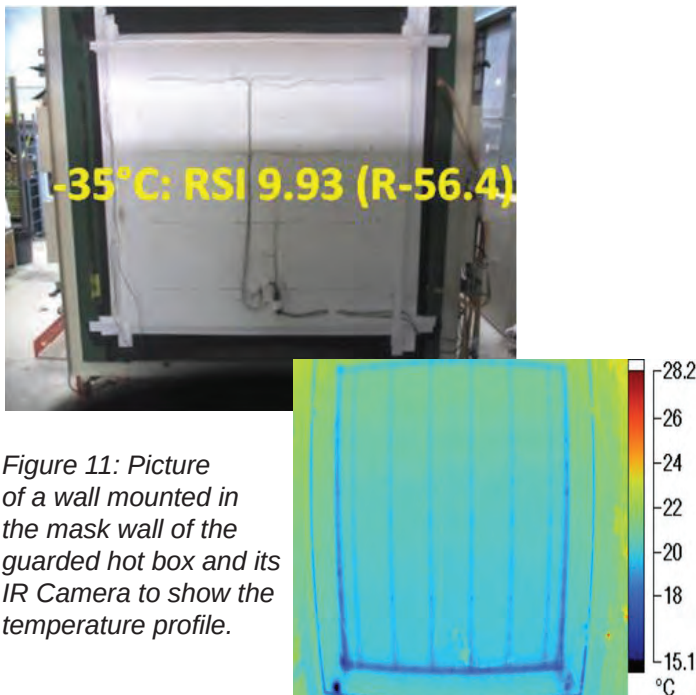


Figure 11: Picture of a wall mounted in the mask wall of the guarded hot box and its IR Camera to show the temperature profile.

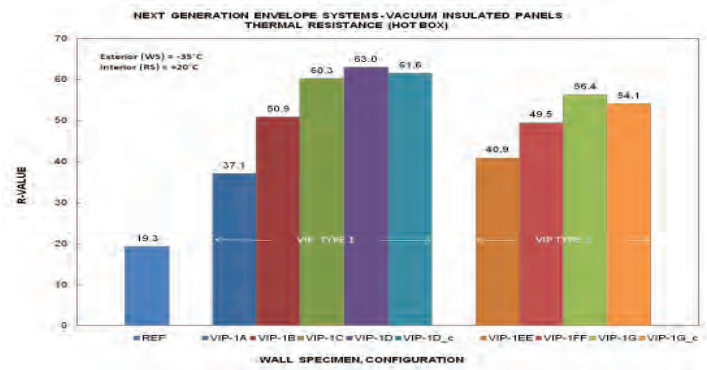


Figure 12: Wall Configuration with Concept 1- Protected Double Stud Summary of Laboratory results (R-Value)

4. Closing Remarks

With the new trend of building energy performance towards Net-Zero-Energy homes with highly insulated walls, the use of VIP could have a role to play in promoting sustainable and eco-friendly houses.

This research was undertaken in support of the uptake of next generation building envelope systems and will enable us to evaluate the innovative technologies in a new and existing housing and commercial building applications.

We learned from our laboratory testing that attention has to be paid to the handling to the edge effect in combination with surrounding material to achieve high levels of airtightness of the wall assembly. A new technique was found during this exercise to overcome to this hurdle using the neoprene on both sides of the VIP.

5. What is Next

This on-going project is, at time of writing, continues to evaluate different wall assemblies with different concepts. A field research project entitled “Field Energy Performance and Hygrothermal Evaluation of Different Strategies of Energy Retrofit for Residential Wood-Frame Wall Systems Field using VIP” has been initiated in order to complement the laboratory work. This research project has been added to an existing work program on field in the context of wall energy retrofit. Other exterior insulation retrofit options were investigated previous to the Vacuum Insulated Panel retrofit systems [23].

The test will be performed in NRC-IRC Field Exposure of Walls (FEWF) test facility for a one year cycle of exposure to outdoor natural weathering conditions. The idea is to examine exterior retrofit, and compare it to a standard retrofit method. The main

focus will be thermal performance, while observing moisture management as well (if a solution traps moisture at the OSB, it is not something that would benefit homeowners).

The advanced hygrothermal tool hygIRC-C will be used at the first stage to design the experiment and then subsequently the model will be benchmarked using the experimental data. Once the benchmarking of hygIRC-C is done, a parametric study will be conducted to investigate the effect of different outdoor and indoor conditions on the thermal performance of those different energy retrofit strategies to assess their energy performance.

6. Acknowledgments

The study team wishes to thank PERD and NRCan committee for their financial support. The authors extended their thanks to Drs. Kumaran and Mukhopadhyaya for their advices and guidance and to Mr. Sherrer for providing us with thermal properties of the VIPs.

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New Modular VIP Systems (For Advanced Handling on Construction Site)

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1. Introduction

After supplying the Building&Construction Industry in Europe with VIPs for over 10 years, two main barriers for further commercialization were identified. Those are availability and complexity of pre-planning.

A lot of customers/users are convinced by the outperforming qualities of Vacuum Insulation Panels and their capability to solve very complex and demanding applications.

Also obstacles such as legal approvals of the building authorities (Fig. 1 + Fig. 2) are overcome.

Several VIP suppliers do have products available that can be used in a lot of internal and external applications based on reasonably low rated values for thermal conductivity.



Fig. 3: Ü-label. External quality control by FIW - Munich



Fig. 4: GSH VIP quality label



Fig. 1: DIBT approval



Fig. 2: Approved building applications

Nowadays, the following steps have to be followed before installing VIPs in the building:

- create site measurements of the area to be insulated
- make a layout drawing of the needed VIP dimensions
- send parts list to the VIP producer
- produce VIPs, according to parts list and mark it according to layout drawing
- deliver VIPs to the building site
- apply VIPs according to layout drawing

Generally, it will take about 15 working days between receipt of the part list (order) and shipment to the construction site.

When talking about the refurbishment of buildings, this delay is usually unacceptable.

Planning phase also takes time and costs money.

Also quality issues are sufficiently managed by external quality controls and quality labels in place, such as Ü-label and GSH quality label (Fig. 3 + Fig. 4).

Special dimensions/shapes, needed to cover 100% of the surface, drives cost as well.

In addition, you need educated and accurate working employees, doing the site measurement as well as VIP laying according to the layout drawing.

In order to achieve a short term supply, all these limitations can be overcome by off the shelf available, smart VIP-systems, based on standard sizes, that can be easily applied with reasonably low thermal performance losses.

The following presentation will show one of these systems in detail including some performance evaluations on the influence of the overall thermal performance.

In addition, some actually available systems will be mentioned.

2. The Vacuspeed® System

It is generally known, that today a huge number of different sized VIPs are used, to cover different surfaces/shapes. As it is not possible to store all these sizes, simple solutions need to be found.

After doing some mathematical calculations, a modular system, just existing of a few standard sizes, turned out to be the optimal solution in terms of minimized remaining areas.

But still, these remaining areas have to be covered. This can be solved by adding cuttable strips of conventional insulation materials. Due to intelligent modular systems, these areas could be minimized to a few centimeters circular (maximum of 12,5 cm).

For sure, using materials with worse thermal conductivities than VIPs will lead to a worse total performance. But after doing intensive calculations by building physicists, the degradation of the total insulation performance is in an acceptable range.

The effects on the U-values in relation to the percentage of conventionally covered area are proven by performance evaluations.

In praxis, the coverage of 94% of the surface should be possible. In this case a U-value degradation of 7 -12 % (depending on thickness) can be expected.

The Vacuspeed® System comprises of four standard sizes – 1.000x500, 500x500, 500x250 and 250x250 mm (Fig. 5).

The cuttable strips (Aluminum covered Polyurethane foam) called Vacuspeed® Cut (Fig. 6) have a dimension of 1.000x125 mm.

Available thicknesses are 15, 20 and 25 mm.

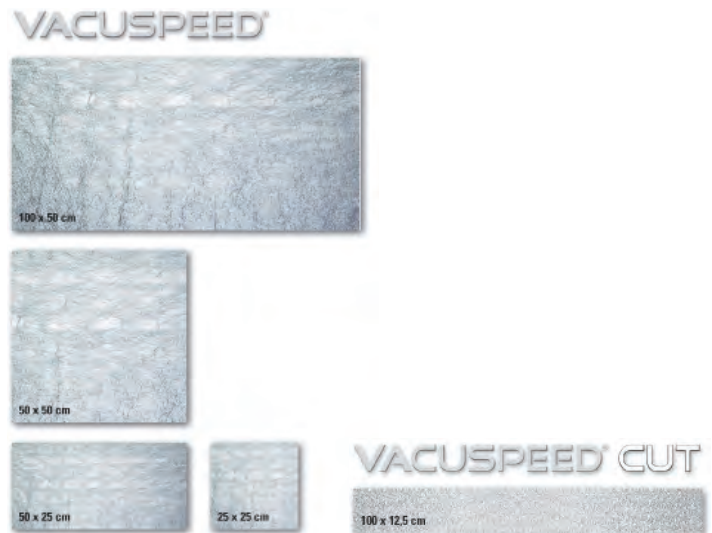


Fig. 5: Standard VIP-sizes Fig. 6: Cuttable PU-foam strip

The VIPs are packed in boxes (Fig. 7), which are specially adapted to the construction site conditions. They are extremely clear arranged, easy to handle, robust and space saving. The packaging units can be moved safely onsite and placed at the building site without problems even via the scaffolding.



Fig. 7: Packaging, adopted to construction site requirements

The surface needs to be measured roughly (Fig. 8), to define the width of the first circular layer of Vacuspeed® CUT.



Fig. 8: Measurement of first circular "Cut"-layer

Cut the strip on size with a commercially available knife (Fig. 9) and set first edge strips. Continue/cover with conventional structure (Fig. 13).



Fig. 9: Customizing of PU-foam strip

Start laying of standard sized VIPs (Fig. 10).



Fig. 10: Laying of modular VIPs

Fit in the final PU-foam strip (Fig. 11).



Fig. 11: Fitting of final PU-foam strip

If requested/required, continue with second layer (Fig.12) for improved performance.



Fig. 12: Laying of second VIP-layer



Fig. 13: Fitting of final floor structure

3. Performance Evaluation

Numerous modeling and simulation has been made in order to find out, what would be the influence of the Vacuspeed[®] Cut to the overall heat transmission coefficient of the covered surface.

The modeling was designed and made by Mühlebach Partner AG [1], a well-known Swiss office for acoustic and building physics.

The basic data used in terms of thermal conductivity for the VIPs, was extracted from a test report to determine the rated value of the thermal conductivity, following the pre-standard SIA 279 [3] and an additional report on the calculation of $\lambda_{25 \text{ years}}$ of VIPs in different sizes, with and without thermal bridge effects [4].

This calculation is basically described by the formula [2] of λ_{eff}

$$\lambda_{\text{eff}} = \lambda_{\text{COP}} + \Psi \times \text{Thickness}_{\text{VIP}} \times \frac{\text{Perimeter}_{\text{VIP}}}{\text{Area}_{\text{VIP}}}$$

with

λ_{eff} effective thermal conductivity of VIP

λ_{COP} thermal conductivity in „Centre of Panel“

Ψ linear heat transmittance

Basic data (Fig. 14) and formulas were transferred to a complex, Excel based calculation program that is available for calculations of single and double layer structures.

In order to achieve thicknesses of 30 mm, a double layer structure is mandatory, as the Vacuspeed[®] system allows thicknesses of maximum 25 mm with one layer only.

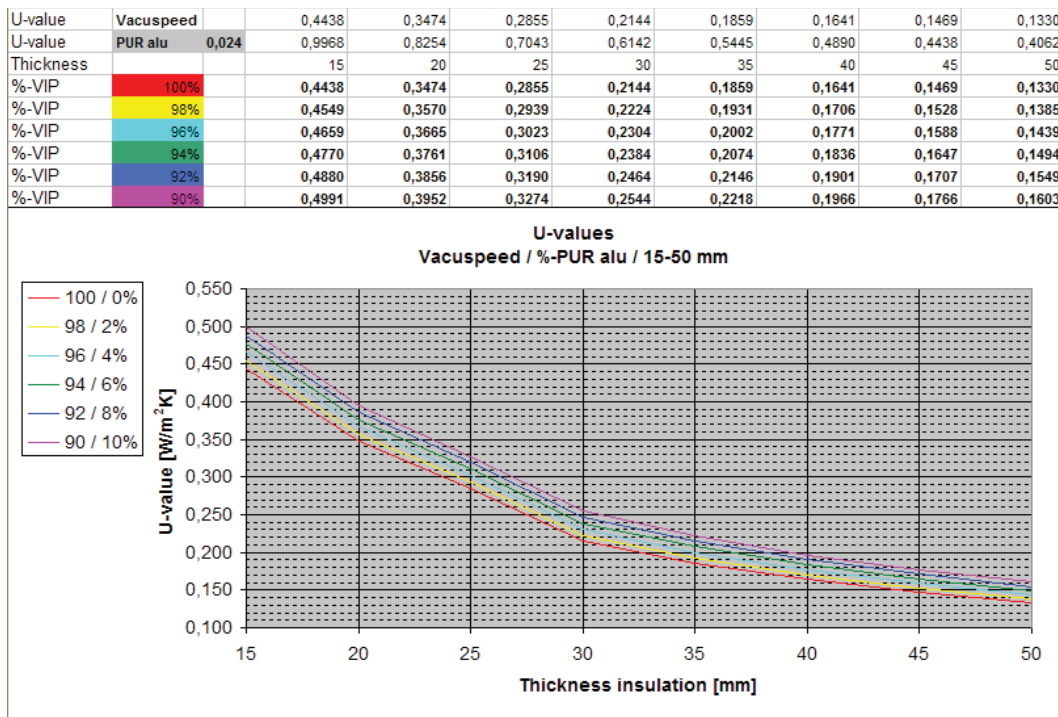


Fig. 16: Table of U-values for a typical flat roof insulation structure, depending on VIP-Thickness and surface – proportion of cuttable strip

Percentages of more than 10 % can only be expected, if surfaces are very small (< 18 m²) and do have an unfavorable room/surface geometry.

In consequence, U-values are between 0,477 W/m²K (15 mm / 6% Vacuspeed® CUT) and 0,149 W/m²K (50 mm / 6% Vacuspeed® CUT)

Compared with a 100% VIP covered surface at the particular thickness, the U-value degradation is around or even below 10%.

Taking into account, that the calculated values are even better than the used λ_D , the degradation would be even lower.

- Paul Bauder GmbH & Co. KG, product name: BauderVIP TE

All these systems are combining standard sized VIPs in modular systems with conventional insulation.

4. Modular VIP Systems on the Market

Following this idea, various systems for facade insulation, flat roof insulation and internal roof insulation are already available on the market.

Such systems are offered for example by:

- Saint-Gobain Weber GmbH, product name: LockPlate (Fig. 17 + Fig.18)
- Saint-Gobain Isover G+H AG, product name: VacuPad 007

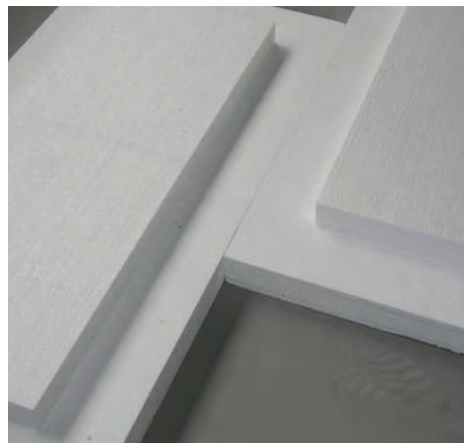


Fig. 17: LockPlate system, Saint-Gobain Weber GmbH

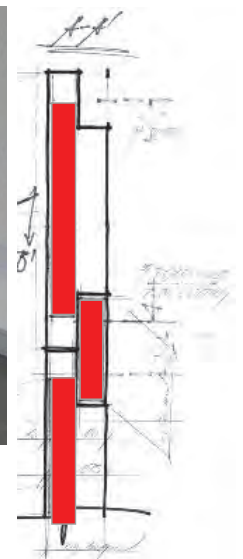


Fig. 18: Sketch of section drawing, showing the function of the LockPlate

5. Conclusion

Modular designed VIP-systems such as the Vacuspeed® system follow the requirements of the building and construction market.

They are easy to use and short term available on the construction site.

Smart packaging allows better handling and secure storage on site.

Even a 100% coverage of the surfaces is not possible in many cases, the impact on the resulting, over all U-value is acceptably low.

Due to the clever system, the remaining areas, that need to be covered with conventional insulation, remain reasonably small.

Therefore modular systems are a perfect solution for building and construction applications, where time/availability is a limiting factor for the use of VIPs.

Most probably these systems will help to bring the benefit of VIPs to this area of application as well.

Survey

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Vacuum Insulated Thermal Storage

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1. Abstract

Thermal energy storage (TES), especially hot water tanks lose energy through the surface. To keep the energy loss low, TES are insulated with materials like Styropor (EPS), Styrodur (XPS) or mineral wool. However, the insulation of TES is not as good as it should be. With Vacuum Insulation Panels (VIPs), it is possible to reduce these losses. We describe a possibility to use VIP for insulating TES. This leads to a reduction of the energy loss. Furthermore, we show that it is also economical to use VIPs for insulating TES.

2. Introduction

The insulation of thermal energy storage (TES) is not as good as it should be. Vacuum Insulation Panels (VIPs) are well known in building insulation for passive houses [1] and are a possibility for TES insulation. This research explores the options to use VIPs for insulating TES. In the last decades, TES became more and more important for space heating of buildings and process heat for industrial processes. Internal energy losses of TES were reduced by using a stratifying system [2, 3]. However, most recent academic research found among other things that particularly the external losses through the covering face of large TES were underestimated [4]. VIPs with a dry, evacuated fumed silicon dioxide SiO_x core have ten times lower heat conductivity compared to conventional insulating materials like expanded polystyrene Styropor (EPS), Styrodur (XPS) or mineral wool [5]. This research project called “small thermal long-term storages” explores theoretically and experimentally the option to use VIPs as an insulation for TES to reduce the external losses. There are few economical and ecological advantages in reducing the external losses of TES:

- With lower energy losses it is possible to reduce the demand of fossil primary energy if the system is heated with oil, gas, etc.. This leads to a reduction of CO_2 emission, which has a special influence with regards to the climatic change [6].
- The advance in energy price, especially gas and oil, are more than the inflation. An academic study, by the German Ministry of Economics and Technologies, estimates the real rise in price at approximately 3.6% [7]. That means lower external losses of TES corresponding to economically measurable values.
- The system efficiency of renewable energy systems is rising.
-

3. Thermal Energy Storage (TES)

3.1 Energy and its storage

Physics deals with energy and matter. The conservation law of energy is a fundamental postulate. The overall energy within an inertial system is constant.

$dE = 0$	(Equation 1)
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There are different definitions of energy (electric, thermal, chemical, kinetic, potential, but also surface, displacement, rotation, drill, etc.). A dynamic process comes along with the change of at least two different types of energy. In the scientific papers of Gibbs, the change in energy can be defined as [8]:

$dE = \xi \cdot dX$	(Equation 2)
---------------------	--------------

where ξ is an intensive value and X is an extensive value. Within an electrical system ξ is equal to the electrical potential ϕ and X is equal to the electrical charge Q ($dE = \phi \cdot dQ$). It is also possible to define the change of thermal energy in the same way:

$dE = T \cdot dS$	(Equation 3)
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where T is the absolute temperature and S is the entropy. Gibbs defined the change in energy with the so-called Gibbs fundamental formulae [8]:

$dE = \phi \cdot dQ + T \cdot dS + p \cdot dV + F \cdot dr + \mu \cdot dn + v \cdot dp + \omega \cdot dL + \phi \cdot dm + M \cdot d\alpha + \sigma \cdot dA + \Theta \cdot d\phi + h \cdot dv + \dots$	(Equation 4)
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Energy storage can always save the extensive value of (Equation 1). Strictly speaking, a TES can store entropy. However, such storage is called heat storage caused by the stored form of energy, which is called thermal or rather heat. Anyhow, in the further sense of this paper about thermal storage, knowing that a thermal storage is strictly entropy storage is important.

3.2 Thermal energy storage (TES)

There are different methods to store thermal energy in the form of energy storage. A possibility to group these different methods is the classification via the physical principle. In this sense, there are sensible heat storage, latent heat storage, thermo chemical storage and sorption storage.

One type of sensible TES is the hot water heat storage. In this case, the sensible heat is stored in a tank filled with hot water. The thermal energy calculation is well known and is defined by:

$Q = m \cdot c \cdot \Delta T$	(Equation 5)
--------------------------------	--------------

where Q is the thermal energy, m is the mass of water, c is the specific heat capacity of water and ΔT is the difference in temperature.

Hot water storage is prone loss as heat is transported through the wall of the storage. This loss results from the heat flow through the coverage is well known as:

$\dot{Q} = \lambda \cdot A \cdot \Delta T / s$	(Equation 6)
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where λ is the heat conductivity, A is the surface, ΔT is the difference between the inner and outer temperatures and s is the size of the material. Briefly, the thermal losses of sensible heat storage depend on the heat conductivity of the insulation.

4. State-of-the-art in Thermal Storage Insulation

The journal Sun & Wind Energy (SWE) has published a state-of-the-market article about solar thermal storages in its December 2009 edition of the journal [10]. This overview of the German market in solar TES comprised 164 solar buffer storages, which can be categorized into 306 different models. The database of these solar TES consists of different values like model type, manufacture, volume, height, size of insulation, type of insulation, price and a few more details. However, storage is not defined for each value. The information about the insulation is set for 196 storages. Therefore, it is possible to calculate the overall heat transfer coefficient (U-value) for these storages (see Figure 1). The insulation of TES with a volume up to 30 cubic meters with an U-value up to 0.25 W/(m²K) and TES with a volume above 30 cubic meters up to 300 cubic meters with an U-value up to 0.18 W/(m²K) is termed TES with conventional insulation.

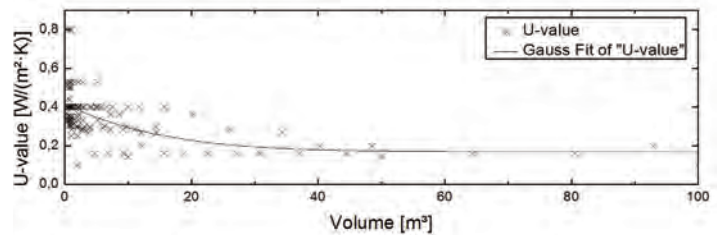


Figure 1: Overall heat transfer coefficient (U-value) of solar TES based on the state-of-the-market overview in the December 2009 edition of SWE [10].

² Strictly speaking, also the heat capacity is based on the physical entropy capacity. Further information about the discrepancy of heat and entropy can be found in [10] and [11]. This discrepancy was found by the then President of the Physical Society of London, H. Callendar in 1911 [9].

5. Advantages in VIP

The physics of the heat conductivity through evacuated insulation material are well known. The heat conductivity in porous materials, such as foamed silica, can be divided into four different heat transfer processes. In the dissertation of Schwab [5] these processes are described by a diffusion model summing up the heat conductivity through the solid skeleton of the core λ_{cd} , the heat conductivity of the gas inside the skeleton λ_g , the heat conductivity via radiation λ_r and a coupled heat conductivity term $\lambda_{coupling}$ [11]:

$\lambda = \lambda_{cd} + \lambda_r + \lambda_g + \lambda_{coupling}$	(Equation 7)
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By evacuating a solid material with open pores, the heat conductivity of the gas inside the skeleton λ_g can be reduced to a calculation value of $\lambda_g = 0 \text{ W} / (\text{m}^2\text{K})$ [11]. The smaller the diameter of the pores, the higher is the pressure of the gas. In Schwab [5] this effect is described by:

$\lambda_{G0} = c_p \cdot \rho \cdot l_G \cdot v / 3$	(Equation 8)
---	--------------

where c_p is the specific heat capacity, ρ is the gas pressure, l_G is the average free length of path and v is the velocity of sound. Detailed information about the physics of the heat conductivity through evacuated insulation material can be found in [5].

The heat conductivity of VIPs with fumed silicon dioxide is reduced on the one hand by small pore diameters and on the other hand by lower pressure of the air inside the pores with a pressure around 10^{-3} bar [11]. In Schwab and Fricke, the overall heat conductivity is described as an overlap of the heat conductivity through the solid skeleton of the core λ_{cd} and the heat conductivity via radiation λ_r , where λ_r is proportional to the cube of the temperature [12] (see Figure 2).

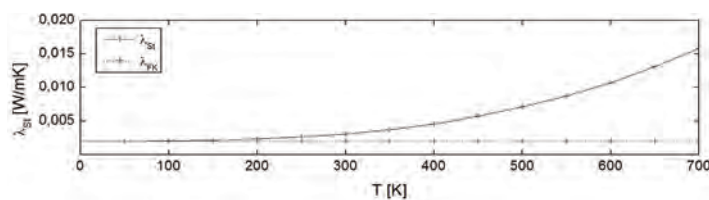


Figure 2: Overall heat conductivity of a VIP with a fumed silicon dioxide core (redrawn from [5]).

The results of the measurements of VIPs made by the Munich Research Institute for Heat Insulation (FIW) with a fumed silicon dioxide core manufactured by Variotec lead to a conductivity of

0.0048 W/m²K [13]. There are a few advantages in using VIPs for the TES insulation. On the one hand, there is the possibility to enlarge the net volume of a tank (with the same gross volume and the same U-value), and on the other hand, the U-value can be enlarged with the same size of the insulation compared to conventional insulated TES. These are the same reasons for which VIPs are well known in building insulation, especially in passive houses. [14]

6. Concept of the Storage

During the time of the research project, two concepts were found to be highly economical. The first concept is a cubic storage with a sandwich wall. The second concept is a cylindrical storage with tubing segments. In this paper, the second concept is described. For a long time, street and railway tunnels are being built with tubing segments. In the past 34 years in Germany, tunnels with tubing segments were built with a length of three kilometers each year [15]. The manufacturer Max Bögl produces tubing segments with different diameters. The concept of the described storage is a modification of a standard tubing segment. The construction of great radial VIPs is not economical and is technically complex. Therefore, the inner side of the tubing segment is constructed linearly and not radially. By adding eight tubing segments to a circle, an inner octagon is formed (see Figure 3). This leads to a modular and economic system that brings storage with different diameters and heights. The storage wall is built with a concrete tubing segment, an inner VIP with a core size up to 100 mm and an inner synthetic foil. The constant temperature resistance of the VIP is defined at 120° C. The coverage has an U-value between 0.05 and 0.10 W/(m² K). Therefore, the external thermal losses of the sensible heat storage are about two to five times lower than the conventional insulated TES.

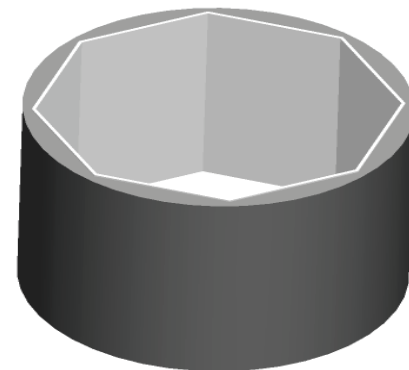


Figure 3: Computer aided design (CAD) model of the cylindrical storage with the inner octagon.

7. Experimental Storage Sengenthal

Within this research project, some experimental storage will be built to test the reducibility of VIP insulated TES. First, the target of this experimental storage is to analyze the producibility of a VIP insulated tank. Therefore, especially the thermal losses will be monitored with infrared thermography, temperature sensors and heat flow sensors within real conditions. One of these storages will be a 200-cubic meter storage at the premise of Max Bögl in Sengenthal (Germany). So far, some of the space heating, domestic water heat and process heat is generated by a local heating plant. The sources of the local heating plant are a firewood boiler and an additional gas boiler. The gas boiler is needed because of the high demand in the winter and the undervalued demand in the summer (see Figure 4).

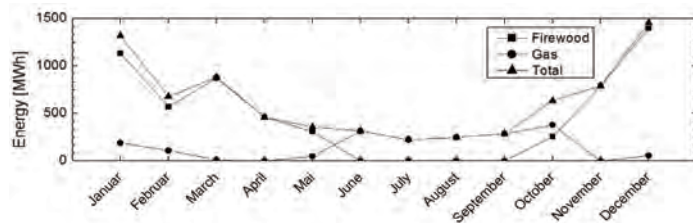


Figure 4: Thermal energy demand of the local heating plant at the premises of Max Bögl in 2009.

A new accommodation facility will be built in the next month with a further demand of 400 MWh each year. So far, there is a plan to install an additional gas boiler to cover the further demand of the building, because the local heating plant is not able to cover the demand of the new building in winter. With the high-insulated TES, it is possible to integrate the new building in the local heating plant and cover the demand of the new building with renewable energy sources. Therefore, an additional solar thermal collector system with about 300 m² will be installed and the storage will be fed when the thermal power output of the firewood boiler is not at the maximum level.

8. On the Economics of High-insulated TES

The question on economics is significant in achieving the target of an economical high-insulated tank. To get an answer for this question three sub-targets have to be analyzed:

- Define the price for a conventionally insulated TES.

- Define the advantage in price of fossil fuel energy sources.
- Define the savings of a high-insulated TES.

The answer for these three questions will lead to the answer of the economics of the high-insulated TES.

8.1 Market price of TES

In the article of D. Mäueler [10] in the SWE journal, a list of 296 solar TES with a defined sum price was provided. These storage data were used to set up a storage database with information about different TES. With this database, it is possible to calculate the specific sum price of a cubic meter storage volume of each storage. Therefore, the sum price of the entire storage is divided by the net volume of the TES. This ratio is a first economical indicator (see Figure 5). However, some of the storages have no recorded sum price. Especially storages with volumes above 6 m³ are not listed with information about their prices. Anyhow, the specific sum price is lower with bigger net volume. Additionally, the variance in price as well as the maximum and minimum price declines with bigger net volume (see Figure 6). To illustrate this topic, the solar TES were grouped and classified by their net volume. Figure 6 shows the grouped data with their minimum, maximum and mean sum prices. The mean specific sum price tends to a price of about 900 Euros per cubic meter.

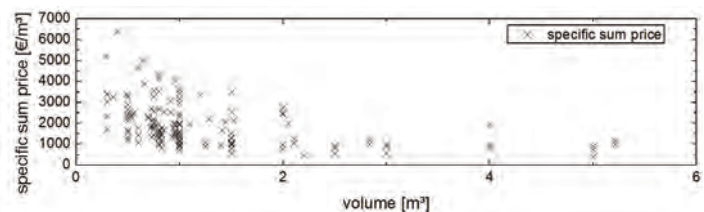


Figure 5: The x-axis shows the specific sum price in Euros per cubic meter storage volume, the y-axis shows the overall net volume of the storage based on the state-of-the-market overview in the December 2009 edition of SWE [10].

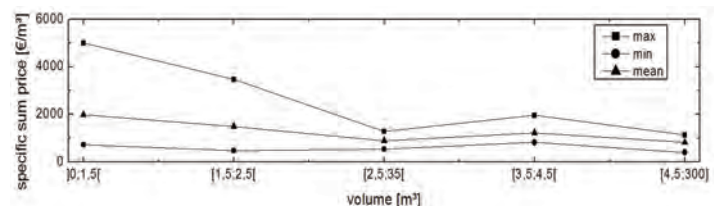


Figure 6: Classified specific minimum, maximum and mean sum prices of solar TES based on the state-of-the-market overview in the December 2009 edition of SWE [10].

Unfortunately, the information about storage arranged by Mäueler gives no information about storage with volumes up to 300 cubic meters. To deal with this problem, the information database has to be extended. The Swiss manufacturer Jenni produces solar TES with volumes up to 300 cubic meters. However, Jenni also only lists prices for storage up to 20 cubic meters [16]. This is because the number of storages with big volumes is less for bulk production, and so the price of such storages will be higher than it normally should be (see Figure 7).

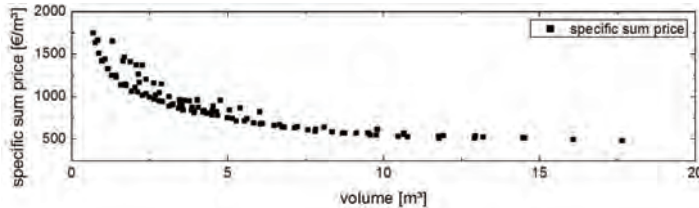


Figure 7: Specific sum price in Euro per cubic meter for Jenni TES (data [16]).

In Figure 6 and Figure 7, it appears that the prices of Jenni are a bit under the mean market price. In other words, the prices of Jenni are placed lower than the mean market prices. In contrast to the database of Mäueler, it is possible to calculate the specific sum price of a square meter of solar TES. This ratio is the key index for calculating insulations for TES (see Figure 8). With the expanded database, the mean specific sum price of a square meter of storage coverage can be estimated to be 200 Euros. With an implied profit margin of 50% the maximum net cost of a square meter is 100 Euros. In the studies of Ochs, the specific price for large storages up to 10,000 m³ is about 100 Euros per square meter [17].

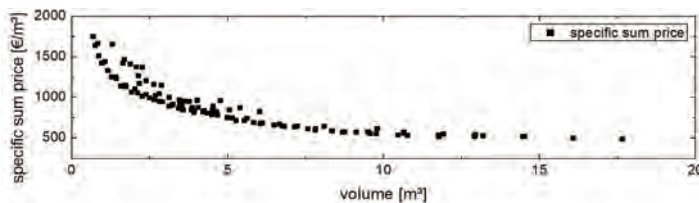


Figure 8: Specific sum price in Euros per square meter storage cover of Jenni TES (data [16]).

8.2 Advantages in energy prices

By knowing the market price of conventional insulated TES, it is necessary to estimate the energy savings and the resulting economical price advantages. The government of Germany published an energy forecast with real advantages in price of about 3.6% [7]. For calculating the energy cost savings this number is taken as the reference. With a current gas price of 5.19 Euros per kilowatt-hour, Figure 9 shows the advantages in the gas

price. Based on this study the mean gas price will be 11.47 Euros within the next 40 years. However, the forecast of energy prices within this long period is not possible (see [7]).

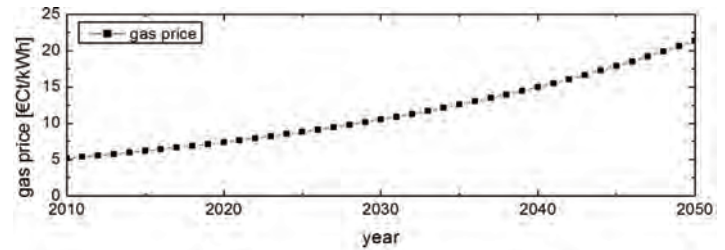


Figure 9: Gas price within the next years according to the inflation rate by Erdmann [7].

8.3 Energy savings

Simulations with the transient systems simulation program (TRNSYS) show that the energy savings of the storage compared to conventional insulated TES within the lifetime period of 40 years of the TES will be about 10 MWh each year. With the coverage of 200 m² that means an energy saving of 50 kWh/m² each year. This leads to a total energy saving of 2 MWh/m³ with an economical saving of about 200 Euro per square meter. Hence, the energy savings can cover the costs for VIPs over their lifetime.

9. Conclusion

Nowadays TES are insulated with conventional insulation materials like EPS or XPS. Thermal losses are quite high and can be downsized by better insulation. A possibility to solve this problem is the usage of VIPs for TES insulation. Therefore, an economical modular concept has been designed with a concrete storage wall insulated with VIPs. The energy savings can cover the additional costs for the insulation over the lifetime of the storage. This paper shows that it is theoretically possible to insulate thermal storages up to 300 cubic meters with VIPs. To test the reducibility and measure the exact thermal losses an experimental TES with VIPs will be researched at a premise in Sengenthal (Germany). After further experimental research on the VIP insulated TES as well as computational fluid dynamic (CFD) simulations and TRNSYS simulations, models will be validated. The project will also provide a computer tool to design VIP insulated TES.

10. Acknowledgment

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VIP System Retrofits of Heritage Buildings

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For heritage masonry buildings, the addition of interior wall insulation is a challenging task. Particularly in cold climates, there can be problems relating to moisture build-up, condensation, structural timber rot and freeze / thaw damage. Generally because the interior heritage appearance must be maintained, there is also limited space available between the inner stone wall face and the interior plaster finish (75mm approx.). Because of this limited space, vacuum insulation panels (VIPs) offer some obvious advantages. However because VIP's are perfect vapor barriers, there is no inward drying and for some installations, it can be a risky retrofit because of variable factors such as material porosity, masonry cracking and local wet spots.

For widespread use particularly for high profile heritage projects; there is a need to develop more robust VIP installation strategies. One option is incorporate a narrow, ventilated and depressurized cavity adjacent to the stone wall. To demonstrate this strategy, it is planned to retrofit VIP insulation to a 1820s stone farmhouse adjacent to the Ecotay Education Centre near Perth, Ontario. This energy retrofit project will also feature stratified air ventilation systems and high-R performance upgrades to the heritage windows and doors. A prototype wall assembly will be installed during summer / fall 2011 and the demonstration project completed a year later. The durability performance of the cavity wall assembly will then be extensively monitored for a minimum of five years.

1.1 Change of Focus

Originally, the intention was to submit a conventional academic paper, but due to my research partner's sudden and serious illness, the detailed energy analysis work has not been completed. As a result, I have been forced to improvise and adopt a more informal approach. Generally, this paper focuses on my plans to retrofit VIP technology to my heritage farmhouse and the system technology that is being developed specifically for heritage retrofit applications.

1.2 The Heritage Challenge

In 2005, armed with a strong passion for history and architecture, I purchased a heritage stone farmhouse near Perth, Ontario. The stone house was built in stages with the original ground floor/ basement constructed in the early 1820s. A second story, also made from stone was added in the 1840s and a third story added in the 1860s using wood-plank construction.

Before buying the house, an energy analysis was completed to evaluate its performance and the result was a 29 EnerGuide rating. In comparison, a typical new house constructed to Canadian building code standards has a 75 EnerGuide rating and an advanced passive solar house has a 85 EnerGuide rating or higher. Although the energy rating was a disappointment, it was no surprise. As an architect and inventor, I was ready to take on the challenge to radically upgrade the energy efficiency of this historically significant heritage building. Although it has taken some time and several design strategies and options have been explored, I am now ready to move forward with what I am calling the Upper Canada House demonstration project. It should be noted that Upper Canada is the former name of Ontario when it was under British rule.

2.0 Interior VIP Retrofit Wall Assembly

2.1 Narrow Interior Cavity for Wall Insulation

Adding wall insulation is perhaps the most demanding task of upgrading a solid masonry building. Initially, I toyed with the idea of putting insulation on the exterior but like most homeowners who live in heritage houses, I made the decision that the exterior appearance cannot be altered and that the insulation had to be added on the interior.

In retrofitting interior insulation, I also made the decision that the inside appearance of the building could not be altered and that in particular, the heritage window moldings and surrounding wood paneling could not be modified. For a masonry building

constructed from fieldstone, wood studs (25mm x 50mm) are typically fixed to the rough uneven inside face of the stone wall and these studs support a lathe-and-plaster assembly. Generally, there is about a 75mm spacing between the inside stone wall surface and the interior plaster wall surface. By replacing the lathe-and-plaster assembly with a special gypsum board and a veneer plaster finish, a cavity of approximately 65mm can be created. For heritage interior insulation retrofits, this is typically the maximum space available.

Given this narrow cavity space, I rejected the use of conventional insulating materials like spray foam or rigid foam sheet because the performance improvement would be too limited especially taking into account the high cost of removing and restoring the interior plaster finish. I checked out the use of fiberglass reinforced aerogel insulation but because of the material's high cost, I also rejected this option. Generally after reviewing the different options, I concluded that VIPs have the potential to become the most cost effective option for this type of heritage retrofit application especially once VIPs are manufactured in high volume in North America.

2.2 Building Science of Interior Wall Insulation

For the past 50 years, the building science of adding interior insulation to solid masonry walls has been extensively studied. The prime concern is condensation within the wall assembly and this condensation can result in frost/thaw damage, mold and wood rot. Different studies have documented and evaluated alternative insulation / barrier design strategies with a common theme being the need to reduce air leakage and the resulting potential for winter time condensation. An early Canadian National Research Council study [1] by Grant Wilson documented that in the summer months, surface moisture exposed to sun is transferred by diffusion towards the inside of the stone wall and this solar thermal pump effect is a prime cause of summer time condensation. .

One influential and authoritative publication on interior insulation retrofits [2] has been written by John Straube, Building Science Corporation. In his paper, Straube reviews the moisture control principles that must be followed for a successful insulated retrofit of a load bearing masonry wall and he presents and compares alternative retrofit strategies. In general, Straube stresses the importance of providing for inward drying and even if this drying capacity is not generally required, it is an essential safety factor if any unforeseen moisture problems occur within the wall assembly.

2.3 VIP Interior Retrofits of Masonry Walls

In recent correspondence with John Straube regarding VIP retrofits, it is his view that most masonry buildings can be successfully insulated on the interior. However, it is not a blanket recommendation and careful review and assessment of each application has to be carried out. One concern is that even if considerable care is taken in taping and sealing the joints between the VIP panels, some air leakage is inevitable. As a result if any gap is left between the VIP panels and the rough stone wall, this will set up convective loops that will transport interior moisture and heat to the cold stone surfaces. Particularly with field stone construction, Straube recommends that a flexible conforming, air impermeable foam material is adhered to the VIP back face. To protect the VIP panel from mechanical damage, rigid foam is also typically located in front of the VIP front face. Despite these various precautions being taken and because there is no inward drying, there always remains some uncertainty whether there will be future moisture build-up problems caused by factors such as material imperfections, surface cracks and local wet spots. Because of these potential retrofit problems, it is my opinion that if architects are to be convinced to specify VIPs for high profile heritage projects, there is a need to develop more robust installation strategies.

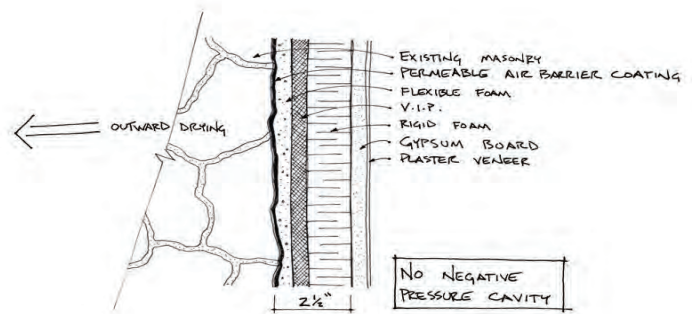


Figure 1. Wall cross section of VIP interior retrofit using flexible foam material

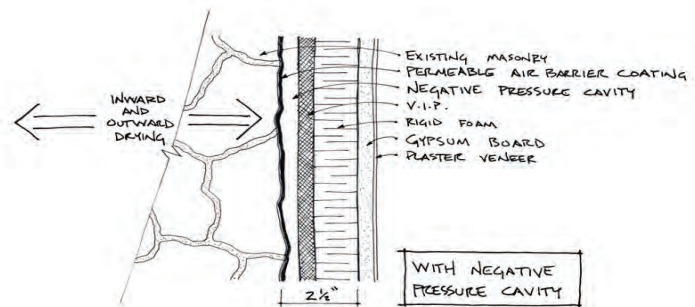


Figure 2. Wall cross section of VIP interior retrofit with negative pressure cavity

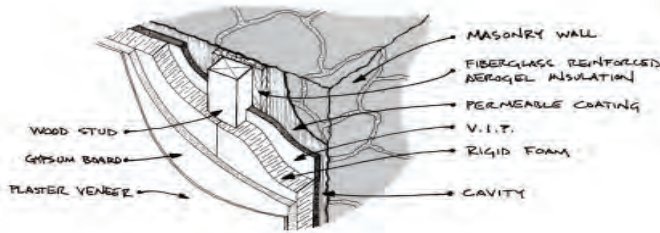


Figure 3. Sketch detail of VIP Interior Retrofit with negative pressure cavity

2.4 VIP Negative Pressure Cavity Installation

To provide for a more robust installation strategy, my proposed approach is to incorporate a narrow ventilated and depressurized cavity adjacent to the stone wall. This strategy is similar to the ECHO basement system pioneered by Doug Walkinshaw in the early 1990s. With the ECHO system, a small variable speed 60 watt blower is used to continually exhaust air at a low rate to the outside from a sealed cavity created around the basement living space. Designed to provide improved air quality by preventing moisture and soil gases such as radon from entering the basement space, this system has a proven twenty year track record.

For VIP stone masonry walls, the continually vented, negative pressure cavity provides for inward moisture drying. To protect the front face of the VIP panel from mechanical damage, the panel is typically installed in combination with rigid foam insulation and the joints between the rigid foam sheets are carefully sealed to form a warm side air / vapor barrier. If there is any air leakage through the sealed joints, the warm moist air is diluted and then extracted through cavity ventilation. Consequently, the strategy is robust and there should be no condensation problems occurring within the wall assembly.

To prevent any localized water leaks, a liquid-applied, highly vapor permeable air and moisture barrier is installed on the back face of the masonry wall. This coating acts as a cold side air barrier and being permeable, it allows for vapor to move in either direction. Various coating materials are commercially available and one preferred material is a silicone elastomeric coating manufactured by Dow Corning.

In the winter, the incoming cold dry air to the cavity can be preheated by a ground loop heat exchanger and in the summer, the same ground loop heat exchanger can cool and dehumidify the incoming hot moist air. The thermal mass of the stone wall construction provides for stable temperature conditions within the cavity and so the VIP assembly is not excessively stressed due to differential expansion. Heat loss across the cavity is reduced by

the VIP metalized packaging acting as a low-emissivity coating. To prevent cold bridges, fiberglass re-enforced aerogel insulation is positioned in the cavity space behind the wood studs. Because the aerogel insulation is permeable, it is kept dry because of the constant cavity ventilation.

For the Upper Canada House Demonstration project, it is planned to demonstrate the vented cavity VIP installation strategy. By installing the VIP panels on an actual heritage building, there are a series of demanding details (e.g. fireplaces) that need to be worked out and demonstrated. The prototype VIP installation will also be monitored to ensure that the design is effective and that there are no technical concerns with the proposed retrofit strategy.

3.0 Heritage Retrofit VIP System Technology

3.1 Air Stratified Ventilation Systems

In addition to providing high insulation levels in a limited cavity space, VIP technology also facilitates the retrofit of less visually obtrusive and more energy efficient HVAC systems. Traditionally, stone heritage houses were heated by wood fireplaces and later wood stoves. Centralized ducting systems were not commercialized until the early 20th century. In the case of my farm house, a centralized ducting system and oil furnace was retrofitted in the 1970's. The ducting system provided heat to the main living rooms but in doing so it destroyed the heritage integrity of the original 1820's ground floor rooms. A key goal of the Upper Canada demonstration project is to remove this visually obtrusive ducting system and retrofit a stratified air ventilation system.

With stratified ventilation systems, preheated outside air is directly introduced at a low velocity at floor level and at a temperature around 19 to 20 °C. The air slowly rises to the ceiling where it is fully exhausted from the room. Thermal plumes rising from people and equipment help to draw cool air up from the floor and further improve air quality. At the present time, detailed system evaluation and monitoring of air stratified ventilation systems is being carried out at the Indoor Environment Research Facility at the Canadian National Research Council.

Typically, air stratified ventilation systems are used for non-residential buildings where cooling loads dominate. For residential buildings, there is concern that perimeter heating can destroy stratified conditions and adversely affect air quality. By raising surface temperatures, high performance VIP insulation can eliminate the need for perimeter heating systems and so help facilitate the retrofit of stratified ventilation systems.

Traditionally houses were planned with a centralized hall / staircase and individual rooms. By utilizing the staircase and centralized halls for air distribution and with supply air entering the individual rooms under the doors, the stratified system only requires small 50 mm diameter exhaust ducts that can be easily hidden within the interior walls. The key advantage of individual rooms is that it is easier to provide variable comfort conditions and energy is not wasted on heating and cooling unoccupied rooms. For heating, room temperatures can be fine-tuned to individual preferences by using radiant heating panels or fast response infrared light bulbs. For cooling, room temperatures can be varied by adjusting ventilation exhaust rates and if required, this can be supplemented by radiant cooling panels operating from ground source cooling.

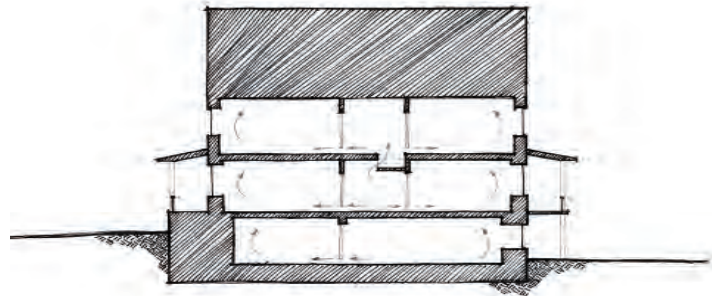


Figure 6. Cross Section B- B of Upper Canada Demonstration Project

3.2 High Performance Windows and Doors

For air stratified ventilation systems to work effectively, there is also a need to prevent window down drafting and this requires that the energy performance heritage windows and doors are upgraded substantially. For the Upper Canada demonstration project, some of the wood windows are nearly two hundred years old and these historic artifacts have to be retained and restored.

My background is in insulating glass industry and for the Upper Canada demonstration project I am working on the development of two new energy efficient window products. One product for operable windows is a removable, lightweight, multi-layer plastic glazing panel (RSI 4 performance) that largely overlaps the VIP insulation in the deeply recessed window opening. A second product is a new encapsulation technology where the sash windows are fixed in position and incorporated within a triple glazed window (RSI 3 performance).

With the introduction of VIP technology, it is likely that the commercialization of vacuum insulating glass units (VIGs) will be accelerated. It is apparent that if wall insulation is RSI 15 or higher, window performance needs to be upgraded accordingly. At present, first generation VIG products are imported from Japan and next year, Guardian Industries plans to set up a North American VIG production facility. In the future, by incorporating multiple glazing films and multiple low-e coatings, second generation VIG products can be developed with a center-of glass performance in excess of RSI 10.

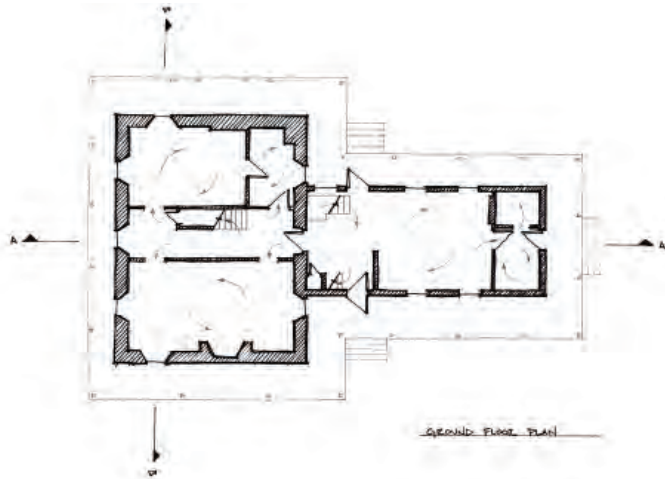


Figure 4. Ground Floor Plan of Upper Canada Demonstration Project

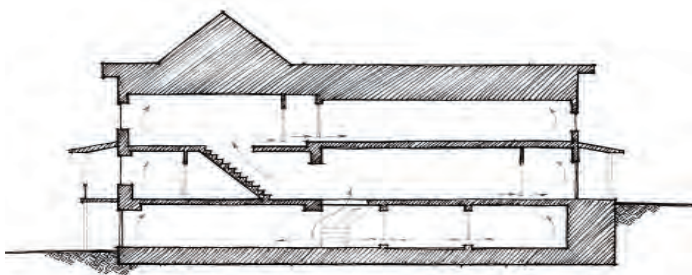


Figure 5. Cross Section A- A of Upper Canada Demonstration Project

4.0 Post Script

4.1 *Project Schedule*

For the Upper Canada House project and depending on the availability of VIPs for the Canadian market, it is planned to install a prototype VIP wall assembly during the summer / fall 2011. The detailed installation techniques will be evaluated and modified as required. The goal is to have fully completed the demonstration project by summer / fall 2012. The durability performance of the cavity wall assembly will then be extensively monitored for a minimum of five years.

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Technical Session 4

Application of VIPs in Construction –III

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Double Layered Vacuum Insulation Panels

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Abstract

Double layers of vacuum insulation panels (VIP) are used more and more, as low energy houses, passive houses, or even energy plus houses are built in an increasing number.

The required thickness of primarily 2 cm VIP in 2004 has reached a value of up to 6 cm by end of the decade. Hence a VIP double layer represents an alternative to thick single layers. The presented study on staggered, non-staggered and thick single layer versions deal with these alternatives tackling thermal bridge and aging effects, which are both dependent on VIP thickness.

1. Preface

The situation of a double layered VIP shall be looked in the perspective of the procedure described in RAL-GZ 960 or the Swiss Quality assurance and declaration procedure, as it was presented at last IVIS. [Brunner, IVIS London2009].

Vacuum insulation panels of a major manufacturer are considered here:

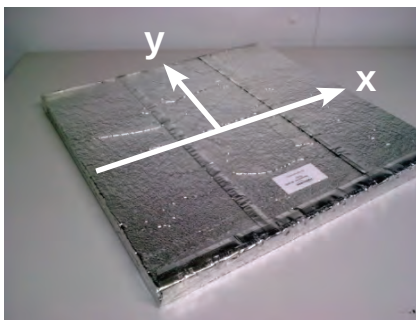
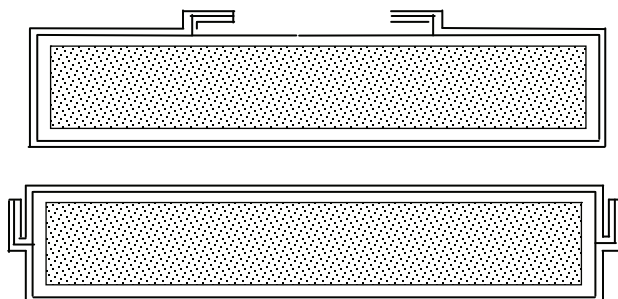


Fig. 1: Left: Picture of a vacuum insulation panel (VIP), right top: schematic cross-section through this VIP along the x-axis. Below: the cross-section along the y-axis.



2. Single Layer

Before looking at the double layer, a single layer shall be considered to have the data, needed to compare it with the former.

A gap of about 3 to 4mm was seen to be typical for installations of VIP on flat roof constructions. [Brunner2008 Vacuum], due to length and width tolerances. So higher edge effect values are now considered, other than in Empa's publication 2004 until 2008, where the ideal potential of VIP was searched. (not forced together anymore as in [GhaziWakili2004], where also rubber sheets had been used, because the aluminium thickness investigated there ranged up to 8 μm . Now a laminate with 3x 100 nm is used with a total thickness including polymeric layers of measured 94 to 98 μm . This laminate type was already investigated in [Brunner2006 FIB] and [Brunner2008 FIB] and is called there Laminate L1.

Intermediate note 1:

The Laminate L1 is called MF2 in [Simmler2005], and MF4 in [IEA Annex39 report Subtask A].

Edge effect type Psi 1 Edge effect type Psi 2



Fig. 2: Picture of the VIP for thermal bridge determination. Two of each of these VIP types, were joined for the measurements in the guarded hot plate device.

Table 1a: Results of thermal bridge measurements with single layer VIP.

Thickness	Measured thermal conductivity mW/(m·K)	Type	Ψ_{joint} W/(m·K)	$\Psi_{\text{edge, without seal}}$ W/(m·K)
15 mm	5.5	Psi 1	0.022	0.011
30 mm	5.5	Psi 1	0.016	0.008
40 mm	5.5	Psi 1	0.009	0.005
Thickness	± ca 0.1 Measured thermal conductivity mW/(m·K)	Type	Ψ_{joint} W/(m·K)	$\Psi_{\text{edge, without seal}}$ W/(m·K)
15 mm	6.3	Psi 2	0.032	0.016
20 mm				0.0147 ¹
30 mm	6.7	Psi 2	0.023	0.012
40 mm	6.8	Psi 2	0.017	0.009

As average, e.g. without considering exact sealing situation, the following ψ -values are recommended to be used (in Switzerland) for this VIP-product (including a common gap between the VIP-cores with often 3mm)

Table 1b: Thermal bridge effect Ψ with single layer VIP, as an average of edges with and without seals.

$\Psi_{10 \text{ mm, edge}}^1$	= 0.020 W/(m K)
$\Psi_{15 \text{ mm, edge}}$	= 0.014 W/(m K)
$\Psi_{20 \text{ mm, edge}}^2$	= 0.012 W/(m K)
$\Psi_{30 \text{ mm, edge}}$	= 0.010 W/(m K)
$\Psi_{40 \text{ mm, edge}}$	= 0.007 W/(m K)

This includes a common gap between adjacent VIP's which is found to be typically 3mm.

The above value for the 20 mm panel is higher than the value 0.009 W/(m K) in [GhaziWakili2004], as that one was a Psi 1 situation only. This value fits well with the results obtained for 15 and 30 mm VIP's (0.011 resp 0.008) in Table 1a considering the deviation of ± 0.0016 W/(m K) given in [GhaziWakili2004].

¹ Value obtained by extrapolation (non-linear)

² value obtained by interpolation

3. Double Layered VIP – Staggered Situation

As described already in the paper [GhaziWakili2011] published recently.

Different thermal bridge situations B to E do occur:

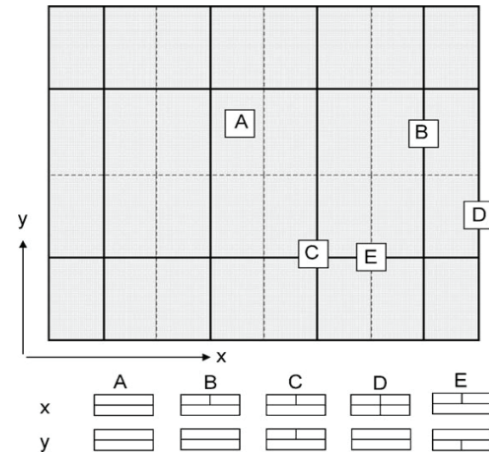


Fig. 3: Double layer of VIP's staggered in the x- and y-directions and the cross-sections of four different types of thermal bridges: (A) undisturbed double layer, (B) single joint in one layer, (C) cross joint in one layer, (D) single joint through both layers and (E) skew cross joint through both layers. Dashed lines indicate the lower VIP layer. Image from [GhaziWakili2011]

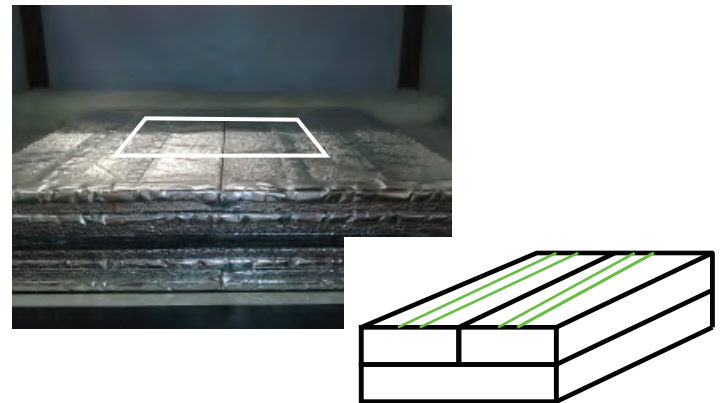


Figure 4: Situation B1, single joint in one layer with vertical projected measuring zone (blue) of the guarded hot plate.



Figure 5: Situation B2 single joint with seal in one layer. A typical gap between the VIP cores can be seen at this 40mm + 40mm situation.

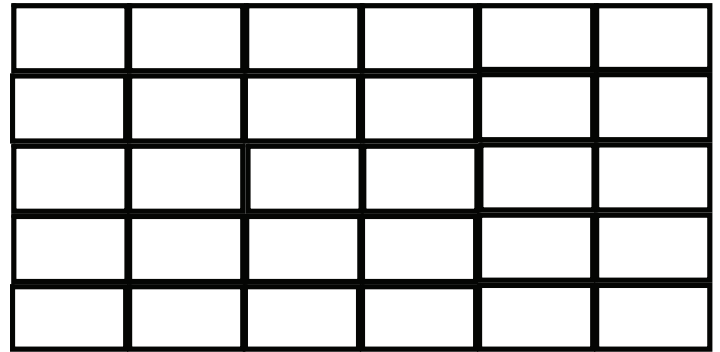
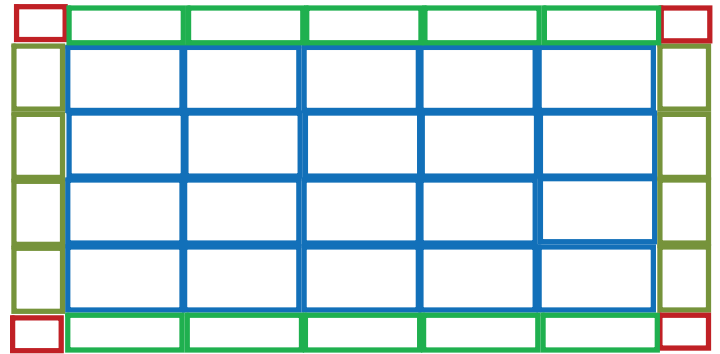
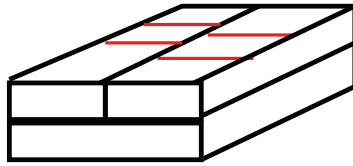


Fig. 6: Sketch of a staggered double layer (Lower layer in black), upper layer shifted with respect to the lower level. Full size (blue), half size (green, olive) and quarter size (red).

Table 2. Situation B.

Sample thickness [mm]	Thermal conductivity $\lambda_{eff, B}$ [mW/m·K]	Length related Psi-value ψ_B [W/m·K]	symmetrical sample situation on both side of guarded hot plate [mm]
Average all thicknesses	4.6 ± 0.2	0.0025 ± 0.0015	2 pieces: 250 x 500 1 piece: 500 x 500

Detailed results are published in [GhaziWakili2011]. The difference between B1 and B2 could not be detected, due to variation in the production of 4.1 ± 0.2 [mW/m·K], a value measured in that paper for situation 2 for checked internal pressure (below 4mbar, average 1.8 mbar).

Situation D is equivalent to a non-staggered double layer situation, and the measured values reported in Table 3 are the same as in Table 1b, calculated for the average of single layer situations of the same thickness with and without seal at edge.

Table 3. Situation D. [GhaziWakili2011]

Sample thickness [mm]	Thermal conductivity $\lambda_{eff, D}$ [W/mK]	Linear thermal transmittance ψ_D [W/mK]
20	0.0060 ± 0.0002	0.0125 ± 0.0018
25	0.0059 ± 0.0002	0.0075 ± 0.0014
30	0.0062 ± 0.0002	0.0096 ± 0.0012

The thermal Bridge effect of a situation D is always to be divided by 2 for each single edge, as the measurement corresponds to 2 edges.

Example 1: Area $6 \times 3 \text{ m} = 18 \text{ m}^2$

Lower Layer 30 VIP with 1000 x 600 x 20 mm

Upper layer 20 VIP with 1000 x 600 x 20 mm

+ 10 VIP with 1000 x 300 x 20 mm

+ 8 VIP with 500 x 600 x 20 mm

+ 4 VIP with 500 x 300 x 20 mm

Psi D / 2 0.00625 18 m (Perimeter of total area)
W/(m·K)

Psi B 0.0025 87 m (Joints)
W/(m·K)

Result: $\lambda_{eff, 25 \text{ years, including edge effects}} = 6.0 \text{ mW/(m·K)}$ for 20 + 20 mm VIP staggered double layer,

This result uses aging data, reported later in this paper, e.g. 5.0 mW/(m·K) for 1000 x 600 x 20 mm without considering thermal bridge.

Example 2: Very large area

A larger area e.g. 10 x 20 m with less type D thermal bridges lead for the staggered area to 5.9 mW/(m•K) . A non-staggered double layer on other hand has 6.3 mW/(m K). Comparing staggered to non-staggered double layer, it can be concluded, when looking at thermal bridge effect only, that the staggering reduces the thermal bridge effect by about 30% for very large surface sizes. This is due to non-zero lateral heat flows.

4. Comparison of Staggered Double Layer (20 + 20 mm) with a Corresponding Single Layer (40 mm)

The comparison of staggered double layer and a single layer depends on the sizes of the area to be insulated, as the weight of different thermal bridge types varies with size of the area (and the size of the single panel). The example above with area 6 x 3 m is leading to 6.0 mW/(m•K).

Comparing a staggered double layer, with a single layer of the same thickness, needs the consideration of 2 distinct effects. These are the thermal bridge effect and the aging effect (where new knowledge on thickness dependence will be presented later in this paper). For same total thickness (40mm) it results in 6.4 mW/(m K for both area, the 6 x 3 m as well as for a very big one. This value is higher, due to higher measured thermal conductivity (Table 1 case Psi 2, and also in GhaziWakili2011).

Intermediate note 3:

The lateral flow is the limited by the heat flow in the joint for increasing thickness. Energy is saved despite slightly rising lambda values, when the thickness increases. As shown for case Psi1 with same measured thermal conductivity in joint situation, clearly lower energy gets lost at the thermal bridge:

Thickness	with joint			
	Measured thermal conductivity	$\psi_{\text{edge, without seal}}$	R-value joint	1/R (near U-value)
	mW/(m•K)	W/(m•K)	K/W	W/K
15 mm	5.5	0.016	2.7	0.37
30 mm	5.5	0.012	5.5	0.18
40 mm	5.5	0.009	7.3	0.14

Thickness	Centor of panel 4.1 mW/(m K)		lost energy due to thermal bridge effect
	R-value COP	1/R (near U- value)	Delta of 1/R (near U-value)
	K/W	W/K	W/K
15 mm	3.7	0.27	0.093
30 mm	7.3	0.14	0.047
40 mm	9.8	0.10	0.035

By the way, both units in 1/R, the Watt and the temperature difference are primarily logged units. No error contribution from actual thickness is in 1/R.

Besides the advantage of a better performance regarding $\lambda_{\text{eff, 25 year, incl. thermal bridge effect}}$ a double layer of VIP has the advantage of better reliability regarding “Infant mortality”, a term borrowed from Reliability statistic. (that describes the decreasing failure rate in the early part of the bath tub curve e.g. [Meeker1998].).

5. Aging Prediction Data

The calculation for the example above uses results from aging prediction for 25 years. These data shall be given here in short, to enable recalculation.

Table 4: Values used above, based on results from chapter following later in this paper

VIP size mm	Thermal conductivity $\lambda_{\text{cop, 25y}}$ [mW/(m K)] without thermal bridge effect	Effective thermal conductivity λ_{eff} [mW/(m K)] incl. thermal bridge effect
1000 x 600 x 40	5.1	6.4
1000 x 600 x 20	5.0	6.3
1000 x 300 x 20	5.3	7.2
500 x 600 x 20	5.2	7.0
500 x 300 x 20	5.5	8.0

Table 5: Thermal bridge parameters

	VIP thickness	Interpolated Psi
$\psi_{\text{edge, without seal}}$	20 mm	0.010 W/(m K)
$\psi_{\text{edge, with seal}}$	20 mm	0.0147 W/(m K)

And equations:

$$\Psi_d = \frac{\dot{Q}_{joint} - \dot{Q}_{1-dim}}{\Delta T \ell} = \left(\frac{1}{R_{p \text{ int}}} - \frac{1}{R_{1-dim}} \right) \frac{A}{\ell} \text{ in W/(m K)} \quad (\text{Eq. 1})$$

$$\lambda_{e_{equivalent}} = \lambda_{Kern} + \Psi_{d,edge} \cdot d \cdot \text{edgelenth/area} \quad (\text{Eq. 2})$$

6. Aging Measurements

Data are needed for the equation

$$\lambda(t) = \lambda_0 + \Delta\lambda(t) \cong \lambda_{0\%} + \lambda_p \cdot p_a \cdot t + \lambda_u \cdot u_q (1 - \exp(-t/\tau)) \quad (\text{Eq. 3})$$

Core related parameters are $\lambda_{90\%}$ as received from manufacturer's production statistic and checked for plausibility with 3 additional lab measurements.

The 90% percentile value of production statistic as received from the manufacturer is $\lambda_{90\%} = 4.4 \text{ mW/(m K)}$. The mean 4.1, min. 3.2, max 4.8. (In future RAL documents $\lambda_{90\%}$ shall to be changed to 90% with 90% confidence, which would add another 0.1 mW/(m K)).

Table 6: Measurement on VIP as delivered with 500 mm x 500 mm and nominal thickness 15, 20, 30 mm

Measurement number	Sample number	Internal pressure mbar	Thickness mm	Thermal conductivity Lambda mW/(m K)	R _{1-dim} (m ² K)/W
1	78 / 80	1.8 / 2.4	16.1 / 16.1	4.1	3.9
2	86 / 88	1.2 / 1.3	21.7 / 21.7	4.0	5.4
3	94 / 96	1.7 / 1.2	31.5 / 31.6	3.9	8.1

Table 7: VIP resealed with higher internal pressure,

Measurement number	Internal pressure mbar	lambda mW/(m K)
4	58	5.3

$\lambda_p = d\lambda / dp \approx ((5.3 - 4.1)/(58 - 0.97))$ is about 0,021 mW/(m K mbar) for this VIP with 500 mm x 500 mm x 30mm

Table 8: VIP resealed to get the moisture dependence

Measurement number	Moisture increase (du) M-%	Internal pressure mbar	lambda mW/(m K)
5	3.06	16	4.8

$d\lambda / du \approx ((4.8 - 4.1) / (3.06 - 0))$ is about 0,23 mW/(m K M-%) for this VIP with 500 mm x 500 mm x 30mm. (opened, ice added and resealed, leading to a weight increase of 45 g water. Weight of addition envelope considered)

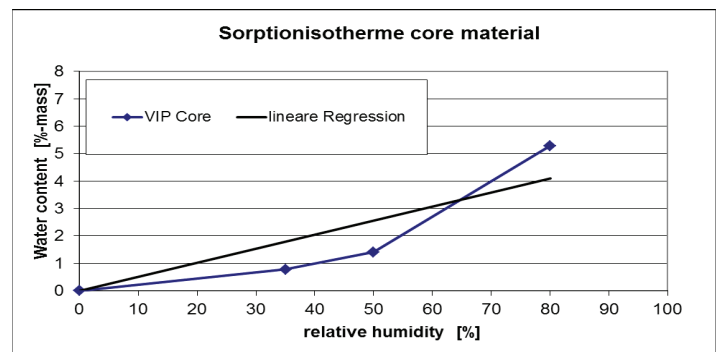
Table 9: VIP vented (opened)

Measurement number	lambda mW/(m K)
6	19

Within the QA Procedure 3 data points of the sorption isotherm have to be measured:

Table 10: Measurements for the sorption isotherm (3 samples)

Climate	Moisture Content (m-%)
23°C / 35% r.H.	0.77 ± 0.08
23°C / 50% r.H.	1.40 ± 0.08
23°C / 80% r.H.	5.28 ± 0.05



The QA-procedure to calculate the 25 year prediction simplifies here with a linearization shown in the next figure:

Fig. 7: Sorption isotherm of core mixture based mainly on pyrogenic silica

The value used here for further calculations is 2.6 %-mass, and not the measured 1.4, because the condition of using a VIP is different from 23°C50%r.h for the cold side of the VIP, but often similar to the warm side for most building applications..

Intermediate note 4:

The value is linearized from 3 point measured on the sorption iso-therm with given relative humidity from the procedure. This simplifying linearization has in this case only a minor influence, as the dry gases dominate (by 90% for most VIP sizes)), while for other VIP Types used in Building applications, the simplified analysis gives dominating influence of water vapour on the pressure increase. But a more detailed analysis has to be done, as this could be only due to the simplifications.

For this case here with small $\Delta\lambda_{25\text{years}}^*$ and bigger $\Delta\lambda_{\text{thermal bridge}}^*$ the $\lambda_{25\text{years, eff}}^*$ is good enough predictable based on this SLP model. (With big $\Delta\lambda_{25\text{years}}^*$ the model is less good, but building application do no longer make sense then.)

Intermediate note 5:

Also for VIP's in refrigerators the warm side is near 23°C50%.h when of used in moderate climate zones. The other side is cold, resp. most time colder on building envelope application in moderate climatic zone, (an argumentation for at least Europe, or the northern part of North America.).

Table 11: Measured internal pressure, with start about 1 month after production.

VIP Size	Internal pressure start *	Internal pressure 131 days	Internal pressure 187 days
mm	p , mbar	p , mbar	p , mbar
250 x 250 x 10	2.41	3.45	3.97
250 x 250 x 10	2.07	3.30	3.58
250 x 250 x 10	2.09	3.19	3.56
deviation*	± 0.07	± 0.09	± 0.09
500 x 500 x 15	2.27	2.88	3.18
500 x 500 x 15	1.83	2.36	2.64
500 x 500 x 15	1.32	1.92	2.20
deviation*	± 0.04	± 0.07	± 0.06
500 x 500 x 20	1.20	1.87	2.02
500 x 500 x 20	1.34	2.05	2.20
deviation*	± 0.01	± 0.03	± 0.03
500 x 500 x 30	1.80	2.54	2.71
500 x 500 x 30	1.29	2.04	2.21
deviation*	± 0.03	± 0.05	± 0.03

* Deviation of 3 blowing repetitions with 3 or 4 lasers distance measuring units

Laminate and folding type related values are

Table 12: Increase in internal pressure and moisture at 23°C 50%.r.H. as well as the moisture increase related time constant.

VIP size	Increase in internal pressure	Moisture related weight increase	Time constant moisture equilibration
mm	$\dot{p}$, mbar / year	$\dot{u}$, %-mass / year	τ , years
250 x 250 x 10	3.0	0.04	51
250 x 250 x 10	2.9	0.05	
250 x 250 x 10	2.9	0.06	
Mean :	2.9	0.05	
500 x 500 x 15	1.8	0.04	85
500 x 500 x 15	1.6	0.03	
500 x 500 x 15	1.7	0.03	
Mean :	1.7	0.03	
500 x 500 x 20	1.6	0.027	117
500 x 500 x 20	1.6	0.017	
Mean :	1.6	0.022	
500 x 500 x 30	1.7	0.018	128
500 x 500 x 30	1.7	0.021	
Mean :	1.7	0.020	

Thickness rule* is not followed as expected: neither pressure nor moisture increase is inversely proportional to thickness.

Intermediate note 6:

Thickness rule: At 30mm thickness a value of half of 1.7 mbar / year for 15mm is expected (IEA Annex39-project), but the measured value was 1.7 mbar / year. 0.020 %-mass / year was measured and not half of 0.03 %-mass / year. Within 4 VIP-types from 4 manufactures, 1 followed the thickness rule within the measurements deviation.

Table 13: Predicted values for climate 23°C / 50% r.H. for a single layer

VIP Size [mm]	250x250x10	500x500x15	500x500x20	500x500x30
Predicted values for 25 years				
Internal pressure p_{total} [mbar]	76	45	42	44
Moisture content u [%-mass]	1.0	0.7	0.5	0.5
Thermal conductivity $\lambda_{cop,25y}$ [mW/(m·K)] without thermal bridge effect for this pyrogenic SiO ₂ based core	6.0	5.3	5.3	5.3
Psi – value (with resp. without seal) [mW/(m·K)]	25 resp 15	16 resp 11	14.7 resp. 10	12 resp 8
Effective thermal conductivity $\lambda_{eff, 25years}$ [mW/(m·K)] incl. thermal bridge effect	9.2	6.9	7.2	7.7

The last row in table 13 represented in a Figure as function of time:

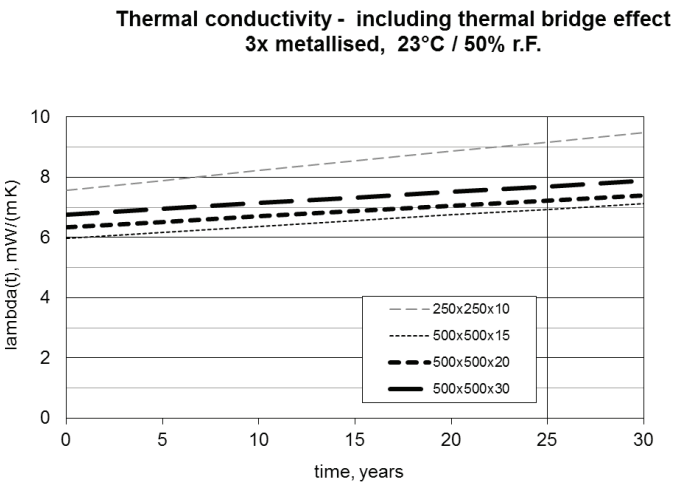


Fig. 7: Aging prediction for measured VIP sizes

For other sizes, using 250x250x10 for size extrapolation, and assuming the same low thickness dependence also for 500x500x10, it is possible to extrapolate to larger sizes:

**Thermal conductivity - including thermal bridge effect
3x metallise, 23°C / 50% r.F.**

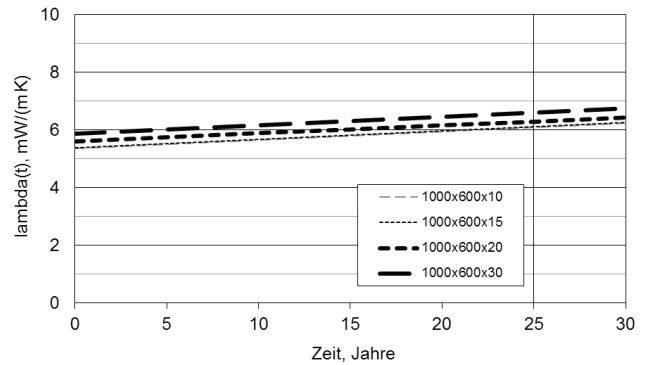


Fig. 8: Aging prediction for larger VIP sizes (both time and size extrapolated)

To do this the thickness rule for the measured thickness had to be adapted.

Table 14: Predicted values for other VIP size (as Table 4) starting with $\lambda_{90\%} = 4.4$ mW/(m K)

VIP size mm	Thermal conductivity $\lambda_{cop,25y}$ [mW/(m K)] without thermal bridge effect	Effective thermal conductivity λ_{eff} [mW/(m K)] incl. thermal bridge effect
1000 x 600 x 40	5.1	6.4
1000 x 600 x 20	5.0	6.3
1000 x 600 x 10	5.1	6.1
1000 x 300 x 20	5.3	7.2
500 x 600 x 20	5.2	7.0
500 x 300 x 20	5.5	8.0

For larger sizes values between 6 and 7 mW/(m·K) are calculated.. So declaration values of 7 and 8 mW/(m·K) are for this VIP used in Switzerland, depending on the VIP size, and no longer on the VIP thickness, as before. With continuous increase expected for the average of service life of other insulation systems such as External Thermal Insulation Composite Systems (ETICS), listed with 30 to 40 years.

7. Lessons Learned

Only about 1/3 of the edge effect can be reduced by staggering the VIP.

VIP size (mm)	$\lambda_{\text{eff, 25 year, incl. thermal bridge effect}}$
1000 x 600 x 20 staggered double layer	5.9 mW/(m K)
1000 x 600 x 40 single layer	6.4 mW/(m K)

Beside the advantage of a better performance regarding $\lambda_{\text{eff, 25 year, incl. thermal bridge effect}}$, a double layer of VIP has the advantage of better reliability regarding “Infant mortality”, related to the production as well as related to installation or damage with reasons occurring later during the service life. The occurrence of “childhood failure” has been shown by Heinemann et al. [Heinemann2009 IVIS, Heinemann2010 VIP-Prove].

The above prediction is based on permeation of dry gases (O₂, N₂, and few amounts of noble gases) as well as water vapour, which is treated separately. Heinemann’s work gives good hint’s, that the prediction will be valid for about 87% resp. 95% of the “population”, i.e. the number of VIPs.

Reliability will increase, with increasing emphasis on production QA and installation experience, as long as the market is willing to pay for it. From the energy saving point of view, this reliability level is already attractive. It is realistic to take into account a small number of vented VIPs, which will result in lower surface temperature on the room side of the construction. The thickness of the VIP should be chosen, so that even if vented this surface temperature reduction does not cause condensation risk nor mould grow.

Due to higher psi –value than published by several other authors (based often on simulation only), and secondly the very small reduction of measured aging data with thickness, the former recommendation to use preferred thick VIP is no longer valid for many manufacture. At least, if we trust measurements more than theory. On the other hand, I got one series, where the thickness rule might be valid.

Aging related parameters are improved by several VIP producer since the IEA Annex39 report data. On other hand we also had seen failure despite QA, some could be solved within weeks with identifying laminate problems, while for another case there was a step back in the way of folding applied to raised reliability back to low level as might be expected.

8. Outlook

As the aging related contribution to effective thermal conductivity is below 1 mW/(m K) over the required 25 years, there is potential to investigate the possibility of longer life times and the occurrence of other deterioration mechanisms. It would also be interesting, to quantify the dependence of VIP lifetime on somewhat warmer environment.

Aging data give room for discussion on thickness related permeation or outgassing. Thickness related permeation could be, where the laminate is 180° folded, but a third tested series is against this hypothesis.

9. Discussion

VIP Service Life Prediction as discussed in literature is in the often cited paper of Schwab et al. [Schwab2005], an elaborate investigation with a 2 times metallised laminate, with still the best dataset $d\lambda / du$ with 0.3 mW/(m K M-%) regarding used a quite unique device. 2 times metallised laminate are an option for non-building application with lower durability requirements from my point of view, as long as they are from the required high quality. Quality problems had been seen with some producers, but not the leading one nowadays.

Also $d\lambda / dp$ is here lower than 0.035 mW/(m K mbar used in [Simmler2005]. There are several producers of VIP, who reach lower values, but there is also the temptation to use cheaper core / envelope material and the RAL, resp. the Swiss procedure gives them the feedback. Interested parties can ask producers for Empa’s test reports. Request for very long Service Life of 100 years like e.g. in the very recent review paper of Alam et al [Alam2011] are hardly too show with organic materials. The well-established External Thermal Insulation Composite Systems (ETICS) has in building planning documents of the Swiss home owner association [Table of building components service life] an average service of 30 years (with 25 to 45 year band) and for 100 years requirements foamed glass granulates or foamglass would be the option, listed with 120 years (with 100 to 150 years band). This it is used e.g. beneath the ground plate of new buildings. It would be interesting to see the potential service life of other insulation material including polymeric materials like EPS (expanded Polystyrene) as used External Thermal Insulation Composite Systems (ETICS), to just name the most frequently used one. There are of course hit’s for longer potential service life, especially for a minority of the “population”, that will not see changes due to reasons independent of the insulation aging. On vented facades, animals (e.g. mice, wasps) can damage, if not installed and maintained properly, e.g. maintenance after storm events.

[Gudmundsson2011] on other hand used too short life times for his argumentations about using VIP on buildings or not. E.g. the 25 years are not the end of the service life time, but just the age to declared insulation materials according to the standards. More insights in the stabilisation package used in Polyethylene would be helpful for application of VIP in hot desert locations. As well as more detail on the polyurethane glue for application of VIP in tropic locations, especially for required lifetime beyond 25 years. Another approach for the 25 year declaration developed in Germany for the DIBt values by 1999, is based on accelerated testing. A 2011 Compendium written in German, gives an overview over practical and legal details of VIP [Herr2011]. This accelerated test procedure was used also by Wegger et al [Wegger2011], and is there compared with literature data. The comment there “it seems that the CUAP falls a little short of covering an aging period of 25 years.” is no longer true, when the scaling factor of 15.3 [Sprengard's Presentation 17.3.2011] is considered. (resp. $1 / 15.3 / 0.5 \text{ year} * 25 \text{ years} = 3.27$) as used by DIBt and FIW in Germany. This accelerated test gets quite reasonable results, as the dry gas permeation is accelerated. But in case of new type of envelopes, like non-metallic ones, the scaling factor has to be new determined again.

VIP size dependency (as in Table 13) is to my knowledge unique for this procedure developed at ZAE and Empa for VIP to be used in building applications. VIP types with aerogel-core are not yet tested by an independent lab to my knowledge regarding the above parameters. VIP types with fibre or foam core do need getters additionally, not only the desiccant, whose behaviour is determined in the sorption curve. Durability approach for VIP with Getters where presented at previous IVIS meetings, called VIA in 1998 to 2003, where VIA had stand for Vacuum Insulation Association. Such types of VIP are widely used outside Europe, and there are also companies advertising their VIP for Building application. In the available English written literature, no durability related testing could be found for VIP with getters since 2003 [Celik2003VIA], despite quite an effort done for searching. Getters as described there likely to identify by pressure testing over half a year, due to the very low pressure.

Psi-values are discussed in depth in [VanDenBossche2010]. Several publications have lower Psi-values, some from my point of view with too air gaps. While some look at new optimised façade application, our approach likes to include less optimal adjacent materials. A thin foam insulation layer is reasonable, but not all the time the case, [Gyrinning2010] had even air as adjacent layer. The staggered layer in Gyrinning et al. [Gyrinning2010] show there only a small reduction on the U-value, what is due the very low lower edge effects under that conditions with adjacent layer as air layer. In general, these values are quite low for Psi-values, especially, when considering, that that envelope is with an additional 0.1mm protection layer.

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In situ Measurements of Façade Retrofitted with Vacuum Insulation Panels

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Abstract

The goal to reduce the energy demand in the built environment applies also on listed buildings with special architectural and societal values. However, the possibilities of retrofitting façades of listed buildings are rather limited. This study concerns a 1930s multi-family building in Gothenburg where the ground floor is composed of 340 mm structural brick and the two upper floors of 80 mm structural timber walls. The façade is externally retrofitted using 20 mm Vacuum Insulation Panels (VIP), covered by 30 mm glass wool boards, which give a calculated reduction in U-value of 64% from 1.1 W/m²/K to 0.4 W/m²/K. Measurements of temperature and relative humidity in the wall from the period January 5 to March 22, 2011, are analyzed for the brick wall. The analysis show improved hygrothermal conditions compared to the case in a reference wall.

1. Introduction

The countries in the European Union have agreed on a reduction of the greenhouse gas emissions. The target is a reduction of 20% in 2020 and 50% in 2050, compared to the emissions in 1990. A similar target is issued by the Swedish Energy Agency concerning the energy use in the Swedish building stock. The need to reduce the energy demand in the building stock applies also on listed buildings with special architectural and societal values. However, the possibilities of retrofitting façades of listed buildings are limited as the appearance, nor the size (thickness), can be changed.

In listed buildings Vacuum Insulation Panels (VIP) might be one of the few solutions that are possible to use in order to decrease the energy use sufficiently so that the goals are reached. VIP is a novel thermal insulation element with a thermal conductivity of around 4 mW/m/K measured at the centre of the panel. With regard to ageing due to intrusion of gases and moisture, the thermal conductivity used in design is 8 mW/m/K. In case of a perforation of the panel, the thermal conductivity rises to 20 mW/m/K [1]. Moisture problems in the existing structure can arise if the insulation gets damaged and the temperature in the wall falls below the dew point.

Different examples of building parts insulated with VIP were investigated in the IEA Annex 39 HiPTI, active during 2002-2005. The conclusion from the annex was that VIP are feasible and could be an important mean for energy efficient buildings, but they were still too expensive to use on broad scale. However, studies on retrofitted façades with VIP show that they are possible to use [2]. An old semi-detached house in Nuremberg, Germany, was retrofitted with 15 mm thick VIP, secured by plastic rails, covered by an exterior layer of 35 mm polystyrene. Another system was tested in Bersenbrück, Germany, where 20 mm thick VIPs were integrated into 20 mm polystyrene on all sides. The panels were covered by 80 mm polystyrene on the exterior. In Trier, Germany, 12 terraced houses were partially equipped with a system of 20 mm VIPs laminated on both sides with polystyrene [3]. The investigations of the conditions after VIP was applied, focuses in all the above cases on the energy and thermal performance in the wall. The risk for moisture damages in an existing structure retrofitted using VIP, is not entirely clear.

The hygrothermal, i.e. heat and moisture, performance of an existing façade after retrofitting with highly efficient insulation elements has been investigated in [4]. The risk of mold growth in the wall needs to be studied to avoid risk of damaging the old construction. This paper is part of a PhD student project where consequences on economy, building technology and energy efficiency caused by the integration of VIPs in an existing façade will be discussed. This paper presents the retrofitting case studied in the project, measurement layout and some initial results from the in situ measurements in the retrofitted façade, in comparison to a reference façade.

2. Retrofitted Façade

For the study, a 1930s multi-family building in Gothenburg was chosen, see Figure 1. The building has three floors, where the ground floor is composed of 340 mm structural brick and the two upper floors of 80 mm structural timber walls. There is no additional thermal insulation in the walls. Over the exterior of the façade, there is a wooden cover boarding, separated from the load-bearing construction by a thin asphalt impregnated paper. The windows in the building were changed in the 1970s,

to a smaller size, fitted in the old window frame with glass wool insulation. Drawings and documentations of the technical details of the building are incomplete, thus the state before retrofitting is hard to evaluate.



Figure 1. The 1930s multi-family building in Gothenburg, retrofitted with VIP.

2.1 Theoretical U-value after retrofitting

In the beginning of the project, the entire façade was scanned by laser to find the exact dimensions of the wall and exact positions of the windows. The measurement showed that the total area of the façade is 133 m², whereof the two timber floors are 89 m² in total and the brick floor is 44 m². There are 12 windows on the façade measuring around 2.3 m² each varying in size and position. It was also found that the entire façade leans several cm between the corners.

One difficult part of the design was to attach the wooden cover boarding on the façade. The chosen attachment involves distances of glass wool boards, 50 mm wide and 20 mm thick, between the VIP. Glass wool has also been placed around the windows, to fill the space to the VIP and to correct the irregularities in positions. Over the entire VIP surface, 30 mm thick glass wool boards are mounted, and before the cover boarding there is a 28 mm wide air space, see Figure 2.

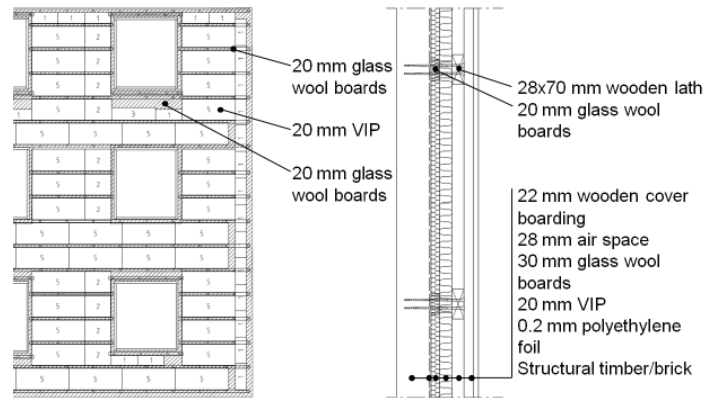


Figure 2. Wall layout after retrofitting with 20 mm VIP and 30 mm glass wool boards.

The original U-value of the wall is unknown, but numerical calculations with the software HEAT2 [5] show that it was around 1.12 W/m²/K, both for the brick and timber walls. After retrofitting, HEAT2 calculations show that the U-value, without considering thermal bridges, is 0.23 W/m²/K. Thermal bridges are created by the multi-layered foil around the panels and by the attachment of the cover boarding through the glass wool. The U-value increases to 0.40 W/m²/K with thermal bridges, which means an increase by 74%. However, the calculated reduction in U-value is 64% after retrofitting.

2.2 Measurements in the façade

The aim of the measurements is to study how the existing structure is influenced when placing additional thermal insulation on the exterior and locate places where there is an increased risk of damages. Around the windows, only 50 mm glass wool insulation is added, which might cause risk for low temperature and possibly condensation. Three different positions around the VIP are interesting to study; behind the centre of the panel, at the VIP-VIP connection and where the VIP is connected to the 50 mm wide glass wool board laths. Figure 3 shows the principal locations of the sensors in the retrofitted wall.

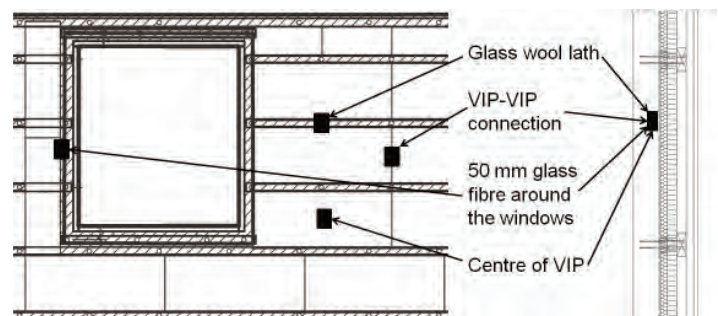


Figure 3. Locations of sensors in the retrofitted wall. All sensors are placed in the existing wall, on the interior of the polyethylene foil and VIP.

Inside the building, sensors are placed in four kitchens and on the exterior façade. The wall next to the retrofitted wall was chosen as a reference case, and one sensor is installed behind the cover boarding on the brick and wooden floors respectively. Measurement accuracy of the sensors is $\pm 2.5\%$ for relative humidity 10 to 90% and $\pm 0.5^\circ\text{C}$ at 25°C . The temperature can be measured between -40°C to 85°C [6]. The size of the sensors is 60x30x60 mm but they have been modified to become smaller, by removal of the pins measuring moisture content. In total there are 15 sensors installed at the site which send hourly readings through a wireless connection to a data acquisition gateway. The data is then transferred through a 3G connection to a network server.

3. Results

The hygrothermal sensors were installed in October, 2010 and deliver data each hour. However, problems with the wireless data transfer and erroneous software updates have caused major data loss during the autumn and winter. Only data from the period January 5 to March 22, 2011 is therefore presented in this paper. The brick wall is chosen for the analysis which is based on 24 hours moving averaged data. Figure 4 shows the temperature in the wall and indoors, compared to the reference wall, indoor and outdoor.

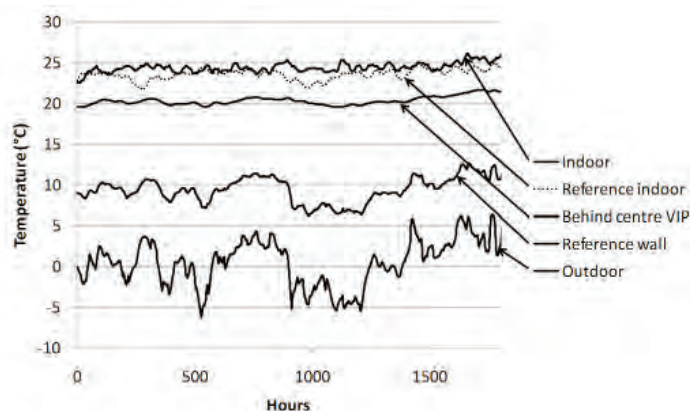


Figure 4. Daily averaged temperature behind the centre of the VIP and indoors, compared to the reference wall, indoor and outdoor. The measurement period is January 5 to March 22, 2011.

Indoor temperature is measured in the kitchen of the apartment closest to the location of the sensors in the wall. During the period, the temperature was on average 0.8°C higher in the kitchen with the retrofitted wall than in the reference kitchen. The higher temperature was caused by an unbalanced heating system in the building which caused the occupants to have their windows open very often, also during the cold season, and many technical appliances generating heat. However, also with this fact taken in consideration, the temperature was on average 10°C higher in the retrofitted wall than in the reference wall. The corresponding relative humidity is shown in Figure 5.

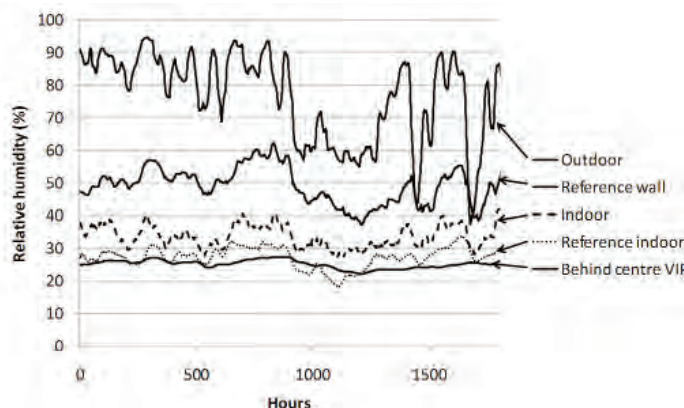


Figure 5. Daily averaged relative humidity behind the centre of the VIP and indoors, compared to the reference wall, indoor and outdoor. The measurement period is January 5 to March 22, 2011.

The relative humidity in the air in the kitchens and in the reference wall were following the changes in the outdoor air closely. Behind the VIP, the relative humidity was more stable with a slower response. The moisture supplies in the kitchens were 3.6 and 1.9 g/m^3 respectively in the retrofitted part and the reference part, which means that the retrofitted wall was exposed to a heavier moisture load than the reference wall. The brick behind the VIP and in the reference wall had a similar moisture supply, on average 0.5 g/m^3 . However, the temperature influence gave an average relative humidity of 22-27% with an average of 25% in the retrofitted wall, and 37-62% with an average of 50% in the reference wall.

The hygrothermal conditions on different locations in the wall, see Figure 3, can be studied. One sensor in the brick wall was mounted on the wrong location, which means that two sensors are located behind the glass wool laths and none behind the VIP-VIP connection. The temperatures at the different locations are presented in Figure 6.

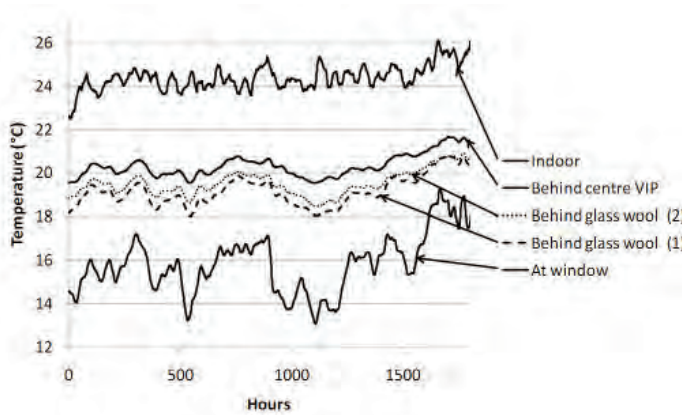


Figure 6. Daily averaged temperatures in the brick wall at different locations behind the VIP. The measurement period is January 5 to March 22, 2011.

All the temperatures measured during the period were following the same pattern, influenced mainly by the outdoor temperature. The temperature next to the window was lowest which was expected since there was least insulation around that location. The influence by the glass wool laths on the temperature was on average 1°C, compared to behind the centre of the VIP. There was a difference between the two measurements behind the glass wool of 0.4°C. The measured vapor contents are shown in Figure 7.

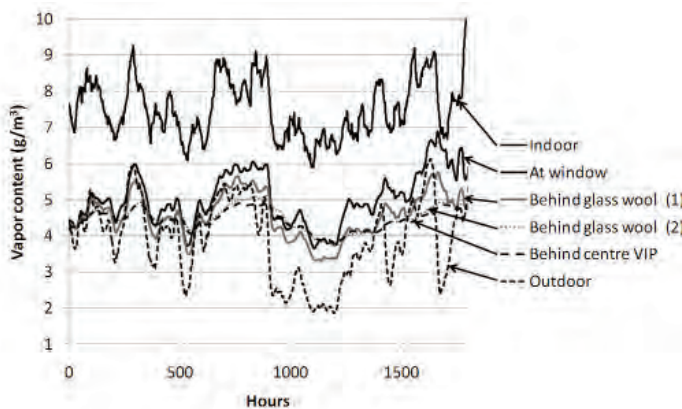


Figure 7. Daily averaged vapor contents in the brick wall at different locations behind the VIP. The measurement period is January 5 to March 22, 2011.

The vapor contents in the wall were higher than outdoors for most of the measured period. Indoors, at the window and at one of the locations behind the glass wool laths, the vapor content was following the changes in the outdoor air faster than in the two other locations. Behind the VIP and at one of the glass wool laths, the response to changing vapor content was slower. The reason for the difference could be a crack in the wall where an air flow is induced. Figure 8 shows the relative humidity at the different locations in the wall.

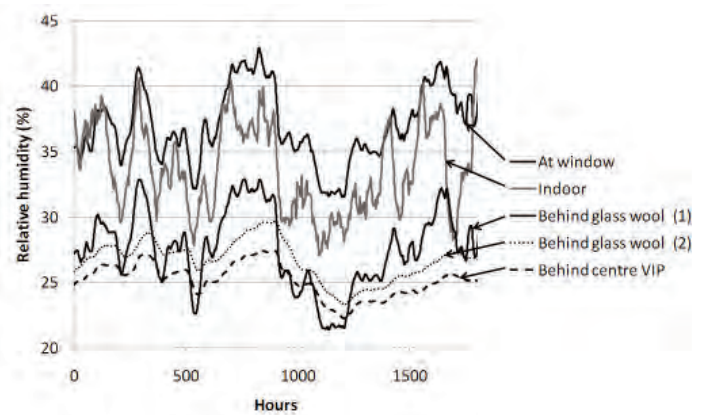


Figure 8. Daily averaged relative humidity in the brick wall at different locations behind the VIP. The measurement period is January 5 to March 22, 2011.

The relative humidity was low at all measured locations of the wall. At the window, the relative humidity is highest, varying between 32-43% with an average value of 37%. There was a difference between the two glass wool lath measurements; one case varies between 21-33% and the other case between 23-27%. However, the difference on the average relative humidity was only 1%.

4. Conclusions

A façade of a protected building was externally retrofitted using 20 mm VIP covered by 30 mm glass wool. After the retrofitting, temperature and relative humidity sensors are monitoring the wall at 15 different locations. For the part of the wall with load-bearing brick, the measurements during the first cold period showed that the relative humidity was lower in the retrofitted wall, compared to a reference wall.

Different locations around the VIP were monitored by the sensors. After the first cold season it can be concluded that the different locations had different hygrothermal conditions. As expected, the temperature was lowest at the window attachment and at the thermal bridges, compared to behind the centre of the VIP.

Future studies involve continued monitoring of the retrofitted wall, together with deepened analysis of the hygrothermal performance of the wall, such as calculations using the mold growth index. Also numerical simulations are needed in order to evaluate the causes of the differing results at the measured locations.

5. Acknowledgements

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Application Of Vaccum Insulation Panels In Low-Sloped Commercial Roofing Systems

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Abstract

In North America, low sloped roofs represent the vast majority of the commercial roofing. With vast roof surface area exposed to the Mother Nature, the low sloped roofs represent a major portion of the urban footprint. To control the heating and cooling loads, the conventional insulation are typically used in these low sloped roofing assemblies or commercial roofing assemblies where they are installed in multiple layers having R-value ranging from R-15 to R-40. With the changing climatic pattern, it is no wonder that these numbers might increase in the future. To address the possibility that whether the VIP can become the next generation insulation in the roofing systems where it can address both the high R-value and increasing thickness, an innovative experimental study has been started at the National Research Council of Canada. The focus of this study is to evaluate the long term performance of the VIP in the low sloped roofing assembly and its comparison with the conventional insulation. This experimental investigation is part of the Program of Energy Research and Development Canada (PERD) study "The Next Generation Building Envelop System". Of the different types of commercial roofing systems available in the market, an adhesive applied roofing system was selected for this study. As the name refers, in adhesive roofing system all the components are adhered used adhesives and therefore it offers a fastener free roofing system. The study evaluates the performance of VIP under two different roofing systems - one is the roof of in-service NRC building M-24 re-roofed with modified bituminous system, and the other is the roof mock up on M-24 roof constructed with EPDM system. The paper discusses the experimental setup and application details of the VIP in the field roof and roof mock up. It also presents and discusses some of the interim results obtained from these roofing systems.

Introduction

Roofing systems generally can be divided into two groups: low slope and steep slope roofing systems. Typically, residential roofs belong to the steep slope roof system group whereas, the commercial or industrial buildings such as, office buildings, warehouses, retail

buildings, plants and factories, often have low slope roofs. This paper focuses on the low sloped commercial roofs.

The roofing community in North America has undergone much change over the last 25 years along, with advances in material science, computer-aided designs and engineering applications. According to a 2000 market survey for the *Canadian Roofing Contractors' Association* (CRCA)[1], the modified bitumen roofing systems have dominated the low slope roof market in Canada by occupying 55% of shares. Data from the *National Roofing Contractors Association* (NRCA)[1] in the US shows that the single-ply low slope roofs have 40% of the market share. Figure 1 shows the changes in the market share for low-slope roofs based on the 2008–09 NRCA market survey. During these eight years, single-ply roofing for new and re-roofing constructions have been increasing and clearly have the largest market share in commercial roofing.

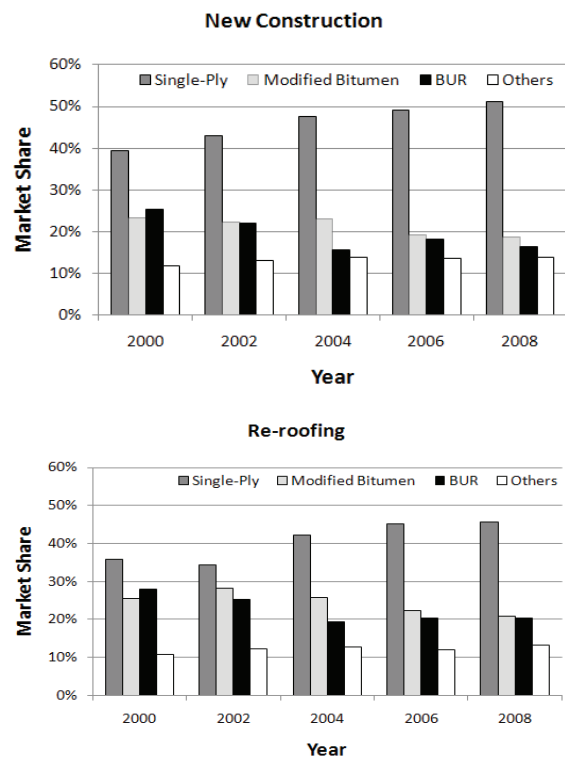


Figure 1: Market Share for Low-Slope Roofs in North America

Within the single-ply roofing, in accordance with the attachment methods of the roof components, it can be grouped into two categories: Flexible Roofing System (FRS) and Rigid Roofing System (RRS) as shown in Figure 2. Typical roofing components in these conventional single-ply roofing systems are, (from interior to exterior)

- Structural deck – steel deck is a common material used to support these roofing systems.
- Vapor barrier or air retarder – Controlling air and vapor movement is critical in roof design. Different options are available such as self adhered film, polyethylene and building paper.
- Insulation – The control of heat loss and gain through a roof system depends almost exclusively on the insulation. Plastic (polyisocyanurate or polystyrene) insulation is used in the majority of these conventional roofing assemblies.
- Protection or cover board – Cover boards enhance the compressive strength performance of the roof assembly. Typical cover boards used in the conventional roofing assemblies are fiberboard, asphalt core board and cementitious board.
- Waterproofing membrane. The waterproofing membrane is available in three different types: Modified bituminous (Mod-Bit), Thermoplastic [polyvinyl chloride (PVC) and thermoplastic olefin (TPO)] and Thermoset [ethylene propylene diene terpolymer (EPDM)]. The Mod-Bit is asphaltic based and comprises of two ply membranes-base and cap sheet, which on integrating as a roof system performs as a one ply membrane. Both the base and cap sheets come in standard width of 1 m (3ft). The thermosets and thermoplastics are single ply membranes composed predominately of synthetic polymer. These are strong, flexible sheets with thickness in the range 45 mil to 80 mil. All the membranes are sealed at joints or overlaps to form continuous waterproofing. Both these membranes are available in different sheet widths ranging from 2m to 4 m (6 ft to 12 ft).

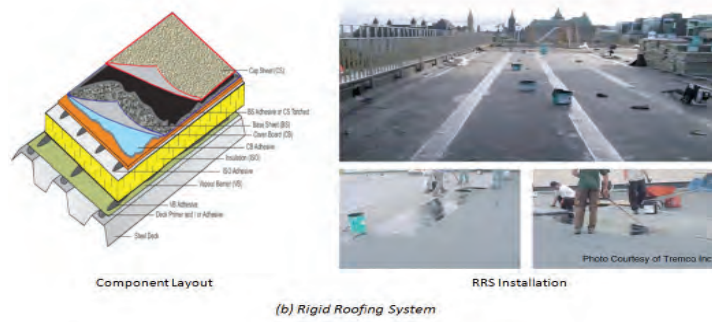


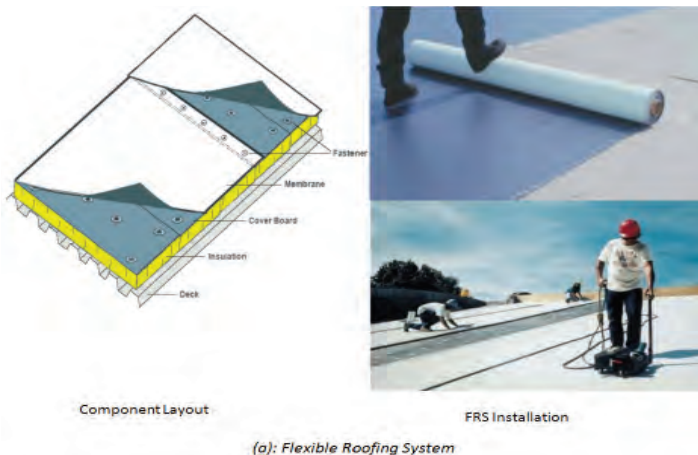
Figure 2: Typical View of Commercial Roofs

In a FRS, the roofing components are integrated using mechanical fasteners, whereas, in a RRS the components are integrated using adhesives. FRS and RRS can react differently when exposed to the same magnitude of wind uplift due to their particular load transferring mechanisms or response. These reactions are caused by different attachment methods, configurations, and application technologies.

As discussed above, to control the heating and cooling loads in these commercial roofing assemblies, the plastic (polyisocyanurate or polystyrene) insulation is used where they are installed in single or multiple layers to meet the thermal performance requirement. In Canada, the National Energy Code of Canada for Buildings (NECB) has prescriptive R-value requirements for the different climate zones across Canada. For roofs, the R-value requirement varies from R21 to R40 across Canada, and therefore to meet this requirement 4 inches to 8 inches of plastic insulation is required to be installed in the roofing assemblies. With the changing climatic pattern, it is no wonder that these numbers might increase in the future. Increasing insulation thickness may adversely affect the roofing system performance in terms of insulation shrinkage, differential movement within multiple insulation layers and other roofing components, membrane wrinkling and membrane pulling as shown in Figure 3 [2].



Figure 3: Effect of Increasing Insulation Thickness on Roofing System [2]



To investigate that whether the vacuum insulation panel VIP can become the next generation insulation in the roofing systems where it can address both the high R-value and increasing thickness, an innovative experimental study has been started at the National Research Council of Canada. The focus of this study is to evaluate the long term performance of the VIP in the low sloped roofing assembly and its comparison with the conventional insulation. This experimental investigation is part of the PERD (Program of Energy Research and Development) study “The Next Generation Building Envelop System”.

Vacuum Insulation Panel (VIP) is a high thermal performance insulation that was developed several years ago for use in appliances such as refrigerators and deep freezers. It was introduced into the construction technology in the last few years [3]. The thermal resistance of VIP is a factor of five to ten better than conventional insulation of the same thickness. Used in buildings they enable thin, highly insulating construction in walls, roofs and floors. VIP in general are flat elements consisting of open porous core material enclosed in a gas barrier/facer foil for air – vapor tightness (Figure 4)[4].The core material imparts mechanical strength and thermal insulating capacity. Within the enclosure, the core material has to maintain the required quality of vacuum withstanding the external load caused by atmospheric pressure. A getter/desiccant is added inside the core material to adsorb residual or permeating atmospheric gases or water vapor in the enclosure. The long term performance of the VIP’s is very much dependent on the performance of the gas barrier.

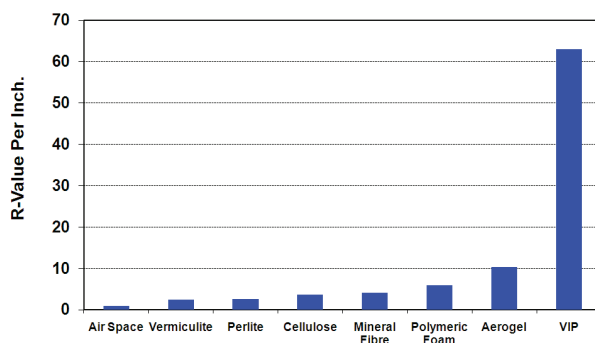
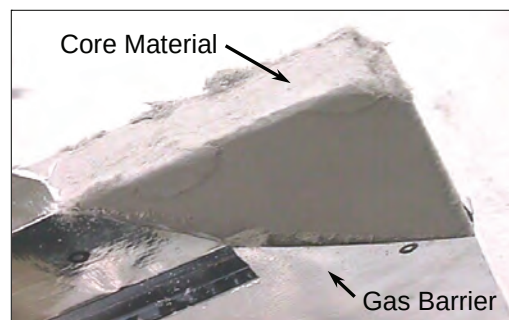


Figure 4: Vacuum Insulation Panel (VIP) and it's Typical R-Value Comparison to Those of Other Insulating Materials [4]

Application of VIP in low –sloped roofing is a little bit of complex task as the roof system installation involves roof penetrations and a lot of foot traffic. However, with the concept of pre-fabricated VIP panels and proper installation techniques roofing could offer a great new opportunity for the global thermal VIP insulation industry. Considering the sensitiveness or limitation of the VIP to penetrations, the present experimental study selected rigid roofing system (RRS) to evaluate the long term field thermal performance of VIP. As mentioned above, in RRS all the roofing components are adhered using adhesives and therefore it offers a fastener free roofing system. Combining VIP with the conventional polyisocyanurate insulation and particle fiber board, composite VIP panels were constructed and installed in the in-service roof of NRC building M-24, which had modified bitumen roofing system, and on the roof mock up of M24 roof that had EPDM roofing system. This paper discusses the experimental setup and application details of the composite VIP, and presents some of the preliminary thermal data obtained from these roofing systems

Experimental Set-Up

The scope of this study is to evaluate the long term performance of the VIP in the low sloped roofing assembly and its comparison with the conventional insulation. Towards this objective, the present study selected an in-service roof of NRC Building M-24 located in Ottawa. Apart from this field roof, two roof mockups were also constructed - one mockup comprising of conventional polyisocyanurate and other mock up constructed with composite VIP. Both these mockups are placed on the rooftop of Building M-24. The difference between the field roof and the roof mockups is the type and construction of roofing system, which will be discussed below.

M24 - Field Roof –Modified Bituminous Roofing System

The roof of building M-24 was 15 year old Built-up roofing system and it was undergoing re-roofing with the new generation rigid roofing system. Figure 5 shows the building M24 and the cross-sectional layout of this new roof, which comprises of a concrete deck, vapor barrier, 75 mm (3 in.) rigid polyisocyanurate insulation, 6 mm (1/4 in.) asphalt cover board, modified bituminous membrane base sheet and modified bituminous membrane cap sheet. This was a modified bituminous roofing system and all the roofing components are integrated with solvent based roofing adhesive. Replacing one of the 75 mm (3 in.) polyisocyanurate insulation, a 1.2 m x 2.4 m (4 ft. x 8 ft.) composite VIP was installed within the roofing system. Figure 6 shows the construction details of the composite VIP with the



Figure 5: Re-Roofing of Building M-24 at NRC with Rigid Roofing System

instrumentation. The 75 mm (3 in.) thick composite VIP as shown in Figure 6 comprised of two layers of 12 mm (1/2 in.) thick VIP panels sandwiched between two layers of 25 mm (1 in.) thick polyisocyanurate on the top and bottom. The VIP panels were available in dimensions of 450 mm x 560 mm (18 in. x 22 in.). With these panel dimensions, constructing a composite VIP with a single layer of VIP panels would have numerous joints, which could lead to thermal bridging issues. To minimize the effect of thermal bridging, a second layer VIP was integrated in the composite VIP. Adhesive selection was one of the critical issues in the composite VIP construction as the adhesive needs to be compatible with both the paper faced polyisocyanurate and foil faced VIP. An in-house thermal conditioning testing was conducted on three solvent based insulation adhesives that are commonly used in the roofing construction, and based on the visual observations and small scale mechanical testing, the appropriate adhesive was selected for the construction process. The steps involved in the construction process is described in Figure 6.

Figure 8 shows the instrumentation setup. During the construction process two thermocouples were installed within each layer making it a total of 10 sensors to measure the temperature gradient, and 4 heat flux sensors on each polyisocyanurate layer (total of eight) to measure the heat flow through the composite VIP. Of the 4 heat flux sensors on each insulation layer, one is designed to measure the heat flow through

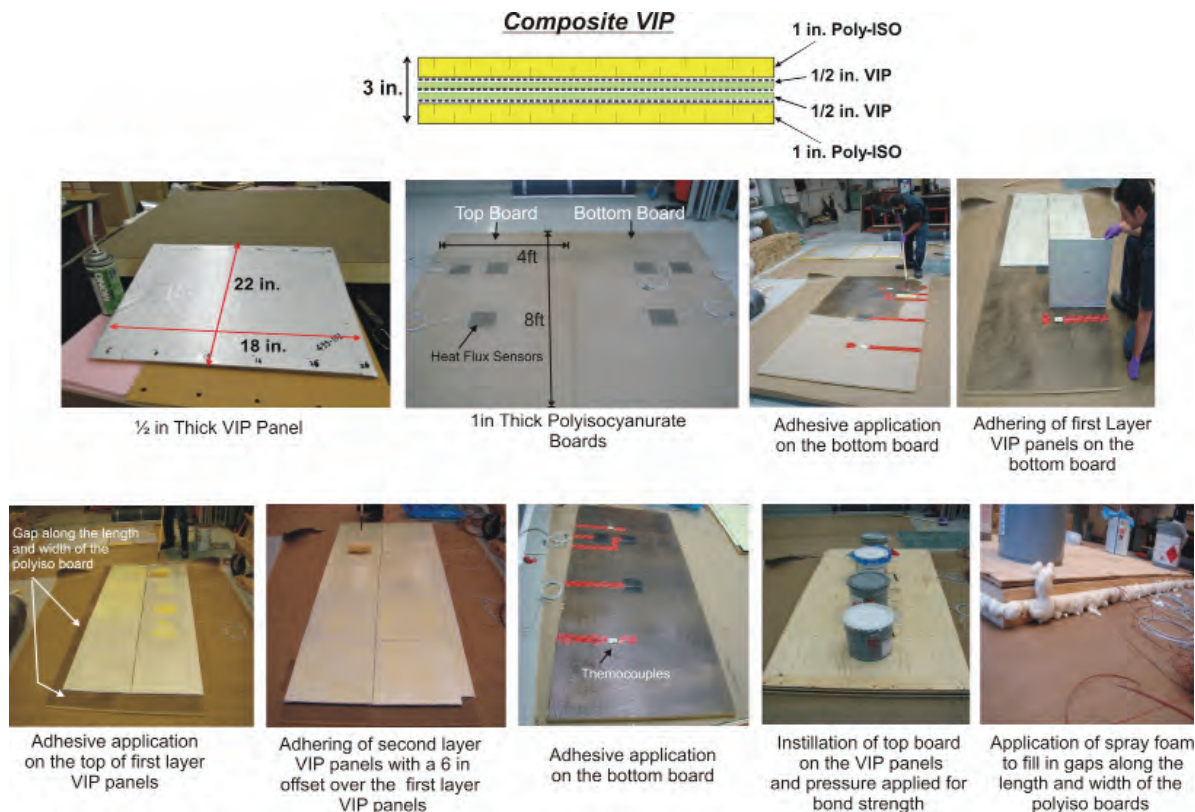


Figure 6: Construction of Composite VIP for Roofing Application

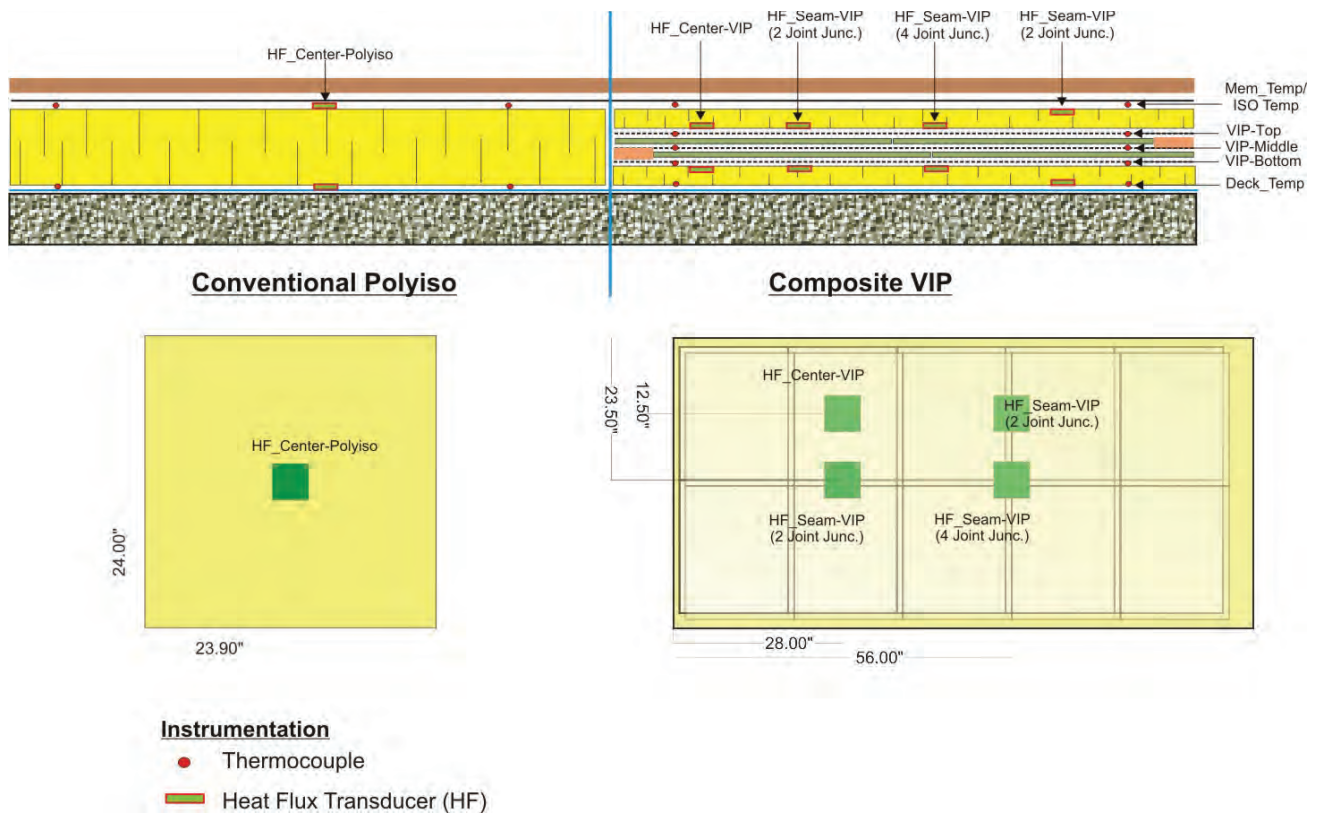


Figure 7: Schematics Showing the Instrumentation Layout

the core or the middle of the VIP panel and the other three to measure the thermal bridging through the VIP panel joints. As one of the objectives was to compare the thermal performance of composite VIP with the conventional insulation side by side, one of the field insulation boards 1.2 m x 1.2 m – 75 mm (4 ft. x 4ft. – 3 in.) thick polyisocyanurate board obtained from the roofing contractor was instrumented with thermocouples and heat flux sensors on both surfaces as shown in Figure 7.

Both the instrumented composite VIP and polyisocyanurate board were carried over to the rooftop of building M-24 and installed side by side on the field of the roof as shown in Figure 8. All the instrumentation wires were carefully directed to the indoor data acquisition system. With the insulation laid, the cover board was adhered to the insulation followed by the torch application of base and cap sheet membranes thus completing the roofing system installation.



Figure 8: Installation Of Composite VIP And Polyiso On M-24 Roof System

M-24 - Roof Mockups - Thermoset Roofing System

The roof mockups were of size 3.7 m x 3.7 m (12 ft. x 12 ft.) and were constructed to replicate the field construction of the RRS. Both the mockups had thermoset membrane i.e. black EPDM membrane. In addition to the membrane, both the mockups comprised 22 Ga steel decks and a self adhered film as a vapor barrier. Insulation was the only component that was different in the mockups. Mockup 1 comprised of 50 mm (2 in.) thick rigid board polyisocyanurate, while Mock up 2 was constructed with 50 mm (2 in.) thick composite VIP. Figure 9 shows the construction of the Mock up 1 and Mock up 2. In Mock up 1, the insulation layout comprised of 1.2 m x 2.4 m - 3 boards (4t x 8ft) and 1.2 m x 2.4 m - 3 boards (4ft x 4ft) - 3 boards, which were adhered to the vapor barrier on the steel deck by a low rise two part urethane adhesive. The insulation boards were instrumented with thermocouples and heat flux sensors as shown in Figure 7. In Mock up 2, 2/3rd of the insulation layout was composite VIP constructed of two layers of 12 mm ($\frac{1}{2}$ in.) thick polyisocyanurate, while the remaining 1/3rd composite VIP was constructed with two layers of 12 mm ($\frac{1}{2}$ in.) thick particle cover board. As the composite VIP panels were constructed with dual layer 12 mm ($\frac{1}{2}$ in.) thick VIP panels the overall thickness of the composite VIP was 50 mm (2 in) matching the thickness of the polyisocyanurate insulation in Mockup 1. Figure 9 shows the top view of the insulation layout in Mock up 2. The construction of the composite VIP is similar to what has been described in M24-Field Roof. The installation of the composite VIP on the vapor barrier/steel deck was also done by using low rise two part urethane adhesive. The EPDM membrane was installed on both the mock ups using a solvent

based membrane adhesive. The overhang membrane along the mockup perimeter was mechanically fastened to the sides of the mockups, and it was overlaid by vinyl siding to prevent from any water ingress into the system. All the instrumentation wiring were carefully hauled inside the mockups and connected to their individual stand alone data acquisition systems.

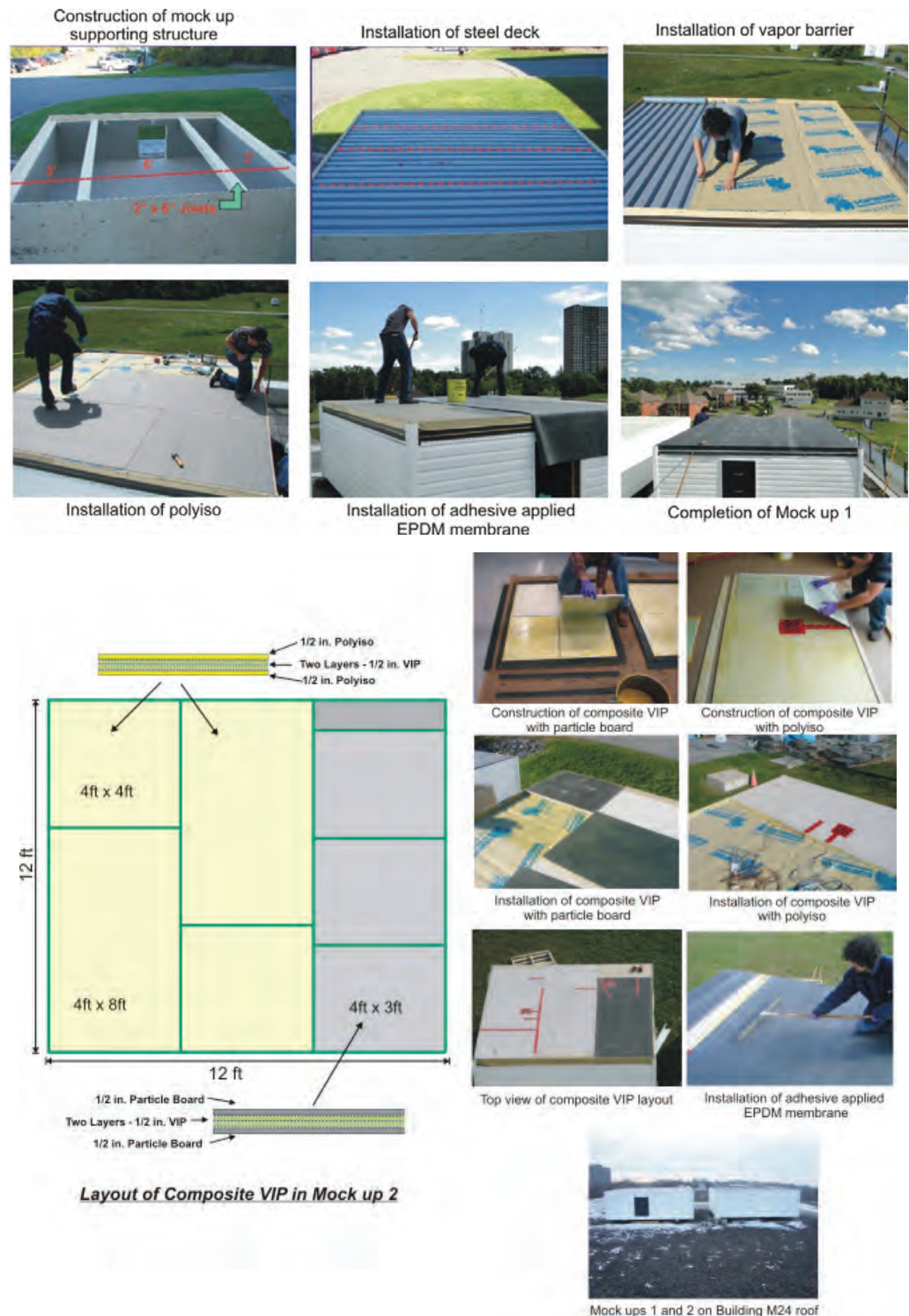


Figure 9: Construction of Mock Up 1-Polyiso and Mock Up 2- Composite VIP

Results and Discussion

The re-roofing of the M-24 was completed in late September 2010, while the construction of the two roof mockups was finished in late November 2010. With the instrumentation connected to the data acquisition system, the thermal data collection started from January 2011. The in-service M24 roof has a conditioned indoor environment. For the mock ups, during winter period heating elements were placed inside to maintain the indoor temperature at 20°C, while there no measures taken yet for summer conditioning. Currently work is going on to address the indoor conditioning issues in both the mockups. The heat flux transducers (HF) were calibrated such that a positive reading represents heat entering the building or the mockups while a negative reading shows heat leaving the building or the mockups. The interim results presented in this paper provide a basic understanding of the thermal performance of polyiso versus composite VIP in roofing systems. As the monitoring of the roofs is being continuing, research updates will be presented in the future on the long term performance of the VIP, energy performance and its interaction with the roofing components.

Temperature and Heat Flow Profile Examples

M24: FIELD ROOF

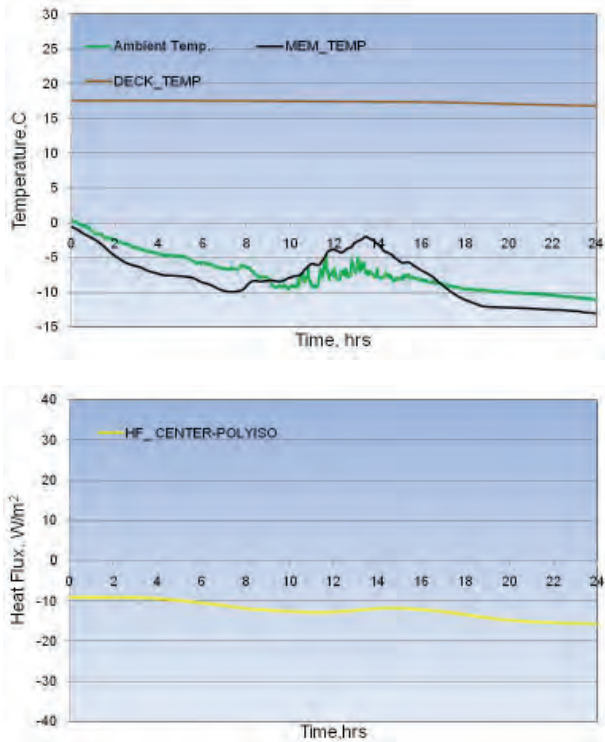
Winter: Figure 10(a) shows the temperature and heat flow profiles of the M24 roofing system on a typical winter day with light snow coverage. As the ambient temperature dropped from midnight to 9:00 a.m. in the morning, the membrane responded to the temperature drop similar on both the polyiso and composite VIP sections. Past 9:00 a.m. as the temperature began increasing to -5°C the membrane temperature on the VIP section measured higher compared to the polyiso section. Even though both the boards (polyiso and composite VIP) are adjacent to each other the membrane temperature varied a lot. The maximum and minimum membrane temperature measured on the polyiso section was -0.5°C and -13°C respectively, while on the composite VIP it was 6°C and -13°C respectively. The temperature between the VIP layers (VIP_MIDDLE) show that the panels were warm throughout the day with low of 5°C and high of 10°C, while the maximum and minimum temperature gradient across the VIP composite was 13°C and 7°C respectively. It should be noted that the maximum and minimum temperature gradient across the adjacent polyiso board was 30°C and 20°C respectively. Comparing the heat flow, the data clearly indicates that there was significant heat loss in the polyiso section of the roof measuring a maximum of 16 W/m² with an average of 12

W/m². On the other hand the composite VIP minimized the heat flux by almost 50% measuring an average of 6 W/m². At the VIP panel joints within the composite, the two joint junction (Figure 10) measured similar heat flux as the center of the VIP, while the four joint junction showed significant heat loss with an average of 12 W/m² almost similar to the polyiso.

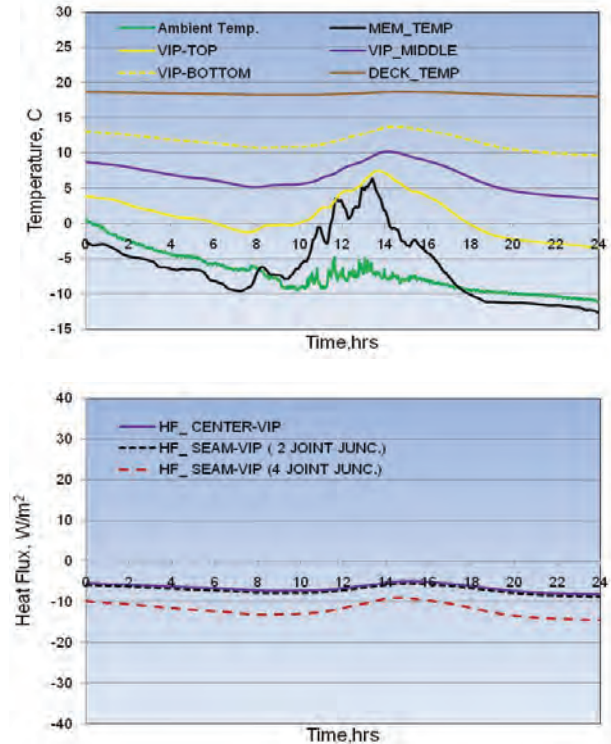
Summer: Figure 10(b) shows the temperature and heat flow profiles within the M24 roofing system on a typical summer day with a maximum ambient temperature of 33°C. On this hot summer day, the modified bituminous membrane measured a maximum temperature of 78°C and minimum of 10°C. During the night the membrane temperature was below the ambient temperature indicating the effect of long -wave radiation. This effect of overcooling is reflected in the heat flow of polyiso section of the roof where an average heat loss of 6 W/m² was measured upto 6:00 a.m. in the morning. With the increase in the ambient temperature, the membrane temperature also increased measuring a maximum temperature gradient of 52°C across the polyiso. Heat started enter the building through the polyiso section of the roof not long after 6:00 a.m, reaching a maximum intensity of 27 W/m² and continued until evening 10:00 p.m at which heat gain change to heat loss. In the case of composite VIP the heat loss due membrane overcooling in the night was only an average of 2 W/m², while the heat gain during the day reached a maximum intensity of 15 W/m². The composite VIP significantly reduced the heat flow by an average of 50% (heat gain and heat loss) compared to the polyiso. However, the four joint junctions of the VIP panels once again measured higher heat flux. From the temperature profile, it should be noted that the top layer VIP panel measured a maximum temperature of 58°C followed by middle layer with 46°C and the bottom layer with 37°C. With VIP panels measuring such high temperatures; it would be interesting to see its effect on the long term performance especially on the gas permeation and insulation efficiency. This will be investigated in the later part of the study as this is one of the research objectives of this field evaluation.

(a) M-24 ROOF: TYPICAL WINTER DAY

Conventional Polyiso



Composite VIP



(b) TYPICAL SUMMER DAY

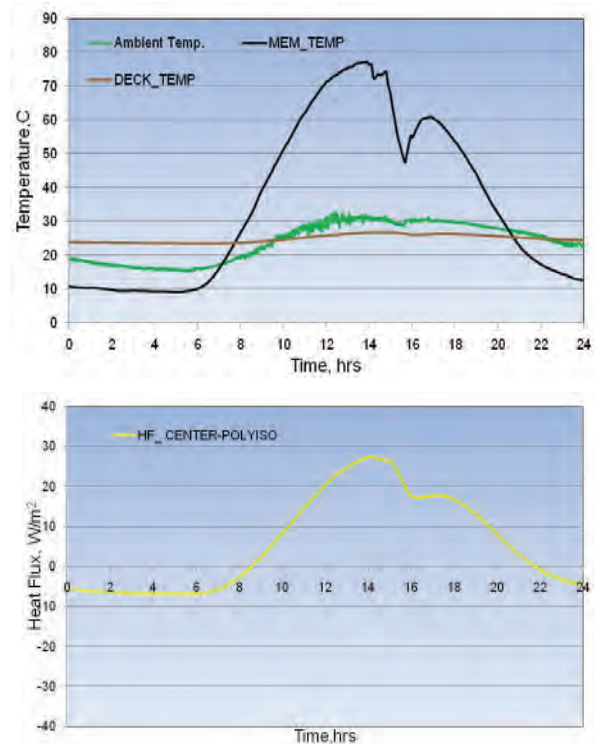
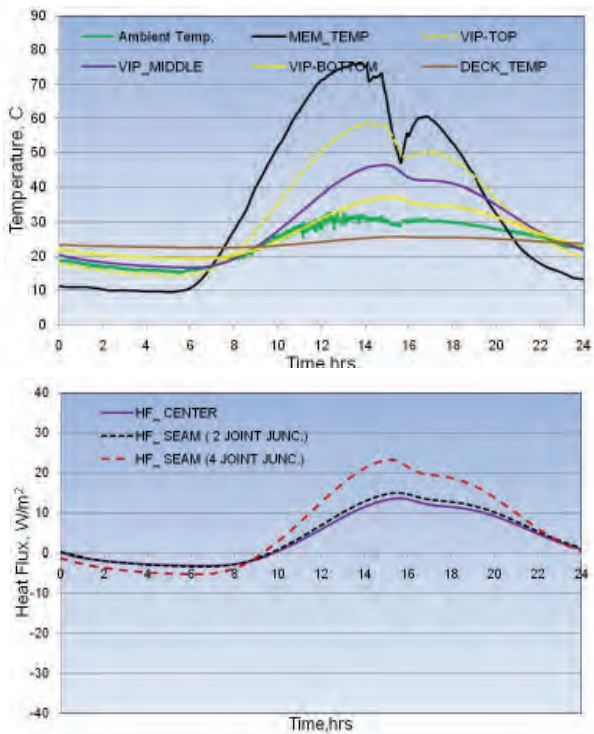
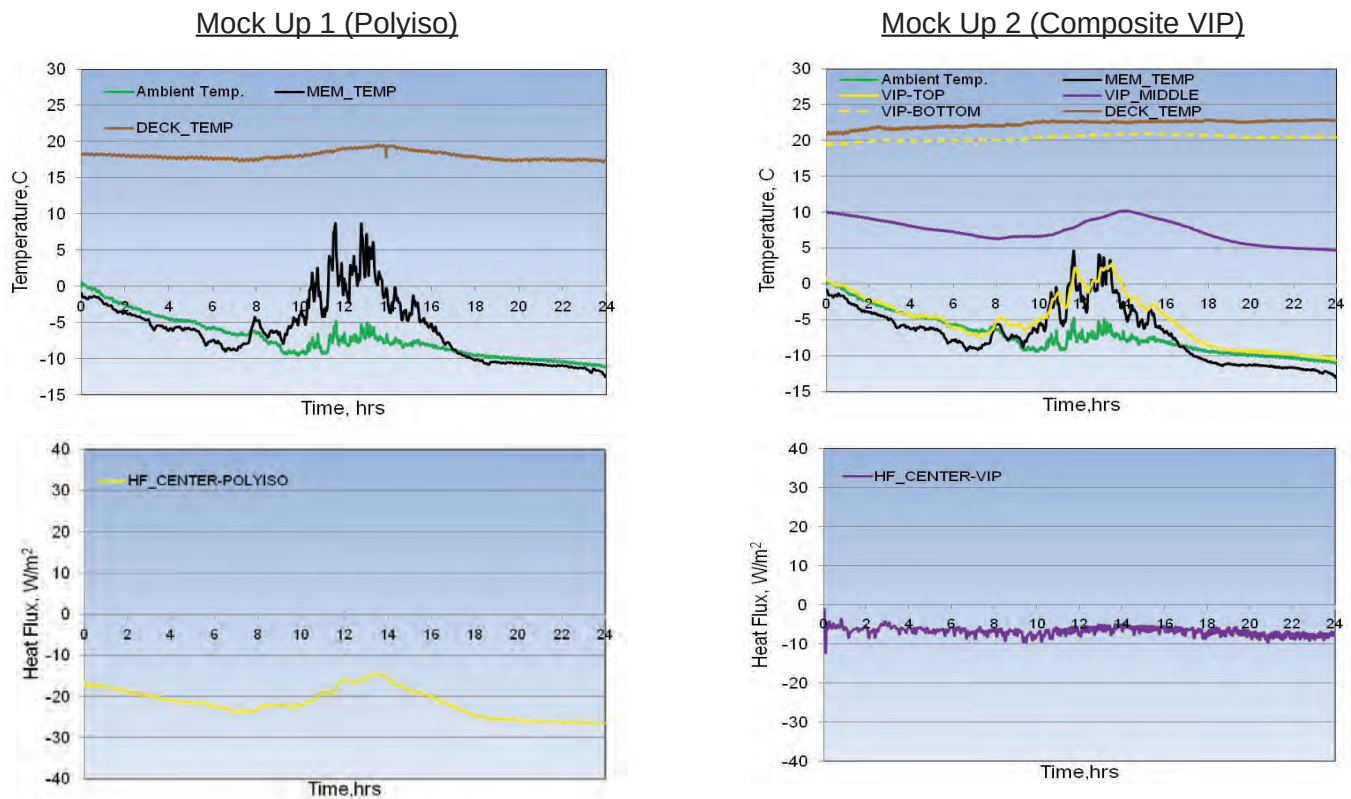


Figure 10: Temperature And Heat Flow Profiles Of The M24-Roof On Typical Winter And Summer Day

(A) ROOF MOCKUPS: TYPICAL WINTER DAY



(B) ROOF MOCKUPS: TYPICAL SUMMER DAY

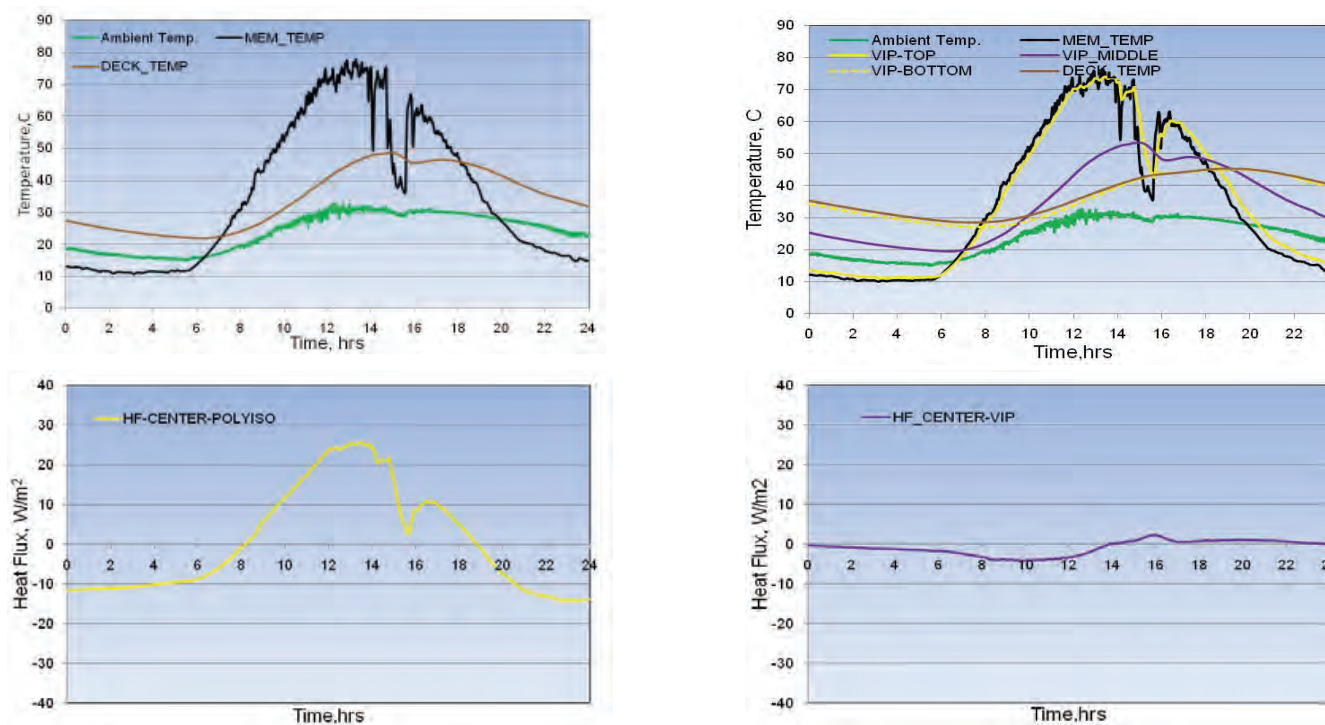


Figure 11: Temperature and Heat Flow Profiles of the Mock Ups 1 and 2 on Typical Winter and Summer Day

M24-ROOF MOCK UPS

In Mock up 2, as explained above 2/3rd of the insulation layout was composite VIP constructed of two layers of 12 mm ($\frac{1}{2}$ in.) thick polyisocyanurate, while the remaining 1/3rd composite VIP was constructed with two layers of 12 mm ($\frac{1}{2}$ in.) thick particle cover board. From the data analysis it showed that both the composite VIP configurations measured similar thermal performance, and therefore the following discussion focuses the composite polyiso - VIP configuration.

Winter: For the same winter day discussed above for the field roof, Figure 11(a) shows the temperature and heat flow profiles of the M24-Roof Mock ups. During the winter months, indoor temperature of both the mock ups was controlled by room heaters. It should also be noted that both the mock ups have 50 mm (2 in) thick insulation compared to the 75 mm (3 in) thick insulation in the field roof. In other words both the mockups have low thermal resistance compared to the field roof. The effect of low thermal resistance is clearly reflected in Mock up 1 where the heat flux varied from 15 W/m² to 29 W/m², when averaged the heat loss (22 W/m²) was almost doubled compared to the field roof with 75 mm (3 in.) polyiso section (12 W/m²). In Mock up 2, the composite VIP significantly minimized the heat loss by almost 72% compared to Mock up 1. Throughout the day the heat flux intensity varied from 5 to 7 W/m² averaging around 6 W/m², which was consistent with the field roof composite VIP section. The temperature between the VIP panels (VIP_MIDDLE) in Mock up 2 followed the same trend as the field roof.

Summer: As mentioned earlier, both the mock ups were not conditioned during the summer months and this resulted in very high indoor temperatures or deck temperatures as shown in Figure 11(b). Therefore relative comparison could not be made of the performance of Mock up 2. Similar to the field roof the composite VIP displayed its high thermal resistance capacity by minimizing both the heat loss and heat gain in the roof system by more than 50% in comparison to the conventional polyiso. With black roofing membrane on the top, the composite VIP measured high temperatures in the range of 50 to 80°C. Monitoring results from periods of several years are needed to verify the effect of these high temperatures on the long term performance especially on the gas permeation, insulation efficiency and any accompanying aging effects. Gaining practical confidence in the vacuum insulation technology is an important prerequisite to further propagate this promising technique in improving the energy efficiency of roofs and buildings.

Conclusions

To investigate the research potential that whether the VIP can become the next generation insulation in the low sloped roofing systems where it can address both the high R-value and increasing

thickness, an innovative experimental study has been started at the National Research Council of Canada. Prefabricated composite VIP insulation boards were constructed in combination of the polyisocyanurate and VIP panels, and were installed in the NRC building M24 field roof with modified bituminous roof system and EPDM roof mock up. This research work started in the early 2011 and the data collection will be continued for another couple of years monitoring the real time long term performance of VIP in roofing applications. The paper discusses the assembly details of the prefabricated VIP configurations and the construction of the roofing systems, and also it presents some interim results comparing the performance of conventional polyiso insulation with the composite VIP. Acting as a thermal barrier in a roof system the composite VIP displayed its high thermal resistance capacity by minimizing both the heat loss and heat gain in the roof system by more than 50% in comparison to the conventional polyiso. With black roofing membrane on the top, the composite VIP measured high temperatures in the range of 50 to 80°C. Monitoring results from periods of several years are needed to verify the effect of these high temperatures on the long term performance especially on the gas permeation, insulation efficiency and any accompanying aging effects. Gaining practical confidence in the vacuum insulation technology is an important prerequisite to further propagate this promising technique in improving the energy efficiency of roofs and buildings.

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VIP Market Development Recommendations Based on the SELF Experimental Building

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1. Preface

Vacuum insulation panels are presently the most efficient thermal insulation available. They are not only thermally very efficient they are often also economically the most attractive solution if the costs for saved building space are correctly considered (Fig.1).

Unfortunately, besides all these benefits, there are also some additional risks that have to be considered. They have been studied by ZAE Bayern and the results have recently been published [1]. The risks are mainly linked to a loss or early degradation of vacuum and consequently to an increased thermal conductivity. Normally this will not cause physical damage but the relatively high construction costs are no longer justified.

A loss of vacuum can originate from faulty production, damage during transportation and mounting and finally damage during service life. Production and transport are basically under the responsibility of the VIP-producer (assuming that packaging arrives undamaged on site), whereas the contractor has the responsibility for careful mounting. Damage occurring during service life may have different reasons and the allocation of responsibility is more complex. It is therefore most important

that good quality control is guaranteed and faulty production or damages during transportation and on site handling can be clearly allocated and reduced to a minimum. The client has to be certain that the VIP-panels delivered and mounted are of good quality.

However, the quality of VIPs delivered on site can hardly be checked. Only mechanical damage is obvious, which normally leads to an immediate loss of vacuum. Production problems, however, can hardly be detected because the vacuum is only reduced and not lost. Unfortunately such production problems can affect a whole production series whereas mechanical damage occurs normally only at single VIPs. Production defects may not be discovered during construction but if they are detected after the construction is completed it is normally disproportional to replace them. It is therefore most important that simple quality checks are possible on site and that faulty VIPs may easily be replaced.

This paper is therefore proposing to apply only standardized VIPs for building construction which might be kept in store before application. This will allow detection of obvious production failures and easy replacement of defective VIPs. It does not substitute the quality control during production; it is rather an additional simple, but important on site check.

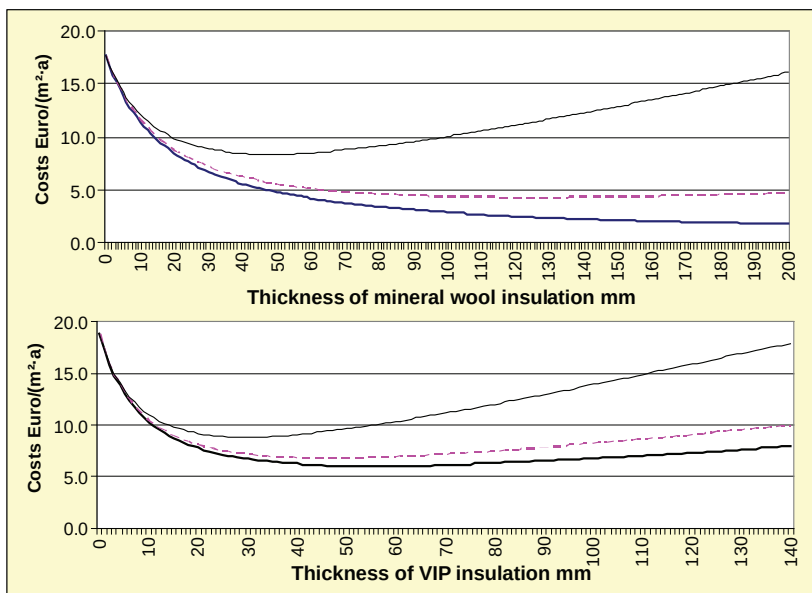


Figure 1: Optimal insulation thickness for mineral wool and VIPs considering insulation costs only —, insulation and land costs ---, insulation, land and building cost —

Assumptions: Insulation on 15 cm brick wall, $\lambda_{\text{mineral wool}} = 0.036$, $\lambda_{\text{VIP}} = 0.008$, service life 80 for mineral wool/ 50 years for VIP, degree days 3735, cost of mineral wool 100 €/m³, cost of VIP 4000 €/m³ + 60 €/m², energy costs 0.10 €/kWh, land cost 400 €/m² (maximum utilisation 0.4 m²/m²land), space renting costs 200 €/(m²·a), floor height 2.8 m, capital costs 4 % p.a.

2. Control Method

There are basically two main types of manufacturing problems that cause damaged vacuum panels:

- Mechanical damage normally leads to a complete loss of vacuum within a very short time. Anyone handling such VIPs will immediately detect faulty panels.
- Production or material problems that lead to a reduced gas-tightness of the envelope. This reduced performance can normally not be observed without adequate testing equipment.

The quality control of the producer is a first and most important test procedure for ensuring the vacuum needed and for avoiding reduced gas tightness. However, due to the fact that there is normally very little time between production and internal quality control, insufficient gas-tightness may often not be detected. The panel will be mounted within a few days on the building site and will be covered immediately by a protection layer. The detection of such a failure is difficult and not really in the interest of the contractor nor of the producer. However the damage can be important because production failures will often affect not only single panels but often whole production series.

The simplest way to reduce this kind failure is the storage of vacuum panels for a long enough period before installation. Panels must clearly indicate the production date. A storage period of 3-6 months would normally be enough to detect safely enough

faulty panels without special equipment. Of course, no one can wait that long if the panels have been specially produced. This concept is only realistic if standardized VIP formats are on stock anyway. Therefore, special formats should be avoided for this reason and also for the many additional advantages listed below.

Advantages of standardized VIP formats:

- More efficient production and therefore lower prices
- Less production waste
- Less production peaks
- Easier construction planning
- Availability of VIPs at distributors
- Clear responsibility if VIPs are damaged upon site delivery
- VIP cores of damaged panels can be efficiently recycled
- Replacement VIPs are easily available any time
- Costs for damaged VIPs replacement upon delivery are much lower than in built in situation

Only two disadvantages have to be considered:

- Higher costs for stock-keeping
- Checking of packaged VIPs may be difficult

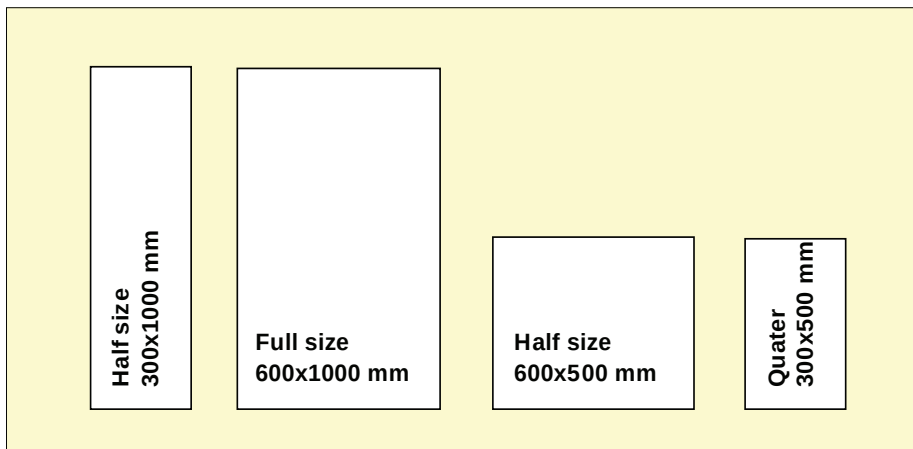


Figure 2: Full size, 2 types of half size and quarter panels are proposed as standard sizes for building applications. Standard panel thickness 20 and 40 mm



Figure 3: The SELF demonstration building from outside (left) and inside (right)

3. Standard Sizes

An optimal assortment of standardized vacuum panels should be available. On the one side it should optimally fulfil the requirements of the market and on the other hand it should minimize production and storage costs. Most probably a modular concept will fulfil these requirements best. Starting from large full size panels also half panels and quarters are easy to apply and can be manufactured without producing waste of core material (Fig. 2).

Empa has experienced the practicability of such an assortment when constructing the SELF demonstration building [2]. SELF is a self sufficient space unit, which is independent from external

energy and water supply. It serves two persons for independent living and working, the whole year and throughout Europe. Innovative technologies are reducing the energy and water consumption to a very low level. Solar modules produce the energy needed for heating, cooling, ventilation, hot water, light, and appliances. Rain water is collected and recycled (Fig. 3).

Minimizing the heating and cooling energy demand was possible with a full insulation of all opaque surfaces with vacuum insulation panels (Fig 4). Despite the fact that the shape of the space unit is completely irregular and no right angles occur it was possible to insulate approx. 90 % of the inner surface with standard VIPs (Fig. 5).

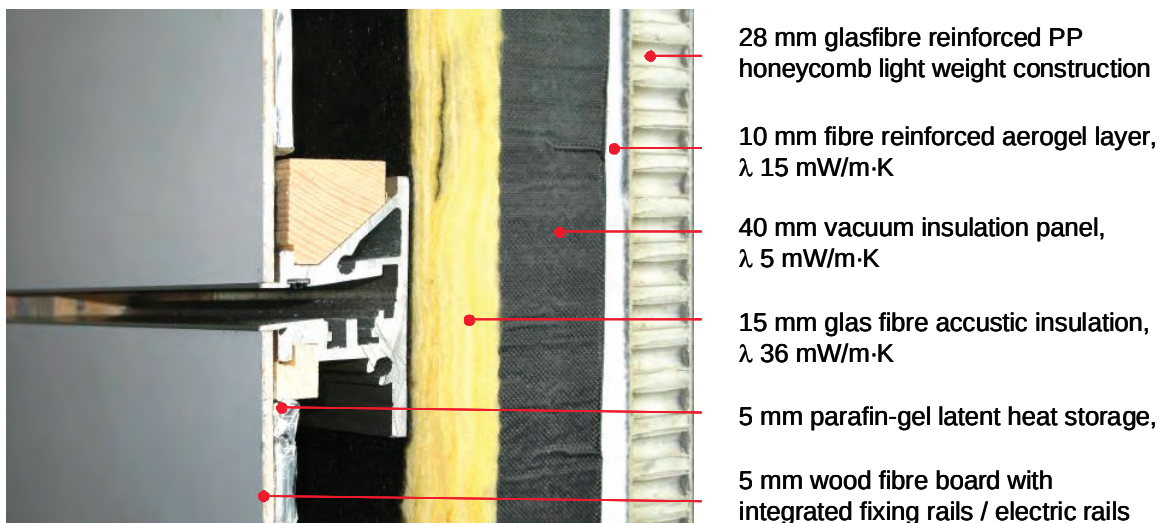


Figure 4: Construction of the light weight building envelope. The U-value of the 150 mm thick building envelope is as low as $0.1 \text{ W/(m}^2 \cdot \text{K)}$ (assuming the 40 mm VIP with a planned service life of 15 year to have a λ -value of $5 \text{ mW/(m} \cdot \text{K)}$).

30 mm spaces between the VIPs have been carefully planned for fixing the panels. Dummy panels out of polystyrene were used to prepare mounting. All gaps have been filled either with fibre reinforced aerogel (λ -value 16 mW/(m·K) or polyurethane foam (λ -value 19 mW/(m·K)). The VIPs were regularly checked and faulty panels were eliminated before mounting and replaced. After 6 month storage of the panels, it was relatively easy to detect production errors. During the construction process only one panel was damaged mechanically. All panels except for floor and ceiling are still accessible for pressure testing. Continuous monitoring – also with infra-red camera – will allow detection of early degradation of the vacuum.



Figure 5: Standards sized 40 mm VIPs were used for internal insulation of the SELF unit. All joints are sealed with vapor barrier tape.

4. Lessons Learned

Working with especially tailored VIPs would have caused tremendous planning and construction effort. Tailored VIPs would have created higher costs and great difficulties to organize replacement for damaged panels. The same problem will occur on building sites. Damaged panels will often not be replaced if no alternative panels are immediately available. The ongoing construction process will not allow waiting for the production of new panels and delivery on site. Even worse, if panels are tailor made they are often immediately mounted and protected. Production errors of whole series will probably not being detected. That might seem to be an advantage for the producer; however, the consequential costs may be extremely high if the damages are detected later.

Only standardized VIP formats that a local distributor or even the contractor may have on stock guarantee the availability and an immediate replacement is possible. At the same time, this concept will allow storage the panels for long enough in order to verify without special equipment, a reasonable intactness of the VIPs delivered to the site.

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Technical Session 5

Long-term Performance of VIP

*(Session Chair – Anil Parekh,
Natural Resources Canada, Canada)*

Mass Transfer in the Envelope of Vacuum Insulation Panels, a Modeling Challenge for Aging Prediction

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1. Introduction

Vacuum Insulation Panels (VIP) are thermal insulation systems able to produce a high building insulation level for a very low thickness. They are made with a porous core material evacuated and encapsulated in an airtight and watertight envelope. The most promising design is based on nanoporous silica for core material and multilayer Al-coated polymer foils for envelope. A VIP built from these elements can reach an apparent thermal conductivity of $5 \times 10^{-3} \text{ W/(m.K)}$ [1], around six times less than a conventional insulation material [2]. This performance has been measured for new panels, but the issue of durability is crucial regarding the performance of the panel in its whole life. Heat and mass transfer models are needed to understand and to predict the ageing's mechanism and velocity of these insulation systems.

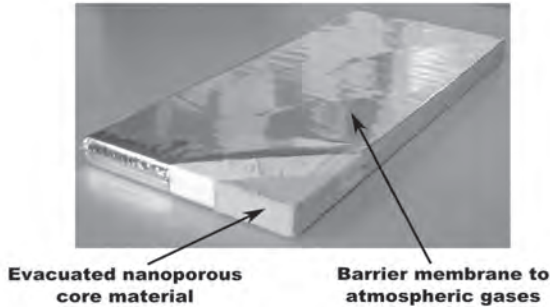


Figure 1 : Design of a Vacuum Insulation Panel [3]

2. Heat Transfer Modeling in VIPs

2.1 Heat transfer in core material

The Figure 2 shows, for several porous media, the experimental thermal conductivity as a function of internal pressure. Both fumed and precipitated silica have a very low thermal conductivity (below 10^{-2} W/(m.K)) for a pressure much higher than the vacuum level required for other media. The use of nanoporous silica is thus absolutely relevant. The usual heat transfer model in nanoporous silica is the parallel flux model [4]. Three modes are considered: the radiative transfer, the conductive transfer in

the solid matrix, and the gaseous transfer. Coupling effects are neglected for a simplified approach where each flux is computed independently:

$$\lambda_{core} = \lambda_{rad} + \lambda_{sol} + \lambda_g \quad (1)$$

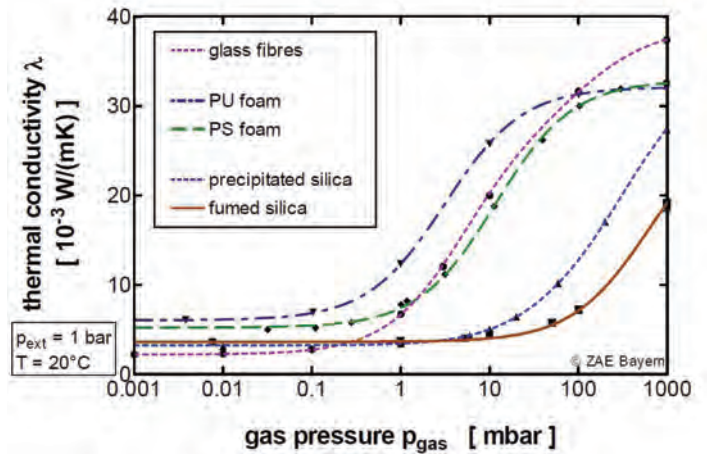


Figure 2 : Thermal conductivity of porous media as a function of internal pressure [2]

Each elementary conductivity can be evaluated by theoretical or empirical equations, as listed below. Few details on these equations are given here, as the main focus of this paper is the mass transfer modeling. Indicative values are given at the end of the part.

Nanoporous silica is not opaque to the radiative transfer. The granular form allows the addition of opaque powders to reduce the radiative transmission. The Rosseland approximation is then used [5-10] :

$$\lambda_{rad} = \frac{16}{3} \frac{\sigma n^2 T_{rad}^3}{\rho e(T_{rad})} \quad (2)$$

The dry solid matrix of nanoporous silica has a thermal conductivity proportional to the vitreous silica, in terms of temperature dependence. The coefficient g between conductivities has been measured, between 0,001 and 0,0025 [8,11].

$$(T) = g\lambda_{sil}(T) = g[(-8,5.10^{-12})T^4 + (2,1.10^{-8})T^3 - (1,95.10^{-5})T^2 + 0,00883T] \quad (3)$$

Humidity strongly changes the heat flux through the matrix, since the water is adsorbed at the surface of the hydrophilic silica. Both composition and geometry are changed. Several labs have experimentally observed the linear influence of the mass water content u (ratio between water and matrix masses) on the matrix heat transfer [9,12,13].

$$\frac{\partial \lambda_{sol}}{\partial u} = B \quad \text{W/(m.K.\%)} \quad (4)$$

The characteristic pore size ($\delta=100$ nm) of silica and the mean free path of air molecules ($L=75$ nm at 300K and 1 bar) are in the same order of magnitude. The Knudsen number $Kn = L / \delta$ is close to 1 and heat transfer through the gas phase is reduced. Using the Knudsen relation, Kanager [14] and other authors [9,10] have estimated the gaseous conductivity :

$$\lambda_g = \frac{\lambda_g^0}{1 + 2\beta Kn} \quad (5)$$

λ_g^0 is the conductivity of non confined air, and $\beta \sim 1,5$. The mean free path is equal to $L = (k_B T) / (\sqrt{2} \pi d_g^2 p)$, so the gaseous conductivity can be rewritten as

$$\lambda_g = \frac{\lambda_g^0}{1 + p_{1/2}(T)/p} \quad (6)$$

$p_{1/2}(T)$ is a fitting pressure which corresponds to a conductivity reduced to half of the non-confined value.

2.2 Envelope thermal bridge

The presence of the envelope on the edge of the panel creates a thermal bridge. The total apparent conductivity of a VIP is the sum of the centre-of-panel conductivity (core material) and the edge equivalent conductivity (membrane thermal bridge)

$$\lambda_{tot} = \lambda_{core} + \lambda_{memb} \quad (7)$$

Two kinds of membranes are considered for the envelope, sometimes referred as AF and MF envelopes [1]. The first family contains the laminated Aluminium Foils, typically foils of 6 to 10 μm of aluminium protected on both sides by polymer thin films

(PE, PET). The second family contains the Al-coated multilayer foils, typically two or three polymer foils (PE, PET), coated with aluminium (20-100 nm thick), and glued to form the complex membrane. The barrier properties of both kinds of membranes to atmospheric air can be close when temperature and humidity conditions are moderated [15]. In Table 1, the apparent thermal conductivity increases due to the envelope are listed, from experimental data of Ghazi et al. [16] and numerical data of Schwab et al. [17], for a 1m x 1m x 2cm panel. The multilayer foils are much more efficient as they increase the heat transfer by around 20% whereas laminated foils increase the heat flux by around 100%.

Table 1 : Relative increase of the apparent thermal conductivity of a panel (panel size 1m x 1m, thickness 2 cm)

Références	Films AF	Films MF
[18] (exp.)	+ 96 %	+ 13 % à + 19 %
[19] (num.)	+ 82 % à + 210 %	+ 0 % à + 28 %

2.3 Total apparent conductivity of a VIP and ageing factors

At a given temperature, the overall conductivity can be written as:

$$\lambda_{tot}(p, u) = \lambda_{rad} = g\lambda_{sil} + Bu + \frac{\lambda_g^0}{1 + p_{1/2}/p} + \lambda_{memb} \quad (8)$$

Table 2 gives indicative values for the parameters in the equation (8) for a pyrogenic silica, at $T=293\text{K}$. The equation (8) shows that two main factors are responsible for the degradation of thermal performance : the internal pressure and the water content, which increase during the lifetime of the panel because of permeation through the envelope. The velocity of the thermal conductivity increase is highly connected to these mass transfers through the envelope.

Table 2 : Indicative parameters for the total thermal conductivity

λ_{rad} [W.(m.K)]	g [adim]	B [W.(m.K.\%)]	$p_{1/2}$ [mbar]	λ_{memb} [W.(m.K)]
0.7×10^{-3}	2.2×10^{-3}	10^{-3}	600	10^{-3}

Mass transfer modeling in VIPs

3.1 Linear model of Sorption / Diffusion

The problem studied here concerns the mass transport of a species i through a membrane of thickness l between two gaseous phases of pure gas (see Figure 3). For a homogeneous and dense polymer membrane, the pure gas sorption / diffusion model is commonly used [18].

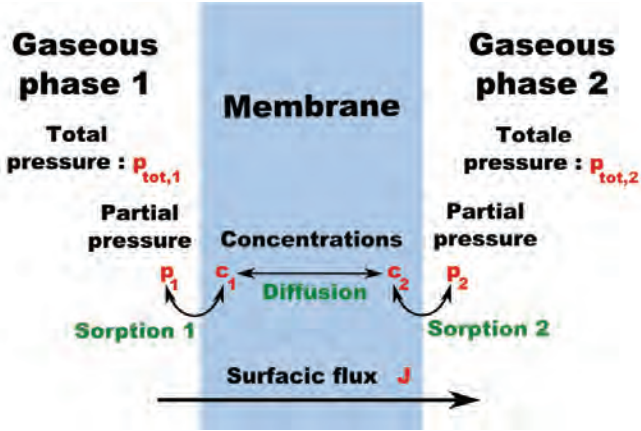


Figure 3 : Gas transport through the membrane, sorption / diffusion mechanism

Diffusion inside the membrane is represented by Fick's Law, a phenomenological law for mass transfer similar to Fourier's Law for heat transfer.

$$J_i = -D_i \frac{\partial c_i}{\partial x} \quad (9)$$

Where D_i is the diffusion coefficient of the species in the membrane.

The sorption at the interface membrane – gas is driven by Henry's Law : at constant temperature, the concentration c_i in the membrane and its partial pressure p_i in the gaseous phase are proportional. The proportionality coefficient is the solubility coefficient S_i of the species i .

$$c_i = S_i p_i \quad (10)$$

It is commonly assumed that the diffusion and solubility coefficients D_i and S_i are only dependant on the (gas, polymer) couple and the temperature. The temperature influence is described by an Arrhenius thermo-activation process:

$$D_i = D_i^0 \exp(-E_a^D / R(T - T^0)) \quad (11)$$

$$S_i = S_i^0 \exp(-E_a^S / R(T - T^0)) \quad (12)$$

For an isothermal system, D_i and S_i are constant. In steady state, it is possible to integrate Fick's Law (Eq. (9)) between interfaces 1 and 2, and then to get the surface flux as a function of the pressure difference:

$$J_i = D_i \frac{c_{i,1} - c_{i,2}}{l} = D_i \frac{S_i (p_{i,1} - p_{i,2})}{l} \quad (13)$$

The permeability is then defined from the diffusion and solubility coefficients.

$$Pe_i = D_i S_i \quad (14)$$

The surface flux is calculated by a simple equation:

$$J_i = - \frac{Pe_i}{l} \Delta p_i \quad (15)$$

The activation energy of the permeability is then given by:

$$E_a^{Pe} = E_a^D + E_a^S \quad (16)$$

And the permeability can be expressed as a function of the temperature:

$$P_{ei} = Pe_i^0 \exp(-E_a^{Pe} / R(T - T^0)) \quad (17)$$

3.2 Identification of experimental data

Ageing models for VIPs have always been based on the sorption / diffusion model for mass transfer so far [1, 15, 19-21]. In these existing studies, the following hypotheses are assumed:

1. The internal and external gaseous phases are binary mixtures of dry air and water vapor.

- The total gas transmission rate GTR_{tot} of each species is split in two parts : the contribution of the panel faces GTR_{surf} , based on an area A and a surface flow rate J_{surf} , and a contribution of the edges GTR_{lin} , based on a length L and a linear flow rate J_{lin} .
- The flux for each species is proportional to the difference of partial pressure. The coefficient of proportionality is called the permeance Π (from the equation (15))

$$J_{surf} = \Pi_{surf} \Delta p_i = (Pe_{surf}/l) \Delta p_i \quad (19)$$

$$J_{lin} = \Pi_{lin} \Delta p_i = (Pe_{lin}/l) \Delta p_i \quad (20)$$

- Permeances are independent of the gas composition
- Permeances are only functions of the temperature, following an Arrhenius Law

$$\Pi_i = \Pi_i^0 \exp(-E_a/RT) \quad (21)$$

Table 3: Conditions of pressure/humidity in measurement boxes (ZAE Bayern [15])

Box	Temperature	Relative Humidity	Water vapor partial pressure
1	25 °C	45 %	1400 Pa
2	45 °C	15 %	1400 Pa
3	65 °C	6 %	1400 Pa
4	25 °C	75 %	2350 Pa
5	45 °C	75 %	7100 Pa

A German laboratory, ZAE Bayern, has conducted a 300 days experimental campaign of VIPs' ageing in order to measure the barrier properties of the envelopes [15]. Panels were made with 3 different envelopes : an aluminium laminated foil AF, and two multilayer Al-coated membranes, MF1 (low quality) and MF2 (high quality). Five measurement boxes have been used, the conditions are listed in Table 3.

Table 4 : Participation of dry air and water vapor in mass flow and total pressure

Box	Size [cm ²]	Dry air participation in total mass flow, AF [%]	Water vapor participation in total pressure, MF1 [%]	Water vapor participation in total pressure, MF2 [%]
1	10x10	6,3	7,5	7,5
2		22,4	2,6	8,9
3		24,3	1,3	4,9
4		4,7	18,1	41,8
5		3,6	14,7	34,8
1	20x20	3,3	10,7	12,7
2		9,2	4,0	8,3
3		9,4	1,7	3,2
4		4,0	26,3	44,2
5		5,5	23,6	37,3

For each box and each membrane, two panel sizes have been tested: 10x10x2 cm³ and 20x20x2 cm³. Mass and internal pressure have regularly been recorded. As notified in the original paper [15], the water vapor pressure has to be subtracted to the internal pressure to get the dry air partial pressure. This water vapor pressure is computed from the sorption isotherm. Table 4 confirms the important participation of water vapor in the total pressure (orange background), but it also shows how that dry air can be an important part of the mass increase of VIPs (green background). The common hypothesis that the mass increase and the water flow rates are equal is not true in all cases.

Duforestel and Kherrouf have developed a method to calculate simultaneously the water and dry air flow rates, from the mass and pressure variations and the linear approximation of the sorption isotherm [22]. The identification of measurements data from ZAE Bayern has been conducted thanks to this method, which is supposed to be more accurate than the one used in the original paper. Some of these results are presented and analysed in the following parts.

The contributions of faces and edges in the total mass flow rates for each membrane are computed from the equation (18) and the measurements on the two panel sizes. For dry air, the numerical resolution gives a flow rate through the faces mostly negative (from inside to outside), which is physically not probable, and one or two orders of magnitude below the edge flow. The surface flow rate is thus assumed to be null, and the dry air flow only due to the edges. Concerning water vapor, the behaviour is different for each membrane. For the AF envelope, the mass transfer occurs only through the faces for low humidity (<45% RH) and through the edges for high humidity (75 % RH). For the low quality MF1 envelope, faces and edges contributions are almost equivalent for

25 °C and 65 °C, and the transfer is only through faces for 45 °C. For the high quality MF2 envelope, edges' flow is the major part of the flow, except for the box number 1 and 5, where faces and edges have similar contributions. If the flow is only through faces or edges, equation (22) or (23) is used. If both participations have to be taken into account, equation (24) or (25) is used.

$$\Pi_{surf,i} = \frac{J_{surf,i}}{\Delta p_i} = \frac{GTR_{tot,i}}{A \Delta p_i} \quad (22)$$

$$\Pi_{lin,i} = \frac{J_{lin,i}}{\Delta p_i} = \frac{GTR_{tot,i}}{P \Delta p_i} \quad (23)$$

$$\Pi_{surf,i} = \frac{J_{surf,i}}{\Delta p_i} = \frac{1}{\Delta p_i} \frac{(A_0 GTR_{tot,i,0} - A_0 GTR_{tot,i,0})}{(A_0 P_0 - A_0 P_0)} \quad (24)$$

$$\Pi_{lin,i} = \frac{J_{lin,i}}{\Delta p_i} = \frac{1}{\Delta p_i} \frac{(P_0 GTR_{tot,i,0} - P_0 GTR_{tot,i,0})}{(P_0 A_0 - P_0 A_0)} \quad (25)$$

The sets of results of boxes 1-2-3 and 4-5 are used to compute the energies of activation, as only temperature is changed, partial water vapor pressure in the first set and the relative humidity in the second set are kept constant. The equation used is:

$$E_a^n = \frac{\partial \ln(\Pi_i)}{\partial (1/RT)} \quad (26)$$

4. Results and Discussion

4.1 Influence of the panel size

The permeance of the AF envelope is plotted as a function of the panel size in order to observe the influence on the mass transfer for dry air (Figure 4) and water vapor (Figure 5). The size has a very slight influence on the linear permeance for dry air, as noted above: this linear permeance identification is a good choice. But for water vapor, the size has a major influence on the surface or linear permeance, so that it is not that easy to separate the faces and the edges contributions.

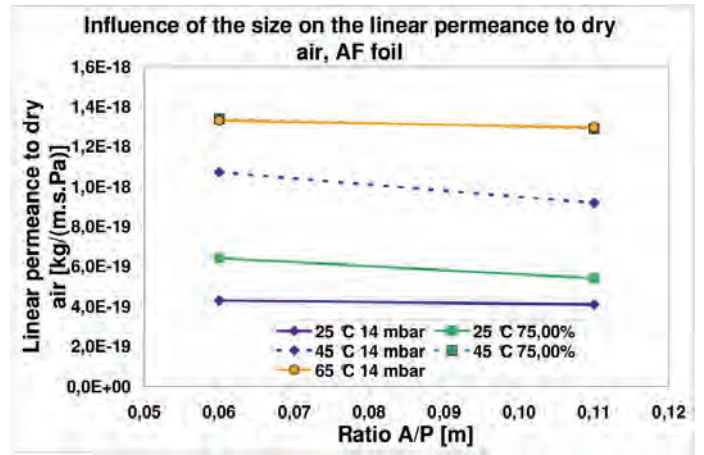


Figure 4 : Permeance to dry air as a function of the ratio P/A, AF foil

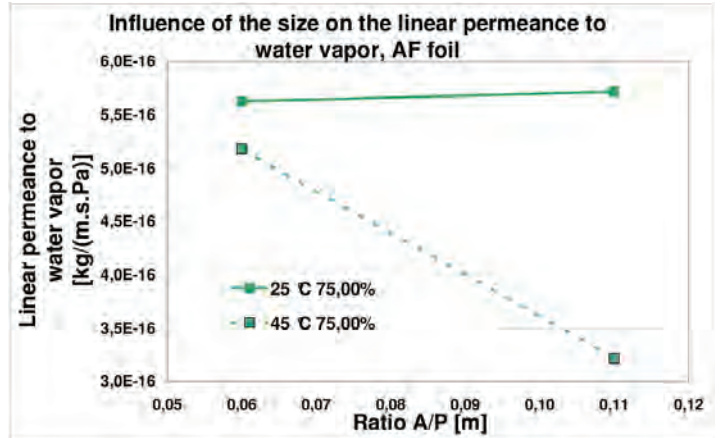
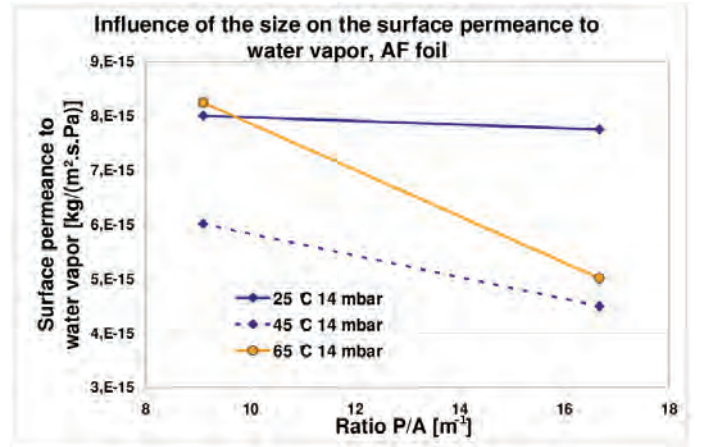


Figure 5 : Influence of the size on the surface and linear permeance to water vapor, AF foil

4.2 Independence of the flux

The results plotted in Figure 6 are in contradiction with the hypothesis of independent fluxes : the permeance to dry air is an increasing function of the relative humidity. From the dry box to the 75% RH box, the values are increasing from 0 to +50% at 25°C, and from 0 to +150% at 45°C. These variations are an indication that a coupling occurs between the dry air and the water vapor fluxes : the amount of water has a really strong impact on the dry air flow rate.

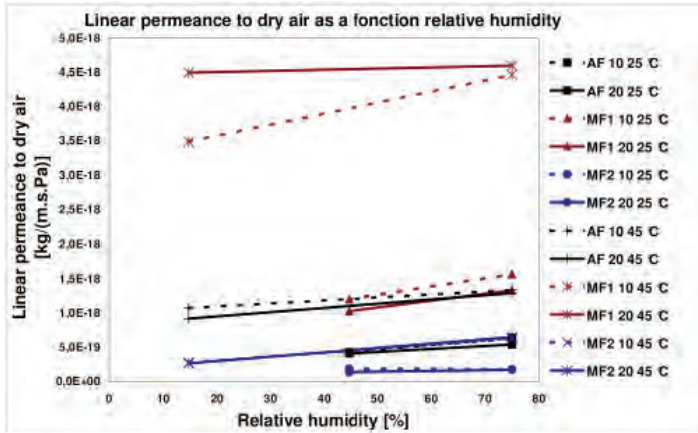


Figure 6 : Permeance to dry air as a function of relative humidity

The variations in the case of water vapor permeance and multilayer aluminised foils are even stronger : the permeance increase is between +45% and +1000% when the relative humidity is shifted from low to high value. The permeance to water vapor is clearly a function of humidity, not only temperature.

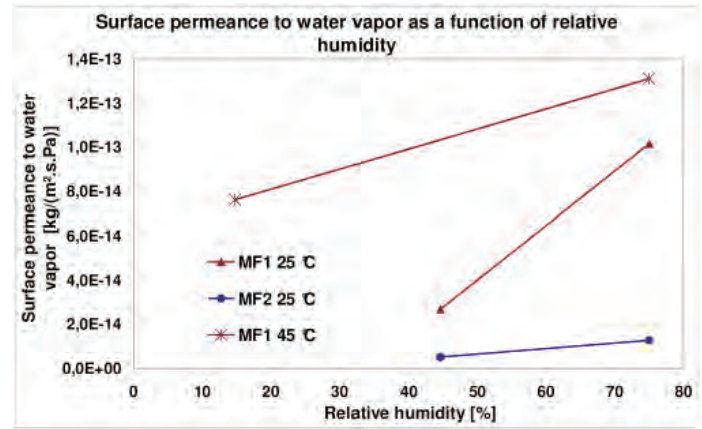
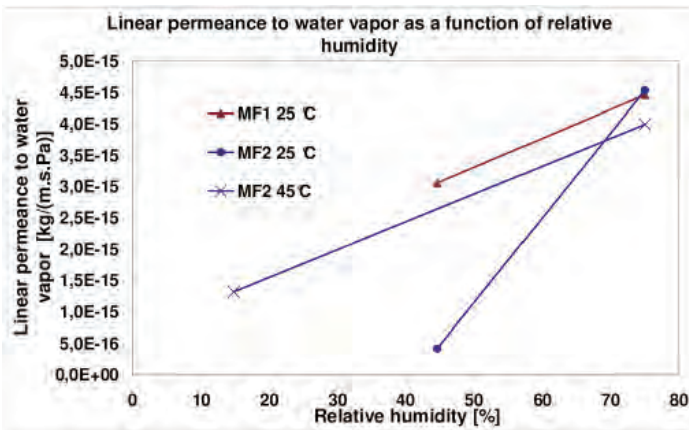


Figure 7 : Permeance to water vapor as a function of relative humidity

4.3 Influence of the temperature and activation energies

The activation energies identified thanks to the equation (21) and the measurements of boxes 1-2-3 are listed in the Table 5. In the case of dry air, the regressions are satisfactory, considering three criteria : order of magnitude (and positive sign), consistency between 10x10 and 20x20 panel's values, and correlation coefficients. The regressions concerning water vapor permeance have however bad results on these three criteria (orange background color in the table). But an alternative model gives better results. This new model considers that the flux is driven by the relative humidity gradient, not the partial pressure gradient. The new flow rate equation is thus the equation (27). For dry air, no alternative model has been tested, as all measurements are made at atmospheric pressure, indeed $p_{da} \sim 10^5$ Pa is almost a constant.

$$J_{vap} = \Pi_{vap} \Delta RH \quad (27)$$

Table 5 : Activation energies of permeances

Gas ($p_{\text{vap}}=1400$ Pa)	Foil	10x10		20x20	
		E_a [kJ/mol]	Correlation Coefficient R^2	E_a [kJ/mol]	Correlation Coefficient R^2
Dry air	AF (lin)	23,9	0,91	24,3	0,96
	MF1 (lin)	32,2	0,97	37,1	0,89
	MF2 (lin)	25,5	0,94	27,4	1
Water vapor (drive = Δp_{vap})	AF (surf)	-9,4	0,61	0,4	0
		10x10 & 20x20			
	MF1 (surf)	2,9	0,61		
	MF2 (lin)	21,9	0,73		
Water vapor (drive = ΔRH)	AF (surf)	34,1	0,95	43,9	0,97
		10x10 & 20x20			
	MF1 (surf)	46,4	0,79		
	MF2 (lin)	65,4	0,96		

5. Conclusion

Modeling of vacuum super-insulation ageing requires the development of a heat transfer model, in order to know the instantaneous thermal performance of a VIP as a function of internal and external conditions. The parallel flux model has showed its ability to answer this question. Despite its semi-empirical approach, the precision is rather sufficient and the reproducibility is good enough for the purpose of ageing modeling.

The classical mass transfer model, based on sorption/diffusion phenomena, has been used for experimental data of ZAE Bayern identification. The lack of consistency between model theory and experimental facts has been illustrated in the paper, in particular through the fact that some hypotheses have not been verified. The coupling of dry air and water vapor transfers is observed, in contradiction with the independent fluxes hypothesis, and the relative humidity seems to be the drive for water transport.

This review about VIP ageing modeling has shown the real need for progress in mass transfer modeling applied to those high barrier foils. It is necessary to develop a model able to reproduce the experimental facts. Possible improvements may come from existing models, like the Dual Mode model [23,24], or ad hoc models, built from experimental data correlation.

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Gas Permeation Characteristics through Heat-Sealed Flanges of VIPs

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Abstract

Not only an outstanding insulation performance but also an extended service lifetime are required in vacuum insulation panels (VIPs). Thermal insulation performance of VIPs is degraded with time due to deterioration of the inner vacuum. The main causes are gas permeation and out-gassing in VIPs. Especially, gas permeation in the lateral direction through heat-sealed flanges has the largest effect. It is thus necessary to investigate the permeation characteristics of the envelope seal materials (typically linear low density polyethylene, LLDPE, and low density polyethylene, LDPE). A measurement apparatus using multiple radial permeation passages surrounded by the permeation gas jacket is designed to measure the gas permeation rate through the polymer films. The measurement shows reliable accuracy compared with other reported results. Further, to reduce gas permeation through the heat-seal, a novel method of employing metal wire the heat-sealed layers is also suggested in this study.

List of symbols

- a outer radius, m
 A_s permeation surface area, m²
 b inner radius, m
 K gas permeability, cm³·cm/cm²·s·Pa
 L total thickness of the specimen, m
 ΔP pressure difference, Pa
 P pressure, Pa
 P_{crit} allowable pressure, Pa
 P_{inside} pressure inside the apparatus, Pa
 $P_{outside}$ pressure outside the apparatus, Pa
 Q gas permeation flow rate, Pa·L/s

R universal gas constant, J/mol·K

T temperature, K

t time, s

t_{crit} critical service lifetime, s

V volume, m³

Greek symbols

δ permeation length, m

Subscripts

atm atmospheric

crit critical

eff effective

1. Introduction

Energy is an indispensable part of human life. The current energy crisis has occurred owing to serious energy depletion and other political factors. Besides, environmental problems such as global warming are also challenging. It is required to overcome both problems simultaneously without deteriorating quality of human life. Not only developing new energy but also reducing the energy consumption is important above all. Considering that building energy accounts for about half of the total energy consumption, the use of VIPs is a most desirable means to meet these ends.

The VIP which is evacuated inside the volume eliminates heat transfer by air in conventional insulation materials of $k \approx 30 \text{ mW/m} \cdot \text{K}$. Insulation performance of the VIP is about 10 times higher than that of conventional insulation materials because eliminating the effects of air [1,2]. Nevertheless, the life time of the VIP must

be guaranteed for 10 to 15 years in appliances or more than 50 years in buildings, which is a formidable goal currently.

Heat transfer in the VIP is coupled with three modes [3]: solid conduction via core material and the envelope, gaseous conduction by residual gas in the VIP and radiation between inner surfaces.

Among these, gaseous conduction depends on time. It is closely related with service lifetime. It is expressed by a function of gas pressure and pore size for rarefied gas [3]. It becomes larger as the inner pressure gradually increases with time.

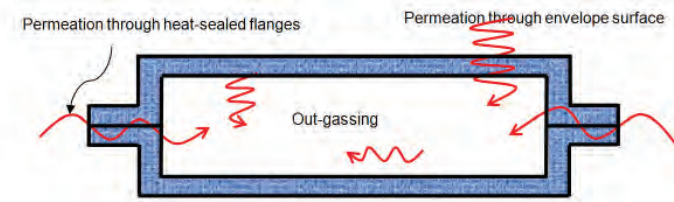


Fig.1: Various gas sources deteriorating vacuum level

Pressure increase is owing to gas permeation and out-gassing [4]. As shown in Fig.1, the gas permeation is composed of permeation through envelope surface and that through heat-sealed flanges, while another major gas source is the out-gassing from the core structure and inner surface of the envelope. It is shown that the out-gassing can be minimized by a baking process in vacuum as a pretreatment [4]. Also, since a metal layer (usually aluminum foil) is usually inserted in the envelope material, it can significantly reduce the gas permeation in the normal direction through the envelope films. Now, the remaining problem is the permeation through the heat-sealed flanges; there is no countermeasure to reduce the gas permeation in the lateral direction through them. This is the for most cases largest gas source. Practically, the gas loads estimated for the VIP with the polycarbonate staggered beam core by Kwon et al. [4] show that the permeation through heat-sealed flanges is the governing factor of pressure increase. Consequentially, it is needed to investigate characteristics of gas permeation of heat-sealed flanges in the lateral direction

In this study, a measurement apparatus is designed to directly measure the gas permeation in the lateral direction through the polymer films such as LDPE and LLDPE films. Then a novel method is proposed to reduce the gas permeation through the heat-sealed flanges.

2. Gas Permeation Through Heat-Sealed Flanges

2.1 Experimental method

The amount of permeation is closely related with permeability K and the gas permeation flow rate Q in a steady state can be expressed by [4],

$$Q(t) = K \cdot \frac{A_s}{\delta} \cdot (P_{atm} - P(t)), \quad (1)$$

where A_s is the permeation surface area, δ is the permeation width, P_{atm} is the atmospheric pressure and $P(t)$ is the pressure with time. Assuming ideal gas behavior inside the VIP, Eq.(1) is modified by Kwon et al. [4] as follows,

$$\frac{dP}{dt} = K \cdot \frac{A_s}{\delta} \cdot \frac{RT}{V} \cdot (P_{atm} - P(t)), \quad (2)$$

where dP/dt is the pressure increase rate, R is the universal gas constant, V is the inner volume and T is the absolute temperature. The pressure increase with time t can be expressed by solving Eq.(2),

$$\frac{P(t) - P_{atm}}{P(0) - P_{atm}} = e^{-K \cdot \frac{A_s}{\delta} \cdot \frac{RT}{V} \cdot t} \quad (3)$$

Using this equation, service lifetime of VIPs can be estimated. For instance, if the allowable pressure is P_{crit} , critical service lifetime t_{crit} is,

$$t_{crit} = \frac{\delta}{KA_s} \cdot \frac{V}{RT} \cdot \ln \frac{P_{atm} - P(0)}{P_{atm} - P_{crit}} \quad (4)$$

As known from above equations, the gas permeability K is the essential information to estimate the amount of permeation or service lifetime of the VIPs.

A measurement apparatus of the lateral direction K starts from a basic idea that if only the side of films is exposed to a specific external pressure, gas permeation in the lateral direction can be measured by monitoring the inner vacuum level change.

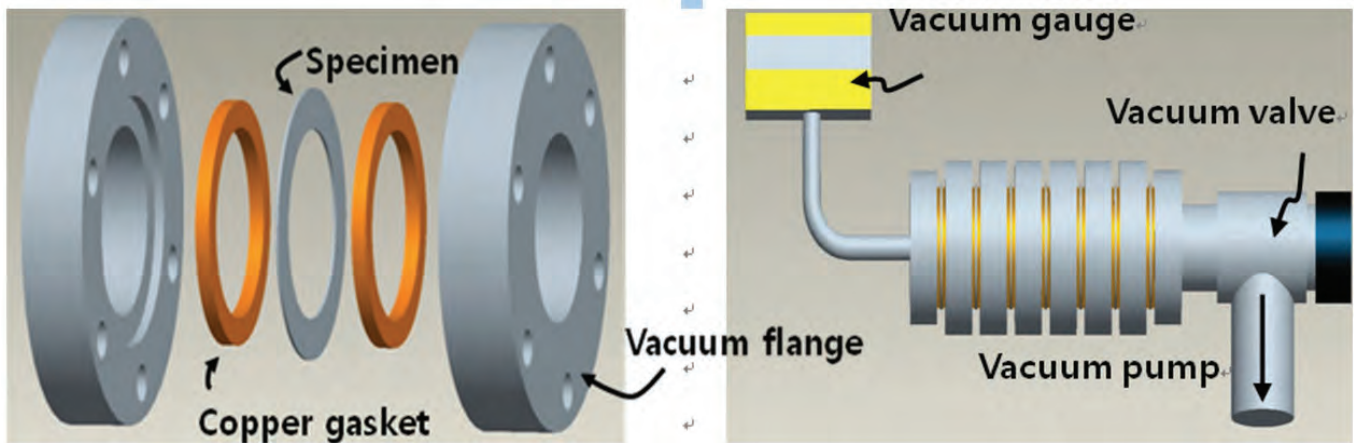


Fig.2: Schematic diagram of a gas permeation measurement apparatus

In the designed apparatus, sample films of torus shape such as a copper gasket are employed as shown in Fig.2. The films combined with two copper gaskets are inserted between the vacuum flanges and then seven such units are perfectly fastened in parallel with bolts. This apparatus is connected to a vacuum gauge on one side and a vacuum valve on the other as shown in Fig.2. It is totally enclosed by copper or stainless steel except the side of films so that gas permeation exists only through the side of films in the lateral direction. Inner volume of this apparatus is evacuated initially. When it is placed in a large chamber filled with high pressure gas as shown in Fig.3, the inner pressure increases due to the lateral permeation generated by the pressure difference. The pressure increase rate, dP/dt , is measured with a data acquisition system. Since the other variables are given as the experimental conditions, the gas permeability K is easily obtained.

2.2 Validation

The measurement apparatus is validated, when possible, experimentally by comparing the obtained permeability with available reference data. The relation of pressure increase rate and permeability from Eq.(2) is modified to express K as follows,

$$K = \frac{dP}{dt} \cdot \frac{\ln(a/b)}{2\pi L} \cdot \frac{V}{RT} \cdot \frac{1}{\Delta P} \quad (5)$$

where a and b are outside and inside radius of the torus films and L is the total thickness of the torus films.

In these experiments, raw LLDPE films of $100\mu\text{m}$ thickness are used as specimens. Outside and inside radii of the specimen are 24.5mm and 18mm , respectively, and the inner volume of the apparatus is 117.7cc . Experiments for O_2 , CO_2 and N_2 are conducted under pressure difference of 80 kPa at 296K . Since experiments in the lateral direction are performed by a direct method for the first time, there are no matching reference data. Thus, experimental results are compared using available data in normal direction. Inner pressure increase with time for O_2 , CO_2 and N_2 is shown in Fig.4. Gas permeabilities obtained by Eq.(5) in a steady state for O_2 , CO_2 and N_2 are 1.58×10^{-13} , 4.19×10^{-13} and $0.42 \times 10^{-13} \text{ cm}^3 \cdot \text{cm} / \text{cm}^2 \cdot \text{s} \cdot \text{Pa}$, respectively. The results are summarized in Table 1. It is shown that experimental values lie within reference values or are similar to those as expected. The measurement apparatus is considered to be successfully validated although the permeation directions are different.

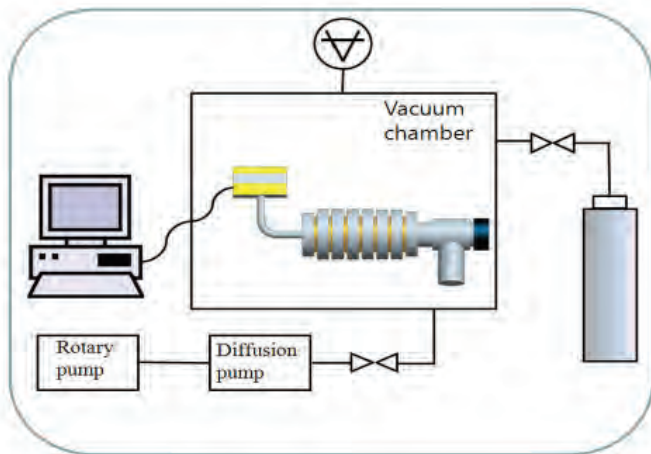


Fig.3: Schematic diagram of the measurement system

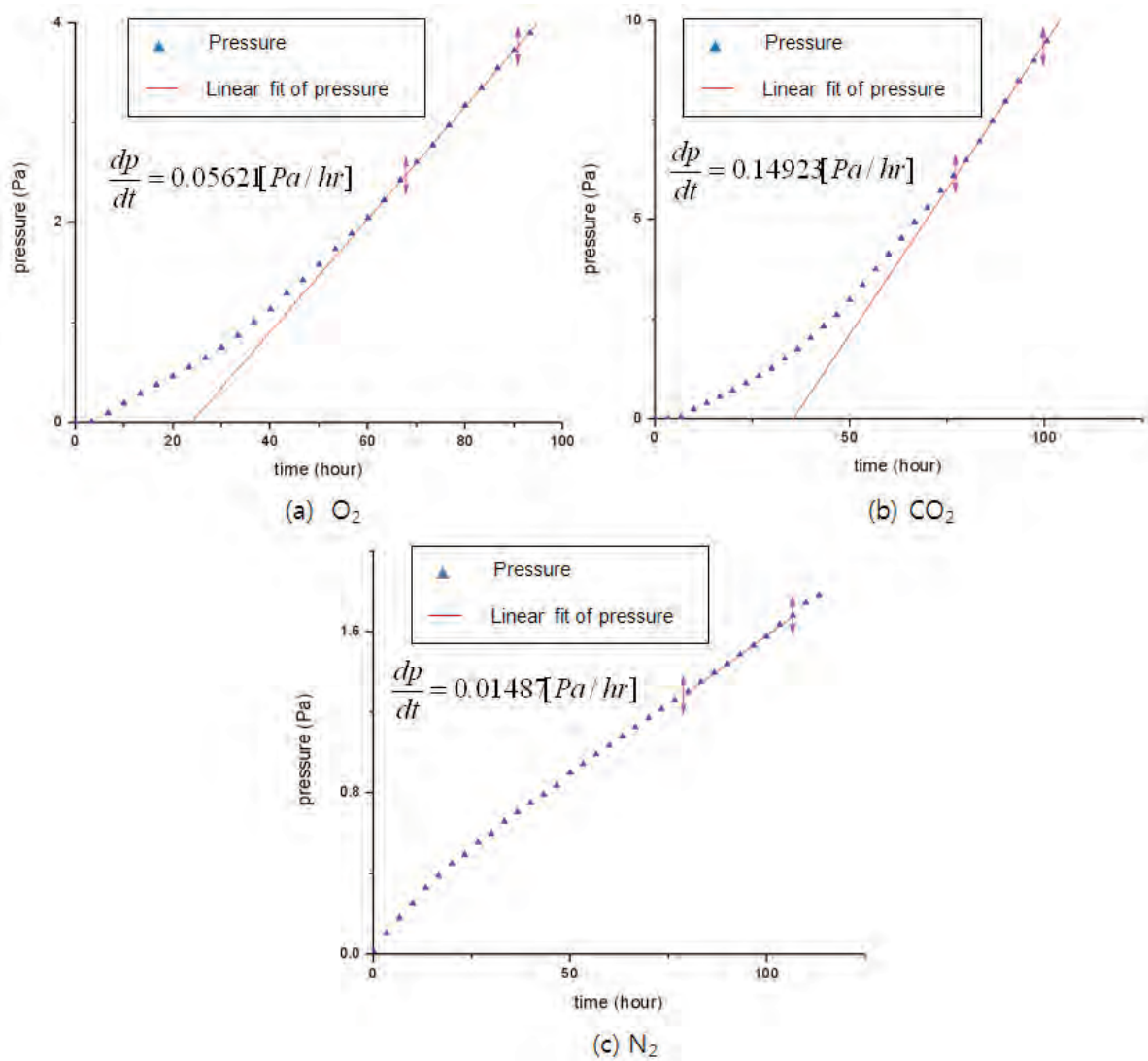


Fig. 4: Permeation rate of the LLDPE films for O_2 , CO_2 and N_2

Table 1 Lateral direction gas permeability through raw LLDPE films for O_2 , CO_2 and N_2 (296 K, $P_{inside} = 0$ kPa, $P_{outside} = 80$ kPa)

	dp/dt [Pa/hr]	Permeability $\times 10^{13}$ [cm ³ cm/cm ² ·s·Pa]	
		Experiment (Lateral direction)	Reference [5-6] (Normal direction)
O_2	0.05621	1.58	0.98-2.17
CO_2	0.14923	4.19	3.38-9.6
N_2	0.01487	0.42	0.73

2.3 Results for heat-sealed flanges

Inner pressure increase by gas permeation through heat-sealed LDPE or LLDPE films is measured again using the aforementioned measurement apparatus. The gas permeability K 's for O_2 , CO_2 , and N_2 are obtained from Eq.(5). The experiments are conducted under the same conditions as before. The reason that LDPE and LLDPE are investigated here is because the envelope films are usually multi-layered as shown Fig.5. While the aluminum foils suppress gas permeation very effectively, both laterally and normally, the LDPE and LLDPE composite layer in between provides a good lateral permeation passage. The two layers are investigated individually. For the LDPE, an LDPE film of thickness 100 μm is preheated and employed as the torus specimen of Fig.2. For the LLDPE, three LLDPE layers of total

of 300 μm thickness are heat-sealed together as a torus specimen. Note that LDPE alone is not heat-sealed.

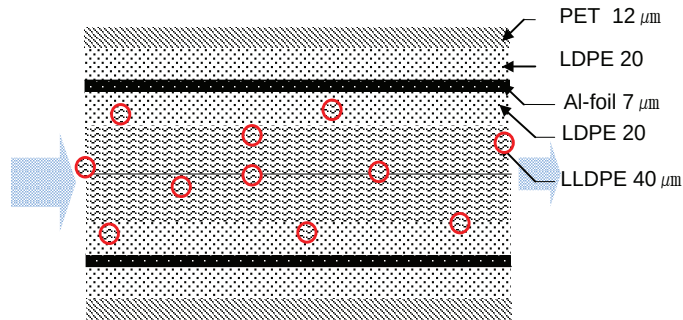


Fig.5: Schematic diagram of the heat-sealed envelope layers

For specimens of the heat-sealed LLDPE films, gas permeability K for O_2 , CO_2 and N_2 is obtained as 1.50×10^{-13} , 4.02×10^{-13} and $0.41 \times 10^{-13} \text{ cm}^3 \cdot \text{cm} / \text{cm}^2 \cdot \text{s} \cdot \text{Pa}$ respectively as shown in Table 2. The permeability of the gases increases in the following order; $\text{CO}_2 > \text{O}_2 > \text{N}_2$.

Gas permeability is defined as the product of diffusion coefficient and solubility [6]. Diffusion coefficient for CO_2 is smaller than that of O_2 [7]. Nevertheless, gas permeability of CO_2 is larger because solubility for CO_2 is much larger than that for O_2 . These permeabilities are compared with non-heat-sealed LLDPE films. As the result, heat-seal effects are found to be negligible since the difference is less than 5% as indicated in Table 3. Furthermore, the gas permeability through the LDPE film is calculated from Eq.(5) as represented in Table 4. Gas permeability through the LLDPE film is found to similar to that of LDPE film.

Table 2: lateral direction gas permeability through heat-sealed LLDPE films for O_2 , CO_2 and N_2 (296 K, $P_{\text{inside}} = 0 \text{ kPa}$, $P_{\text{outside}} = 80 \text{ kPa}$)

	O_2	CO_2	N_2
dp/dt [Pa/hr]	0.12645	0.41351	0.04304
Permeability $\times 10^{13}$ [$\text{cm}^3 \text{cm} / \text{cm}^2 \cdot \text{s} \cdot \text{Pa}$]	1.50	4.02	0.41

Table 3 Comparison of permeability through heat-sealed and non-heat-sealed LLDPE films for O_2 , CO_2 and N_2 (296 K, $P_{\text{inside}} = 0$, $P_{\text{outside}} = 80 \text{ kPa}$)

		O_2	CO_2	N_2
Permeability $\times 10^{13}$ [$\text{cm}^3 \text{cm} / \text{cm}^2 \cdot \text{s} \cdot \text{Pa}$]	Heat-sealed films	1.50	4.02	0.41
	Non-heat-sealed films	1.58	4.19	0.42
Difference (%)		5.0	4.0	2.3

Table 4: Gas permeability through the heated LDPE films for O_2 , CO_2 and N_2 (296 K, $P_{\text{inside}} = 0 \text{ kPa}$, $P_{\text{outside}} = 80 \text{ kPa}$)

	O_2	CO_2	N_2
dp/dt [Pa/hr]	0.06072	0.20184	0.01885
Permeability $\times 10^{13}$ [$\text{cm}^3 \text{cm} / \text{cm}^2 \cdot \text{s} \cdot \text{Pa}$]	1.54	4.98	0.48

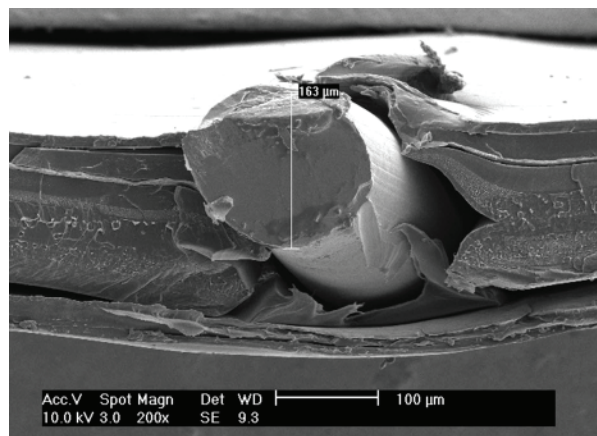
3. Methods to Reduce Gas Permeation Through Heat-Sealed Flanges

3.1 Metal wire sealing method

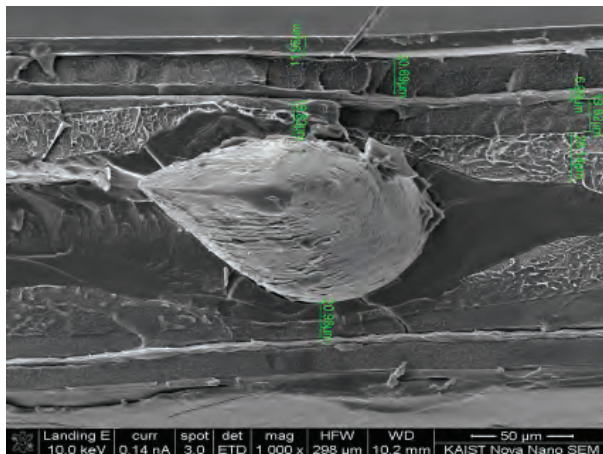
From Eq.(2), pressure increase rate is proportional to the surface area, which is the product of sealed perimeter and polymer layer thickness, and inversely proportional to the sealed width. The amount of gas permeation is reduced by minimizing sealed perimeter and thickness of the polymer layers or increasing the width of the sealed edge. A method to insert metal wire between heat-sealed layers in the heat-sealing process is proposed so that it minimizes thickness of the heat-sealed polymer layers. Practically, this significantly reduces the polymer thickness above and below the wire by viscous thinning of the polymer during the heat-sealing process. Because metal wire blocks a passage where gas travels very effectively, resistance of the gas permeation becomes large. As the result, it makes gas permeation reduced as far as the metal wire perfectly adheres to the polymer layers. If not adhered well, by providing the vacant passage between the wire and the polymer, permeation speed is rather accelerated. A pretreatment is thus needed, since otherwise the wire may not completely adhere to LLDPE layers as shown in Fig.6. One of the solutions is to coat the wire with LDPE. It is known that LDPE

sticks to metal better than LLDPE and LDPE is easily sealed later with LLDPE by heating. To coat the wire with polymer, the wire must be heated and a high temperature is maintained for a certain time in LDPE powder bath. Then the powder is adhered onto the surface of the heated wire.

Fig.6 shows the result. It shows that the wire enclosed with LDPE is perfectly adhered to polymer layers. The polymer layers thickness between Al-foil layers is decreased by the metal wire. This is expected to slow down inner pressure increase in VIP significantly. Further research is under way for the sealing improvement.



(a) raw metal wire



(b) metal wire coated with LDPE

Fig.6 SEM images of metal wire in the heat sealed flange

4. Conclusion

A measurement apparatus to measure the gas permeation through heat sealed flanges is designed and reliability of the apparatus is successfully verified.

Using this permeation apparatus, permeabilities in the lateral direction of heat-sealed and non-heat-sealed LLDPE films are obtained. From the two results, the effect by heat seal is found to be negligible. Also, permeability of LDPE films is measured. The permeability of the gas increases in the following order $\text{CO}_2 > \text{O}_2 > \text{N}_2$. Also, a method to decrease gas permeation is suggested in this study. Inserting the metal wire between heat-sealed flanges is proposed. Adherence between metal wire and polymer layer is achieved by coating the wire with LDPE powder.

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An Investigation on Long-Term Thermal Performance of Vacuum Insulation Panels (VIPs)

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Abstract

Use of Vacuum Insulation Panels or VIPs, as thermal insulation, in building envelope construction offers many advantages such as increased energy efficiency of exterior building envelopes, thinner wall thicknesses, optimum space use, reduced material consumption, etc. Nevertheless applications of VIP in building envelope constructions are few and far between. There are a number of unresolved questions that are keeping VIPs away from successful adaptation in the construction industry, and undoubtedly long-term thermal performance is one of those questions.

Building envelopes in North America have a service life of 50 years or more. Hence, long-term performance is indeed a very important parameter to be considered for selection and design of VIPs as the insulation materials for exterior building envelopes. At present VIPs are available from different Asian, European and North American manufacturing sources and come with wide ranges of choices in terms of R-value/in, size (length $\times$ width $\times$ thickness) and shape. However, there exists very little credible information about the long-term thermal performance of these available VIPs.

This paper presents (1) thermal measurement data of VIPs aged primarily in controlled laboratory environment for about seven years, (2) observations from field performance of VIP, and (3) observations from accelerated aging tests carried out in the laboratory on a number of commercially available VIPs.

1. Introduction

Buildings are undoubtedly one of the most primary, valuable and durable parts of our societal infrastructure and also consume up to 40% of our total national energy requirement [1, 2]. Thermal insulation is a key component that determines the energy efficiency of the built environment. In Canada and elsewhere in the world, energy efficiency improvement through insulation upgrade of buildings is considered as the key parameter to check continuous growth of global energy consumption [3-5]. Hence, durable and high performance vacuum insulation panels or

VIPs (up to 10 times more thermally efficient than conventional thermal insulation materials) are being considered as the next generation thermal insulation for new building envelope construction and energy upgrade/rehabilitation of existing building envelopes. However, there exist a number of challenges [6] and aging of VIPs with time and resulting deterioration of thermal performance is one of them. Researchers across the world have been trying to address this issue through laboratory investigation, numerical modeling and field investigation [7 – 17]. It is hoped that eventually a standard test method will be developed to predict the long-term thermal performance of VIP.

2. Aging of VIP – What Do We Know?

The primary mechanism for aging of VIP is due to loss of vacuum (i.e. increase of pressure). The loss of vacuum is caused by gas or vapour permeation through barrier or sealed barrier joints, and offgassing of core materials. It is expected that getter/desiccant inside the VIP core will adsorb gas/vapour molecules and maintain vacuum or low pressure. However, getter/desiccant has a saturation limit and eventually with time gas pressure inside the VIP will increase slowly and thermal insulating capacity of VIP will reduce gradually. The rate of reduction of thermal insulating capacity or aging of VIP with time depends on a number of factors such as (i) air and vapour permeability of barrier materials; (ii) air and vapour permeability of barrier seam/joint; (iii) change of core material thermal conductivity with the change of gas and vapor pressure etc. It is well known that if the core material is the only variable component, aging of VIPs constructed with nano-porous core materials is much slower than VIPs made with micro-porous core materials [18, 19].

A number of researchers have theoretically explained this aging phenomenon and numerically derived the aging relationships as a function of material properties and time [13, 20] to predict the long-term thermal performance of VIPs. However, these aging theories and numerical models have very limited practical applications due to the lack of reliable and consistent input parameters (i.e. permeation properties of barriers and seams, characterization of core materials etc.). In addition, absence of

standard material specifications, test methods and quality control for VIPs also complicate any attempt to develop a practical method for the prediction of long-term thermal resistance of VIPs.

Attempts have been also made to characterize the long-term thermal performance of VIP through accelerated aging of VIPs [7-9]. As always, the relationship between accelerated aging test results and real life performance of VIPs remains the missing link.

A number of field applications/investigations have also been reported in the literatures [15], specifically from Europe, but co-ordinated effort to monitor and document the long-term thermal performance of VIPs in various types of constructions at various geographic locations remains a necessary task yet to be realised.

This paper presents selected preliminary results from laboratory and field studies, being conducted at the National Research Council Canada - Institute for Research for Construction (NRC-IRC), with the aim to identify issues related to the long-term thermal performance of VIPs. It is hoped that observations presented in this paper will eventually aid development of a practical test method for the prediction of long-term performance and quality control of VIPs.

3. Experimental Program

Three different aging experiments conducted in this study are: (i) Laboratory aging for nearly 7 years; (2) Field aging for nearly 1.5 years; and (3) Accelerated aging over a period of 8 months. Following sections outline the details concerning these three aging investigations.

3.1 Laboratory Aging

In 2003, NRC-IRC procured 20 VIP specimens (300mm × 300mm × 19mm) and initial thermal resistance of these specimens, as measured in the laboratory, varied between RSI 4.29 and RSI 4.85. At the very beginning, four of these VIP specimens were exposed to ambient laboratory condition (50±10% RH and 22±2°C temperature) and another four were exposed to elevated room temperature (32°C) and relative humidity (90%) conditions for sixty days. However, these exposures had no measureable influence on the thermal performance of the vacuum insulation panels [17]. Thereafter, these panels had been stored in controlled laboratory ambient condition and thermal performance of each VIP was measured at regular intervals to assess the long-term stability of thermal properties [6].

3.2 Field Aging

Three 1150mm × 750mm × 12mm VIP specimens were installed in a test hut located at the NRC-IRC campus in Ottawa (see Fig. 1). The VIPs were installed in an existing test hut wall and sandwiched between two layers of expanded polystyrene (XPS) as shown in Fig. 2. Appropriate thermocouples (TC) and heat flux transducers (HFT) were installed (Fig. 2) to monitor temperature gradient and heat flux across the wall cross-section. The thermal resistance of VIP specimens used for the wall construction varied between RSI 3.67 and RSI 3.99 when tested in the laboratory prior to installation.

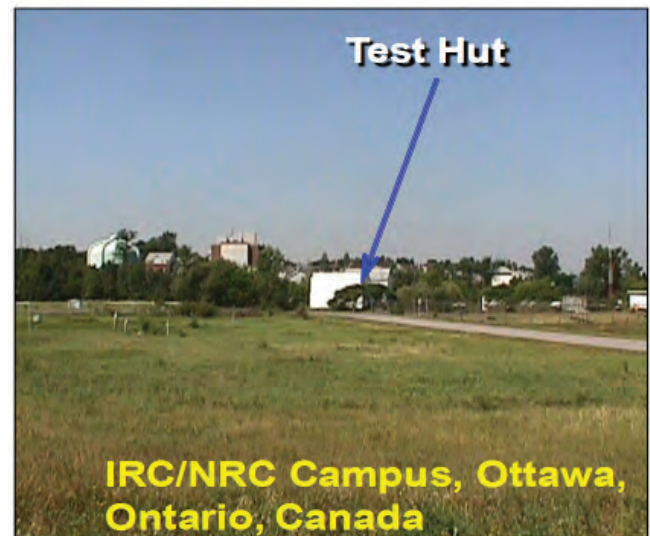


Figure 1 – Test hut at NRC-IRC Ottawa, Canada

3.3 Accelerated Aging

In this study five different VIP products were subjected to alternated extreme temperature (70°C in an oven with very low humidity that is used to dry materials) and relative humidity (95% at 23°C) conditions for accelerated aging for a week each and continued over a period of about 8 months. The temperature and relative humidity conditions chosen here represent the extreme possibilities in Canadian building envelope applications where VIPs would not be exposed to direct solar radiation and used in association with other traditional insulations.

The five VIP products came from different manufacturers and made with different core and barrier materials. Each VIP product consisted of three specimens (A, B, C). The nominal dimensions of each VIP product are shown in Table 1. The VIPs were received at various dates before the extreme temperature and humidity exposure began and one product was the same that had been already aged in the laboratory for the past seven years (see the section titled ‘Laboratory Aging’).

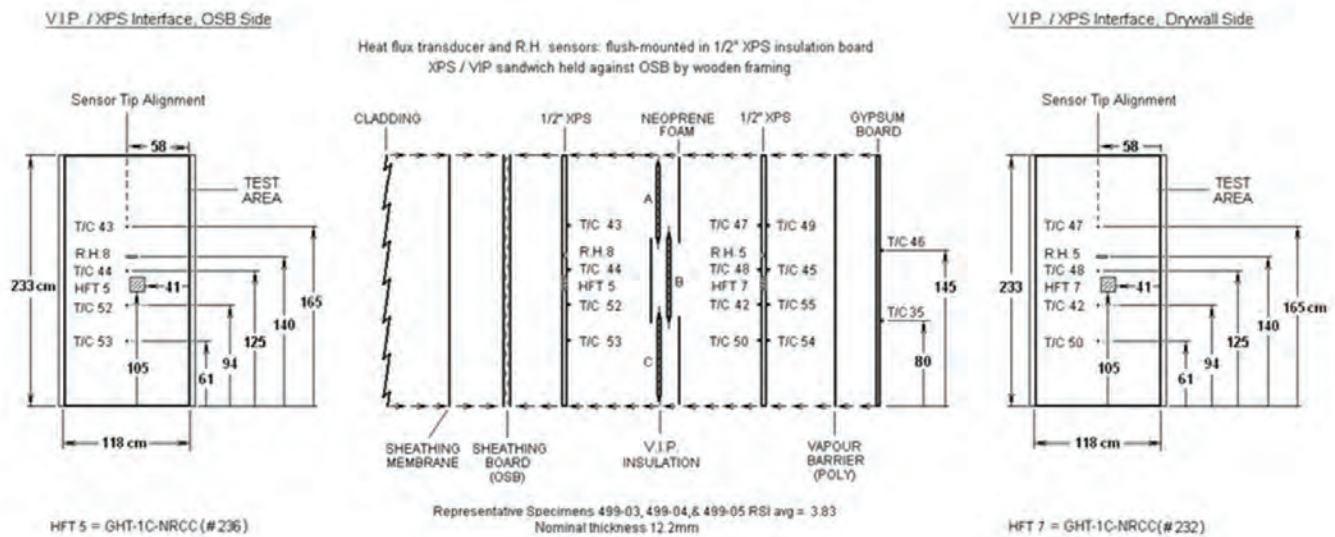


Figure 2 – Construction details of test-hut wall insulated with VIPs

Table 1 –Nominal Dimensions of VIPs

VIP Product ID	Nominal Dimensions (mm)		
	Length	Width	Thickness
482-171	300	300	20
487-61	300	300	20
487-88	300	300	25
487-115	300	300	25
499-106	560	460	12

Table 2 - Initial Aging of Vacuum Panels

VIP Product ID	Date of as Received Test	Date of Initial Test	Time Period [days]	Aging Rate [%/year]
482-171	2003.09.22	2010.11.02	2598	1.74%
487-61	2009.11.07	2010.10.30	358	7.11%
482-88	2010.01.28	2010.10.27	272	6.26%
487-115	2010.03.16	2010.10.28	227	4.22%
499-106	–	2010.10.29	–	–

Before the aging tests started, from laboratory measurements, the initial aging rates were assessed. Table 2 shows the initial aging rates of the panels (average of three specimens) as they were measured at the time of receiving and at the beginning of accelerated aging tests. For confidentiality reasons and avoid comparison between various commercial products, the actual thermal resistance values of the specimens are not published in Table 2. It should be noted that the VIPs indicated by the product 499-106 were received at the beginning of accelerated aging tests. The precise manufacturing dates of VIPs investigated in this study are unknown. This could be the primary reason for the difference in initial aging rates between various VIP products. The VIPs indicated by product 482-171 were received in 2003 and had lower aging rate because of its 7 years exposure time (i.e. aging rate of VIPs slow down with time).

4. Results & Discussion

4.1 Laboratory Aged VIPs

Thermal characteristics of VIPs, aged for about 7 years, are shown in Fig. 3 [6]. The reduction of thermal insulating capacity of VIPs with time is very evident in these observations. The maximum recorded reduction in 7 years is about 19% and the minimum is about 10% and the average stands around 13%. These reductions are certainly significant and the aging trend is definite.

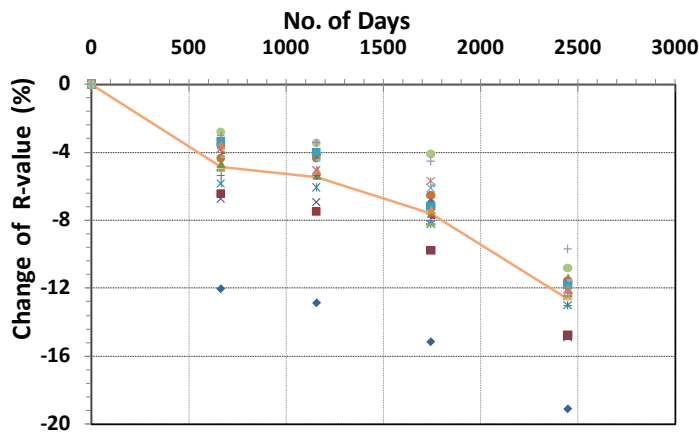


Figure 3 – Aging (7 years) of VIPs in NRC-IRC laboratory

4.2 Field Aging

The performance of VIPs installed in the NRC-IRC test hut wall is being monitored since 2009-2010 winter. The recorded thermal performance of VIP under dynamic temperature conditions is shown as a function of time in Fig. 4. In general, there appears to be no evident thermal performance degradation of VIP during 18 months of field exposure. However, as would be expected, due to lower mean temperature the thermal resistance of VIP seems to be marginally higher during the winter months. The monitoring of thermal performance of VIPs installed in the test hut will continue and further observations will be reported in due course.

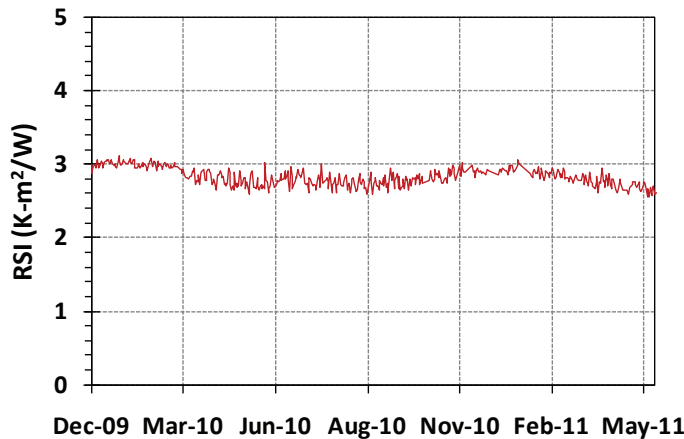


Figure 4 – Field aging (1.5 years) of VIP in Ottawa, Canada test hut

4.3 Accelerated Aging

The relative changes in thermal performance of all VIPs, where the initial thermal resistance is set to 100, are shown as a function of each cycle in Fig. 5. It is very clear from this plot that some VIPs age faster than others. It is interesting to note that two of the specimens, 487-115-A and 499-106-B failed. Physical and visual examination of respective specimens confirmed loss of vacuum in failed VIPs. Interestingly enough, the specimens 487-88 A, 487-88 B, and 487-88 C demonstrated 10 percent increase in thermal resistance after the first temperature cycle at 70°C. The exact cause of this increase is not known. However, following the increase, the aging of the specimen demonstrates a similar pattern to the other VIP products.

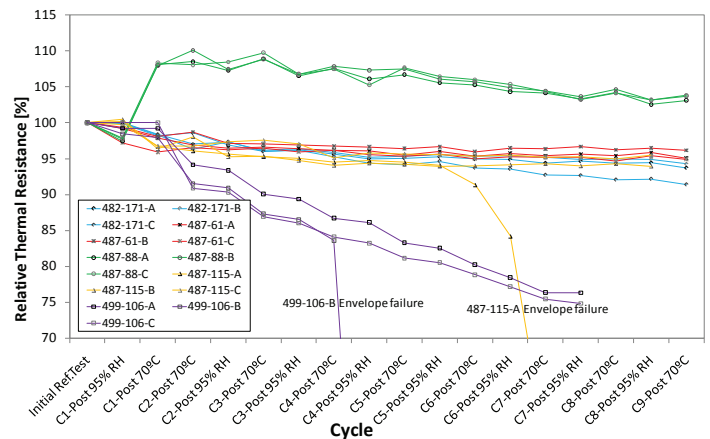


Figure 5 – Accelerated aging effects on 15 VIP specimens (5 products)

It is also apparent that the aging rates of 3 specimens for each VIP product were very similar. The average relative aging characteristics of five VIP products are shown in Fig. 6. In the two cases where one of the specimens had an envelope failure, these specimens were removed from the average calculations after the failure.

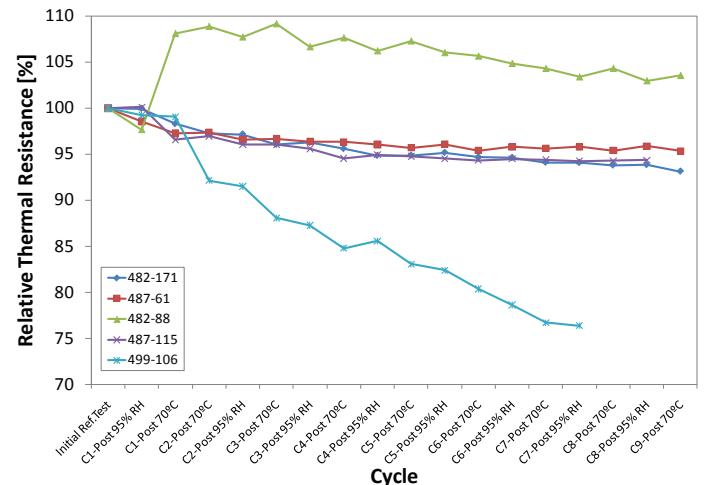


Figure 6 – Accelerated aging effects on 5 VIP products

In general, it is to be noted that thermal resistance for several of the VIPs is higher after the 70°C and lower after the 95% humidity exposure. This trend is most obvious in 487-88.

The average aging rates of each of the VIPs during the temperature and humidity cycling was determined by conducting a linear regression of the resistance measurements after and including the initial reference test measurement. In the case of 487-88, the calculation was based on the aging after the first cycle. The results are shown in Table 3. The overall aging of the VIPs resulted in a decrease in thermal resistance ranging from 0.37% to 3.51% per complete temperature and relative humidity cycle. The VIP product 499-106 had the highest aging rate in response to the cycling. Its aging rate was more than 6 times greater than that of VIP product 487- 61. Incidentally, VIP product 499-106 had the highest thermal resistance per unit thickness compared to other VIP products.

Table 3 - Aging rate of VIPs

VIP Product ID	Aging Rate During Cycling	
	%/cycle	r ²
482-171	0.72%	0.88
487-61	0.37%	0.69
487-88	0.84%	0.89
487-115	0.62%	0.70
499-106	3.51%	0.96

5. Conclusions

The experimental observations and discussion presented in this paper lead to following conclusions:

1. Majority (13 out of 15) of VIPs investigated in this study keep their physical stability intact while subjected to extreme temperature and humidity conditions.
2. Some VIPs (2 out of 15) physically failed to withstand repeated extreme temperature and humidity conditions.
3. Apart from one exception, all VIP products investigated in this study showed reasonable thermal stability while exposed to extreme temperature and humidity conditions.
4. Rate of thermal degradation of VIPs is as important as the initial thermal resistance of VIPs for its application in the construction industry.
5. Most of the VIPs are thermally and physically stable but some of them (minority) are not. However, there exist no methods or mechanisms to identify good or bad VIP products or specimens.

6. Relationship between field and laboratory aging of VIPs is the biggest challenge to predict the service life and design thermal resistance values of VIPs.

6. Acknowledgements

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Development of New Heat Sealing Technology “Wave Seal” for Long Term Performance of VIPs

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1. Introduction

Thermal conductivity of Vacuum Insulation Panels (VIPs) mainly depends on solid conductivity (λ_s) and gas conductivity (λ_g). Especially, since pore diameter of glass-fiber VIPs are longer than that of fumed-silica VIPs, thermal conductivity of glass-fiber VIPs largely depend on gas conductivity. Therefore, it is necessary to reduce gas permeation from laminated film when we use glass-fiber VIPs for housing.

The gas permeates inside of VIPs in two ways. One way is permeation from the surface of laminated film, and the other is from the edge of sealed area. The permeation from the surface is getting lower by improvement of coating technology. However, generally, for the edge of sealed area, the only improvement method is material change for sealant layer of laminated film.

The paper is described about the development of heat sealing technology for long term performance of VIPs.

2. Theory of Gas Permeation from the Edge of Sealed Area

2.1 Conductance of gas permeation

Gas permeation of films are defined by the Fick's first law. The amount (Q) and the conductance of gas permeation (C) are described as follows.

$$\Delta Q = C \cdot \Delta p \quad (1)$$

$$Q = P \cdot \frac{A}{L_w} \cdot \Delta p \cdot t \quad (2)$$

$$A = D \cdot L_{VIP} \quad (3)$$

$$C = P \cdot \frac{D \cdot L_{VIP}}{L_w} \quad (4)$$

Q: Amount of gas permeation [mol]

C: Conductance of gas permeation [mol/s/Pa]

Delta p: Differential pressure between atmosphere and inside of VIPs [Pa]

P: Gas permeation rate of sealant layer [mol*m/m²/s/Pa]

A: Cross-sectional area of the sealed area [m²]

L_w: Width of sealed area [m]

D: Thickness of sealant layer [m]

L_{VIP}: Length of sealed area [m]

2.2 Dependence of width and thickness on the conductance

As formula 4, the conductance of gas permeation is inversely proportional to the width of sealed area and is proportional to the thickness of sealant layer.

The dependence of width and thickness can be obtained from the experiment data on laminated film with aluminum foil (Figure 1 and Figure 2).

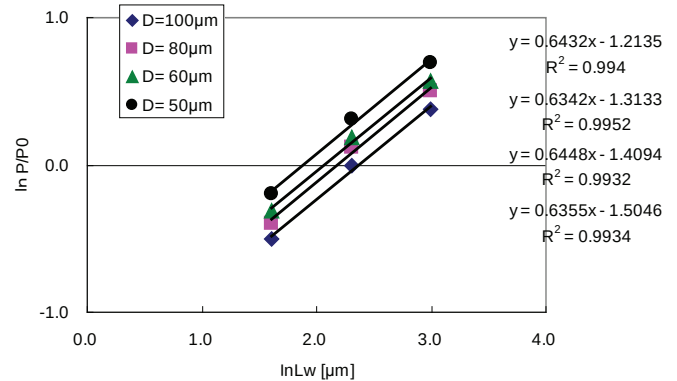


Figure 1: The dependence of the amount of gas permeation on width of sealed area (P_0 : gas permeation rate as $L_w=10\text{mm}$, $D=100\mu\text{m}$)

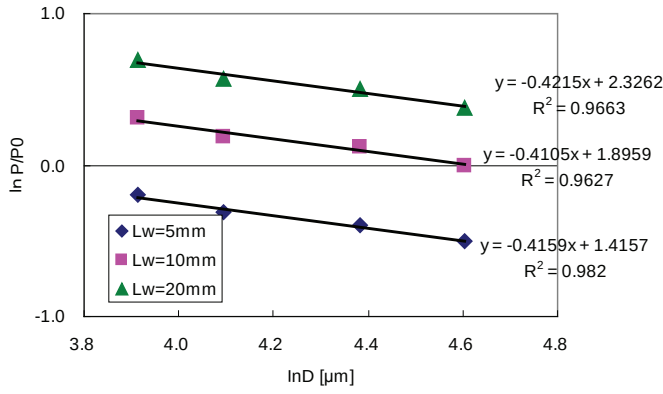


Figure 2: The dependence of the amount of gas permeation on thickness of sealant layer (P_0 : gas permeation rate as $L_w=10\text{mm}$, $D=100\mu\text{m}$)

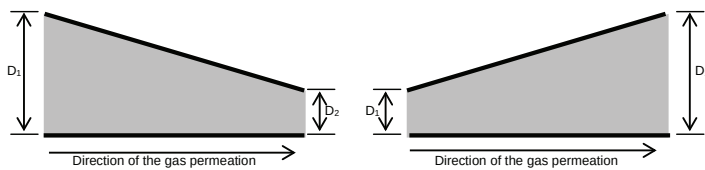
The gas permeation rate of sealant layer (P) and the conductance (C) are described by the following formula 4 by results of Figure 1 and Figure 2.

$$P = P_0 \cdot e^{0.46} \cdot D^{-0.42} \cdot L_w^{0.62} \quad (5)$$

$$C = P_0 \cdot e^{0.46} \cdot 10^{-3} \cdot D^{0.58} \cdot L_w^{-0.38} \cdot L_{VIP} \quad (6)$$

2.3 Correction factor of trumpet-model

Trumpet-model is well known for correction factor of the conductance, but it can't be applied to laminated films of VIPs. Gas diffusion coefficient is constant in sealant layer, so the gas concentration is not uniform. In Figure 3, the correction factor of the conductance (β) is assumed as below.



$$\beta = \frac{D_2}{D_1} \quad (D_1 > D_2) \quad \beta = \frac{D_1}{D_2} \quad (D_1 < D_2) \quad (7)$$

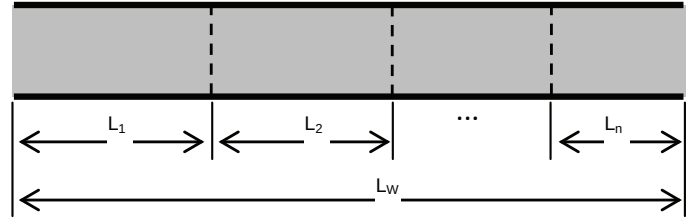
(a) The thickness of sealant layer is gradually decreasing.

(a) The thickness of sealant layer is gradually increasing.

Figure 3: Trumpet-model for correction factor of the conductance

2.4 Synthesis of the conductance

As shown in Formula 6, the conductance is inversely proportional to the 0.38 power of width of sealed area. Thus, in Figure 4, the synthesis of the conductance (C_{total}) and the correction factor of the conductance (β) are assumed as below.



$$\frac{1}{C_{total}} = \frac{1}{\beta_1 \cdot C_1} + \frac{1}{\beta_2 \cdot C_2} + \dots + \frac{1}{\beta_n \cdot C_n} \quad (8)$$

$$\beta_n = \left(\frac{L_w}{L_n} \right)^{0.8} \quad (9)$$

Figure 4: Calculation model for synthesis of the conductance

3. Development of New Heat Sealing Technology “Wave Seal”

3.1 Method

To reduce the amount of gas permeation from the edge of sealed area, it is important to reduce the thickness of sealant layer. But the thinner it is, the strength against puncture gets smaller. Therefore, we tried to make sealed area thin by using a heat sealing die (Figure 5). In Figure 6, sealant material flows to the surrounding by the projections of the die and sealant layer is formed like a “Wave”.

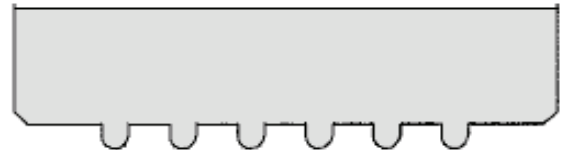


Figure 5: Cross-sectional view of a heat sealing die

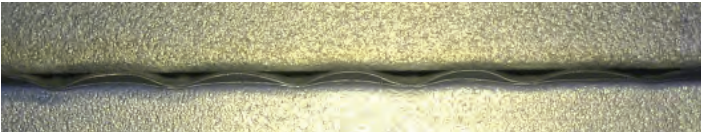


Figure 6: Cross-sectional view of sealed area

4. Conclusion

Gas permeation of VIPs made by new heat sealing technology “Wave Seal” become half compared with conventional models.

3.2 Verification

In Table 1, some VIPs are evaluated for the conductance and the characteristic of gas permeation. As a result of the verification, they are confirmed (Figure 7).

Table 1: list of evaluated samples

Types	L_w [m]	D [m]	Heat sealing die	Conductance [mol/s/Pa]
1*	0.010	0.0001	Flat	9.54E-03
2*	0.020	0.0001	Flat	4.77E-03
3	0.020	0.00005	Flat	3.19E-03
4	0.020	0.00002 ~0.0002	Figure 5	2.02E-03

Condition

VIP's size: 0.175 x 0.280 x 0.008 [m]

Laminated film: Aluminum foil (6 μ m) is laminated between outer Nylon layer (40 μ m) and inner PE sealant layer.

* conventional models

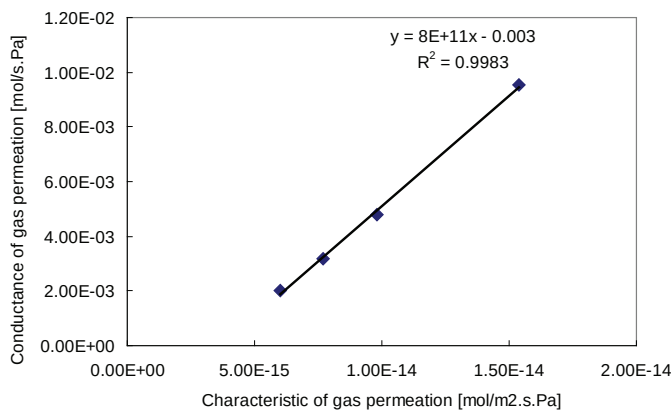


Figure 7: Results of the characteristic (experimental value) and the conductance of gas permeation (calculation value).

Technical Session 6
Advances, Challenges and
Opportunities – I

*(Session Chair – Dr. Wahid Maref,
NRC- IRC, Canada)*

Free-Form, High Energy Performance, Transparent Vacuum Envelope

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Keywords: monolithic silica gel insulation, aerogel, energy reduction, space saving, thermal insulation, transparent vacuum insulation panels, structural panel, lightweight envelope, free-form panels, transparent panels, high energy efficiency.

Abstract

This article examines a new lightweight, slim, high energy efficient, light-transmitting, self-supporting envelope system, providing for seamless, free-form designs for use in architectural projects. The system exploits vacuum insulation panel technology. The research was based on envelope components already existing on the market and patents and prototypes built by independent laboratories, especially components implemented with silica gel insulation, as this is the most effective transparent thermal insulation there is today. The tests run on these materials revealed that there is not one that has all the features required of the new envelope model, although some do have properties that could be exploited to generate this envelope, namely, the vacuum chamber of vacuum insulation panels, the use of monolithic aerogel as insulation in some prototypes, and reinforced polyester barriers. These three design components have been combined and tested to design a new, variable geometry, energy-saving envelope system that also solves many of the problems that other studies ascribe to the use of vacuum insulation panels.

1. Introduction

Energy efficiency is coming to the forefront in the architecture, as, apart from the significance of a reduced environmental impact and increased comfort for users, the current energy crisis and economic recession has bumped up the importance of the financial cost of energy.

Since the Kyoto Protocol was signed in 1997, governments all over the world have been trying to reduce part of the CO₂ emissions by tackling building “energy inefficiency”. In Europe

today, the tertiary and housing sectors account for 40.7% of the energy demand, and from 52 to 57% of this energy is spent on interior heating [1]. The new world energy regulations, set out at the European level by the Commission of the European Communities in the First Assessment of National Energy Efficiency Action Plans as required by Directive 2006/32/EC on Energy End-Use Efficiency and Energy Services, [2] indirectly promote an increase in the thickness of outer walls, which, for centuries, have been the only way of properly insulating a building.

The use of vacuum insulation panel (VIP) systems in building aims to minimize the thickness of the building's outer skin while optimizing energy performance. The three types of vacuum chamber insulation systems (VIS) most commonly used in the construction industry today –metallized polymer multilayer film (MLF) or aluminium laminated film, double glazing and stainless steel sheet or plate [3]–, have weaknesses, such as the fragility of the outside protective skin, condensation inside the chamber, thermal bridges at the panel joints, and high cost, all of which have a bearing on on-site construction [4].

Apart from overcoming these weaknesses and being a transparent system, the new F²TE³ (free-form, transparent, energy efficient envelope) system that we propose has two added values. The first is the possibility of generating a structural skin or self-supporting façade. The second is the possibility of designing free-form architectural skins. These are research lines that the Pritzker Architecture Prize winners Zaha Hadid, Frank Gehry, Rem Koolhaas, Herzog & de Meuron, among many other renowned architects, are now exploring and implementing.

To determine the feasibility of the new envelope system that we propose, we compiled, studied and ran laboratory tests on the materials and information provided by commercial brands. We compared this information to other independent research and scientific trials on VIPs, such as Annex39 [5], and on improved core materials, such as hybrid aerogels and organically modified silica aerogels [6], conducted by independent laboratories like Zae Bayern in Germany [7], the Lawrence Berkley Laboratory at the University of California [8] or the Technical University of Denmark [9].

After studying the results, we discovered valuable innovative ideas that we exploited to design the new high energy efficient envelope that should outperform the elements now on the market.

The remainder of the article is structured as follows. In Section 2 we explain the rationale of the epistemological study of the system, and how the experimental study combining computer simulations and empirical trials was run. In Section 3, we describe the design of the proposed envelope system (F²TE³), explaining the solutions adopted in this new system and the improvements on other existing systems. Section 4 analyses how the F²TE³ system overcomes the weaknesses detected in existing VIP systems. Finally, Section 5 discusses final conclusions.

2. Research

2.1 Epistemological study of the system

Today both vanguard architecture and the conventional building industry are demanding a constructive system such as is proposed in this research: a lightweight and slim, free-form and seamless, high energy performance system, which facilitates the passage of natural light and natural backlighting and can be used to design self-supporting structures.

After a comparative study of over 147 commercial products and industrial prototypes with each other and against data gathered from studies and independent laboratories, we determined that no system combining all these features exists as yet. Similar systems are not absolutely free form or translucent, are not seamless and/or have a very limited thermal response, among other weaknesses already listed above. The proposed system overcomes these flaws.

2.2 Experimental study

We compared the results of the epistemological study with the findings of empirical experiments and computer simulations run on commercial panels and prototypes to which we had access.

2.2.1 Computer simulation

Because of the shortage of information about aerogel and the impossibility of acquiring a sample, we used the DesignBuilder program to conduct a trial by computer simulation under the same environmental conditions as the empirical trials (see Figure 1).

Free-Form, High Energy Perform

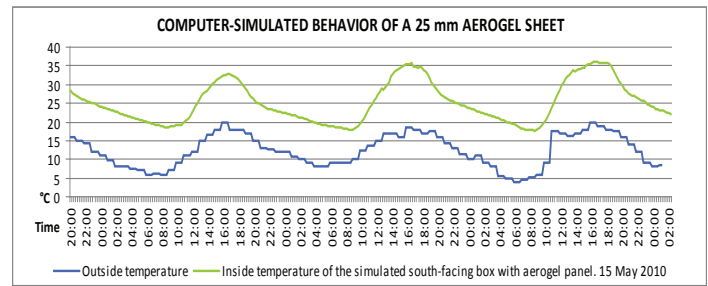


Figure 1: Computer simulation for a 25mm thick sheet of silica aerogel with density 50-150kg/m³ over 78 hours.

3.2.2 Empirical trials

We ran trials to measure the energy performance of the material. These trials were run at the UPM [1] School of Architecture's Department of Building and Architectural Technology using boxes with an inner volume of 60x60x60cm, insulated with 20cm of expanded polyurethane. One of the box faces was left open by way of a window. The study elements were placed in this opening using a specially insulated frame. The trial involved exposing two such boxes to a real outside environment to study their behaviour. The two boxes had two different windows: one was fitted with 6+8+6 double glazing with known properties as the reference element and the other was fitted with the panel that we intended to study. Data-loggers were placed inside each box for monitoring purposes. There was a thermal sensor on the outside to capture the temperature to which boxes were exposed. The boxes were set in a south-facing position as this is the sunniest exposure (Figure 2).

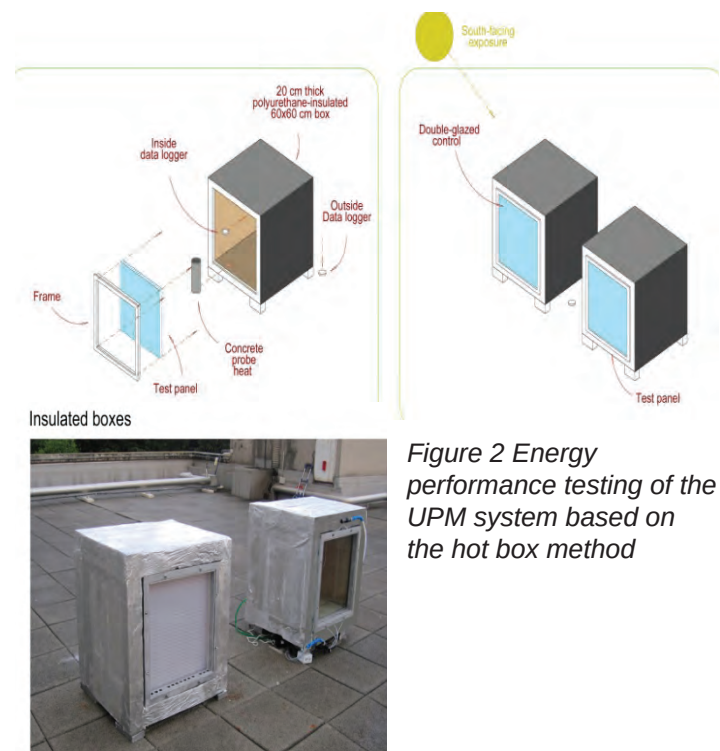


Figure 2 Energy performance testing of the UPM system based on the hot box method

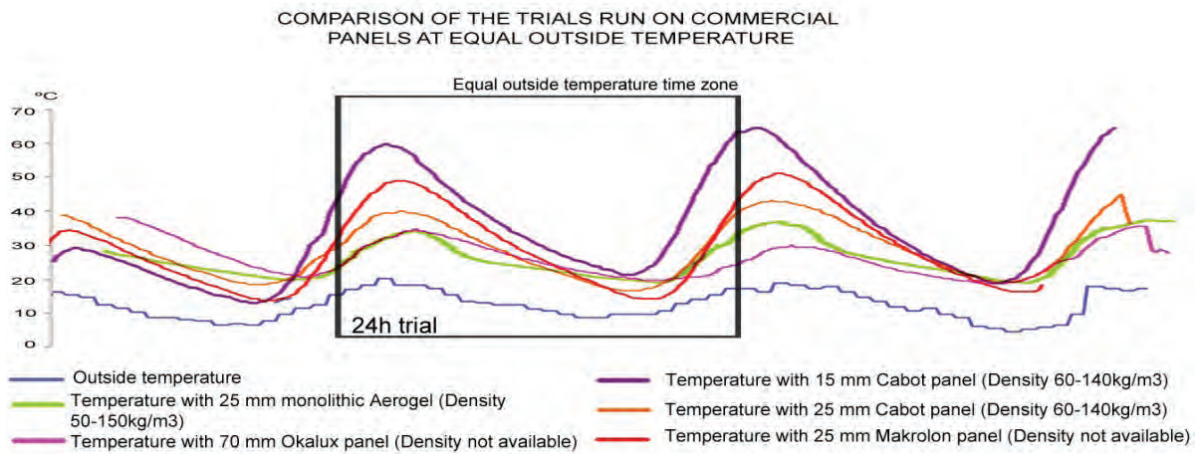


Figure 3: Comparison of empirical data of commercial systems with computer simulation of 25 mm thick sheet of silica aerogel with density 50-150kg/m³ over 78 hours (temperatures inside the test boxes)

We ran 28 temperature-measuring trials using this system, and compared the performance of different thicknesses of commercial panels with 6+8+6 double glazing. Of these trials, the four panels that best combined high light transmittance with a good energy efficiency level were evaluated against the data of the computer-simulated aerogel trial (see Figure 3).

This research confirms that VIP panels perform better than the other tested systems. It also reveals that, by combining some features of existing elements, such as the vacuum chamber, a core of monolithic aerogel, sandwiched between glass fibre barriers, an innovative system can be designed. This system offers a new free-form, seamless, self-supporting, slim, transparent, high energy efficient VIP envelope, thereby improving on, theoretically, the properties of many of the VIP panels now on the market.

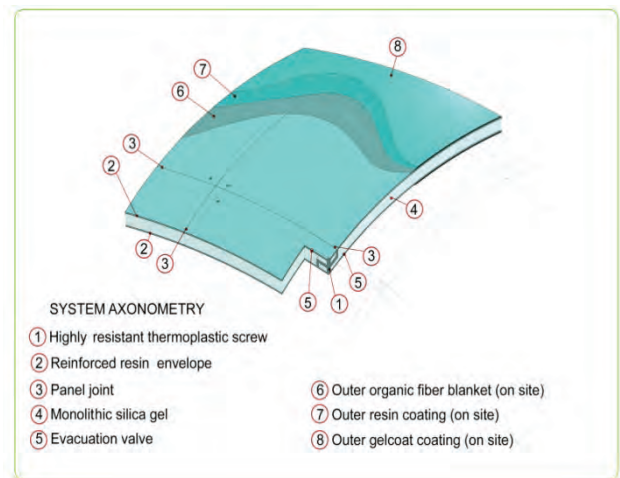


Figure 4: F²TE³ system axonometry

3. Proposal for a Free-Form Transparent Energy Efficient Envelope (F²TE³)

We propose a free-form design envelope system fabricated with cellulose fibres and polyester resin (or acrylic-based organic resin), and a vacuum core to insulate with monolithic aerogel at a pressure of 50-100hPa. Being a self-supporting component, the system can perform structural functions, and seams between panels are concealed by an outer coating applied in situ (Figure 4)

F²TE³ dimensions: The minimum thickness of the modelled system panels will be 25 mm, and the sheet width, although variable, will be at most 600x600 mm. The weight per unit area will range from 15 to 7 kg/m², and the minimum admissible flexion radius will be approximately 4000 mm. Other features are:

- Light transmittance, τ_{D65} : from 59% to 85% approx.
- UV absorption: approx. 20%
- Total energy: approx. 61%
- Horizontal and vertical U-value: 0.50 W/m² K
- Thermal conductivity coefficient: 0.01 W/m K, estimated
- Possible heat-and humidity-induced dilation: 3 mm/m approx.
- Operating temperature: -70 to +80 °C
- Weighted sound reduction value: estimated at 26-45 dB
- Impact resistance: should be within the EN 356-PSA limit
- Fire resistance: European (EN13501) resistance regulations compliant

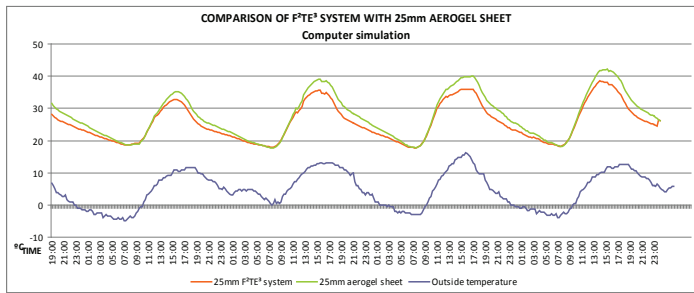


Figure 5: Comparison of a computer simulation of a 25mm thick sheet of silica aerogel with a density of 50-150 kg/m³ with the F²TE³ system over 96 hours.

System assembly: The F²TE³ system is composed of the dry-seal connection of male and female edged panels (two female sides and two male sides on each panel that fit together seamlessly) as previously designed by the draughtsperson. Once the construction is in place, it is given an outer coating of fibres and resins and finally a gelcoat coating to protect the assembly from external agents.

Testing: A 25 mm thick prototype F²TE³ system was computer simulated to examine its energy-saving behaviour compared with a computer-simulated aerogel envelope of the same thickness (Figure 5)

As shown in Figure 5, the F²TE³ returns a better result than what would be achieved with monolithic aerogel without a barrier envelope (not feasible due to aerogel hydroscopy). The flat heat loss curve indicates that the U-value is very small and eventually equals the values for aerogel, whereas F²TE³ has a 5°C edge over aerogel for capture.

4. F²TE³ Response to the Weaknesses of VIP Systems

Most studies conducted in the field of VIP elements (VIS) [1] determine that there are four key obstacles to the use of these systems in the building industry: a) fragility of the outer skin, b) thermal bridging at panel edges and joints, c) vacuum chamber moisture permeation, and d) price. On top of these weaknesses, there is the added obstacle of a single element having to provide both transparency and energy efficiency, plus a new demand from vanguard architecture for generating free forms by means of monocoque systems.

Theoretically, the new F²TE³ overcomes all the above objections raised against VIPs, offering the added values of transparency and free-form design:

a) Fragility of the outer skin: As the new system has to be a transparent and self-supporting structure, we have replaced the fragile outer barrier elements, such as a metallized polymer multilayer outer skin, double glazing and thin stainless steel sheets, with an element composed of highly resistant reinforced fibre resin.

b) Thermal bridge at panel edges and joints: Commercial panels are not designed to be assembled to form seamless elements. The new system that we propose is purposely designed to generate monocoque elements through a system of male and female panels. This system eliminates the thermal bridge between the panels (see Figure 6).

c) Moisture in the vacuum chamber: One of the key problems of VIP systems is condensation forming inside the chamber. Although some studies estimate that the hydroscopic silica smoke is capable of absorbing most of the minimal amount of condensation that forms without compromising its load-bearing or thermal capacities, the fact is that humidity inside the chamber ends up turning the monolithic aerogel opaque.

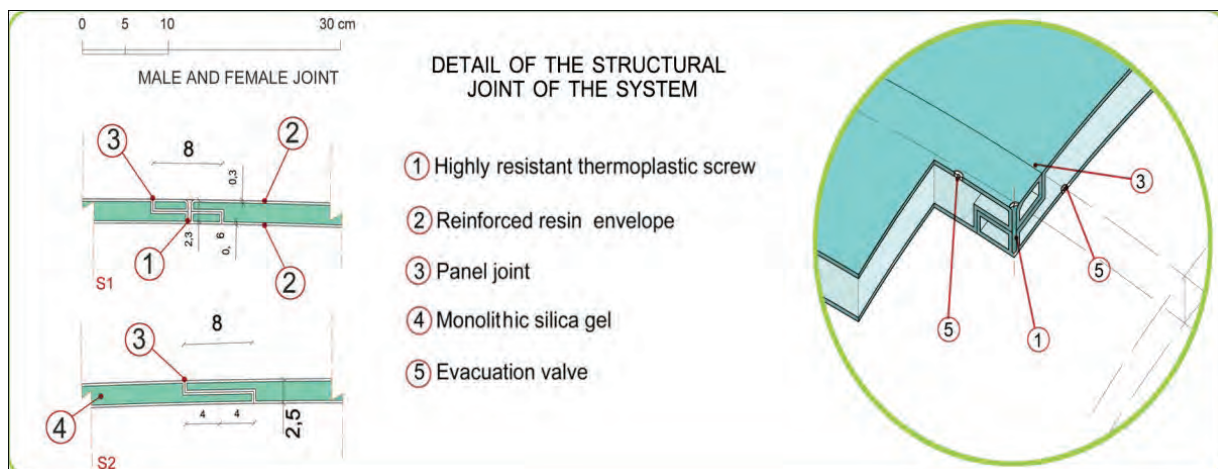


Figure 6: Detail of the male and female joint of the F²TE³ system.

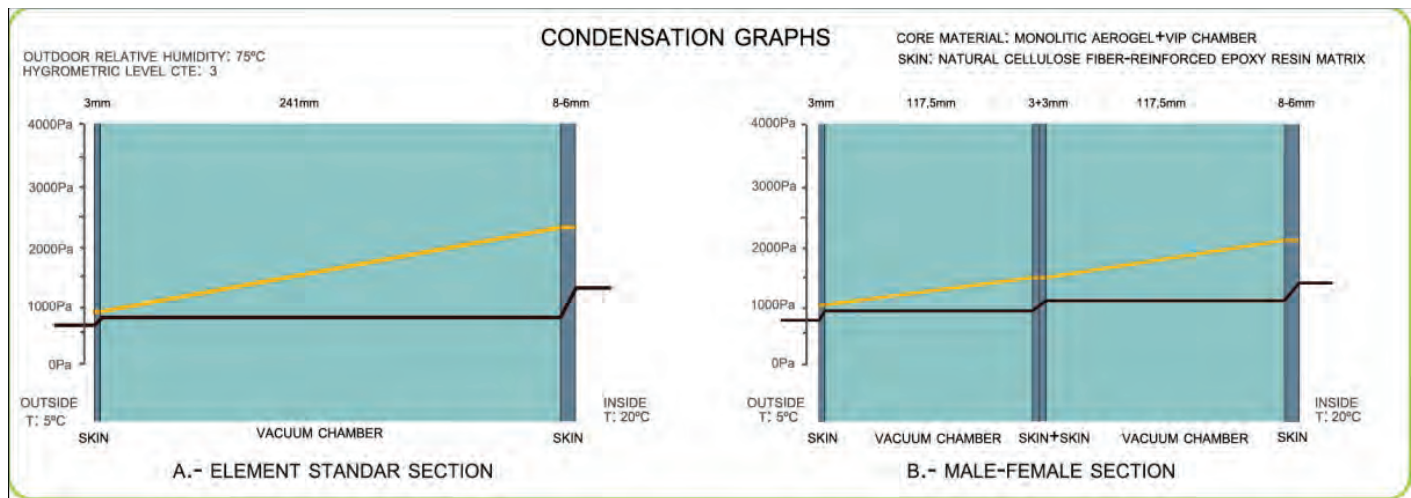


Figure 7: Condensation graphs for a standard section and a male female section of the new F²TE³ system.

F²TE³ solves this problem by modifying the barrier thickness. The outside face is 3 mm thick compared with the inside face that should have thicknesses ranging from at least 6 to 8 mm to prevent condensation forming inside the chamber. We used the COAG's memorias2 program to plot the condensation graph of the new envelope, and the resulting sections are shown in Figure 7.

F²TE³ has a water vapour permeability value of 0,3 g/m²d (for 3mm thickness) less than some commercial VIP panels (0,5 g/m²d).

d) Price: VIP systems are now much higher cost than traditional building systems (approximately 200 €/m²). However, Technical University of Denmark (DTU) studies [9] show that the mass produced product, using a fully automatic 10 m³ autoclave (as the sol-gel process is the most expensive part of the fabrication of this system), could be commercialized for less price.

For the purposes of our calculations, we will take a 150 m² detached dwelling and assume that the F²TE³ system costs 300 €/m² (If we use an conventional autoclave of 600 ml capacity (Parr Instrument Company, Moline, IL, USA) from the Air Glass Laboratory). On the other hand, the mean cost of a 6-12-6 double glazing aluminium window with a thermal break is 360 €/m², whereas a plastered, double hollow brick lined, 4 cm thermally insulated, 6 inch rough brick conventional wall with single-layer finish costs on average 85 €/m². Assuming that the mean percentage of glazing is 45%, the current cost of a conventional envelope including the façade glazing is 162 €/m².

The surface area of the envelope for a 150 m² dwelling is 375 m². The cost of building a conventional wall will be 60,750 €, whereas F²TE³ costs 112,500 €, meaning that F²TE³ costs just over double the traditional system at this stage.

Note, however, that the net internal area of the dwelling built using the F²TE³ system is 148 m² (at 2.5 cm thick the envelope only takes up 0.833% of the gross external area), compared with 135 m² for the traditional system (at 30cm thick it takes up 9.7% of the gross external area). Therefore, developers using the new F²TE³ system can commercialize an additional net internal area of 13 m². Assuming that the final sale price per square metre of net internal area is 4,000 €, there will an additional gain of 53,560 €. This, deducted from 51,750 €, which is the result of subtracting the price of the conventional building skin from the cost of the proposed envelope, results in a net profit of 1,810 € for developers using F²TE³.

Clearly, this calculation does not take into account either the potential saving thanks to the use of the new system as a structural element (which could amount to a 20% saving over the total cost of executing the building works) or the potential time and labour saving using this new building system compared with the traditional envelope.

According to DIN standard 4701, "there would be an annual saving of from 0.9-1.3 l of oil or 1.0-1.5 m³ of gas per m² of naturally lit surface area, leading to U-value reductions of 0.1 W/m²K". The F²TE³ surface area would be the sum of the walled areas (168 m²) and glazed areas (206 m²). Accordingly, with a U-value of 0.35 W/m²K, compared with 0.44 W/m²K for the conventional wall and 1.2 W/m²K for the glazing, the proposed system achieves a saving of 2083 l of oil (0.7€/l) and 2403m³ of gas (0,55€/ m³). This is equivalent to an annual saving of 1458€ in oil or 1322€ in gas for the consumer and a CO₂ reduction of approximately 4.9 kg per year.

Transparency, energy performance and variable geometry: Of the three types of translucent and transparent insulation now on the market (plastic fibres, gas and aerogel), we found that the best core material for the new F²TE³ system is aerogel, [2] [3] as it offers:

1. *Transparency*: aerogel compares with glass in transparency (87.6%)
2. *Insulation*: aerogel is an excellent insulator. According to published data, [4] the thermal performance of a 70 mm nanogel-filled VIP panel is better than a 270 mm cavity filled wall
3. *Core material*: thanks to its porosity and friction joint sealing, silica smoke is the material that many studies [4] recommend as VIP core material, provided that there is an outer protective skin. This also has a barrier function in order to maintain the vacuum of the panel
4. *Lightness*: aerogel is only three times heavier than air [5], and although the density of the aerogel that we use as insulation is higher (50-150kg/m³) remains very light.
5. *Versatility*: monolithic aerogel can be shaped as required [6].

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5. Conclusions

F²TE³ is a slim façade system that provides high energy efficiency. It has a seamless surface, providing for variable geometry and the option of building self-supporting structures into the same transparent system skin. The study conducted as part of this research has shown that the prototype F²TE³ system outperforms other systems existing on the market, offering added value in terms of structure, transparency and variable geometry, and overcoming the traditional weaknesses of VIPs.

6. References

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New Insulating Material from the Sunflower Stem Used as Alternative Core for Vacuum Insulation Panel

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Key words: Vacuum Insulation Panel (VIP), Core Material, Thermal conductivity, Thermal insulation, Thermal Properties.

Abstract: In this work, a new eco-friendly insulating material, using the sunflower stem has been implemented. Currently, this part of the plant is not commercially recoverable. This insulating material, as a plate, has the advantage of being very light ($d = 80\text{kg.m}^{-3}$) and having a thermal conductivity comparable to conventional insulating materials, around $42\text{mW.m}^{-1}\text{.K}^{-1}$. This material can be used as an alternative core material for vacuum insulation panels. The first trials under low vacuum of 2mbar have reduced the thermal conductivity by 50%. These results are encouraging and give hope to achieve conductivity values similar to those of conventional vacuum insulation with lower costs.

1. Introduction

The vacuum insulation panels (VIPs) have thermal insulating capacity about a factor of 10 higher than of polystyrene boards or polyurethane foams of equivalent thickness [1,2]. Their thermal conductivity can reach 4mW/mK at room temperature [1,3,4,5]. These panels are one important way to reduce space conditioning energy usage.

Vacuum insulation panels (VIP) consist of an open porous core material which has to withstand the external load caused by atmospheric pressure, as well as a sufficiently gas-tight envelope (multilayered shell) to maintain the required quality of the vacuum and prevent vapor from entering [6]. The VIP has various applications such as buildings, refrigerators and cryogenic devices [7]. Very often, bulk type materials in the form of powders, foams and fibers [1,2] or honeycomb [8] are used as the core material.

In the building sector, the PIV will significantly increase the energy efficiency [1,9,10,11]. The lifetime of VIP with getter and double enveloping structure is expected to be more than 20 years, however, further long-term experimental investigation is necessary [12]. Nevertheless, their high cost and low puncture

resistance are two barriers to overcome in order to increase their use in building [6].

An interesting research project is to develop ecological and thermally efficient VIP based on plant materials [13,14]. This leads to a new generation of insulation that we can call "Agro-VIP". The manufacture of these insulators requires the introduction of new processes. In this work, we propose a new VIP core material obtained from the sunflower pith. Studies of morphology, porosity, thermal stability and thermal conductivity have been made.

2. Materials and Methods

Material

The sunflower stem (Figure 1) is composed of 88% w/w of bark fiber and 12% w/w of sunflower pith.

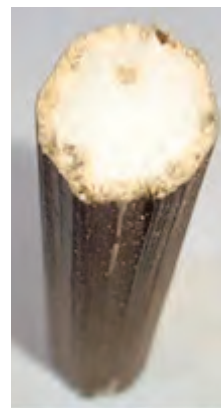


Figure 1 - Cross section of the sunflower stem.

The fibrous bark forms the outer portion of the fiber. This is a layer of wood type, consisting of long fibers wrapped in thin brown particles. Its density is estimated at 430kg.m^{-3} . The sunflower pith is white. It is very light, its density is estimated at 35kg.m^{-3} . It has a porous structure and alveolar, which gives it a low density.

Experimental Methods

Microscopic observations were carried out by 3D Digital microscope HIROX-KH-7700. 2.11 MP Camera. Magnification: from x1 to x7000. Resolution: down to 0,5 micron. 360° inspection, without any contact or moving. 3D and 2D measurements: depth, angle, height, volume, surface, roughness, etc.

Sorption-desorption analysis was performed using Dynamic Vapor Sorption unit (SMS, UK). The measurement is performed by a Cahn balance of great precision. Measurements of adsorption isotherm at 8 levels of relative humidity, from 0% to 90%RH at 25°C.

The thermal stability of the films was analyzed by thermogravimetric measurements, using a Netzsch TG 209F1 thermo-microbalance (Germany). Measurements have been performed at 20°C/min under a nitrogen atmosphere (15ml. min⁻¹). A sample mass of about 5 mg has been used to perform this test.

The thermal conductivity measurements were carried out using a measuring plate kept hot λ -Meter EP 500 of the German company Lambda-Meßtechnik GmbH Dresden. This method is standardized according to ISO 8302 08-91, NF EN 1946-2 07-99 and NF X 10-021 12-72. The size of the measurement surface is 150x150mm², with a temperature gradient of 10°K.

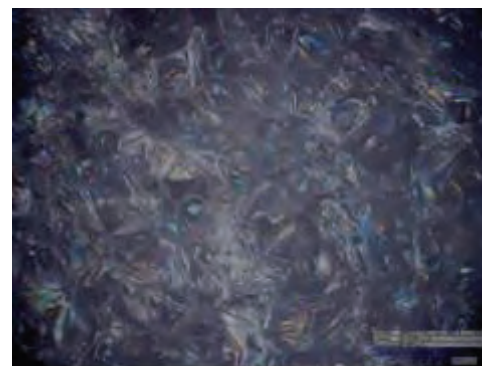
Scanning electron microscopy was performed using low Vacuum HITACHI S3000N. No metallization required for materials. Measurements were done at room temperature.

The particle sizes distribution was performed using Mastersizer 2000 particle size analyzer. Broad measuring range: from 0.02µm to 2000µm.

X-ray microtomography was performed by SKYSCAN micro CT1172. X-ray source: 20-100kV, 10W and <5µm spot size.

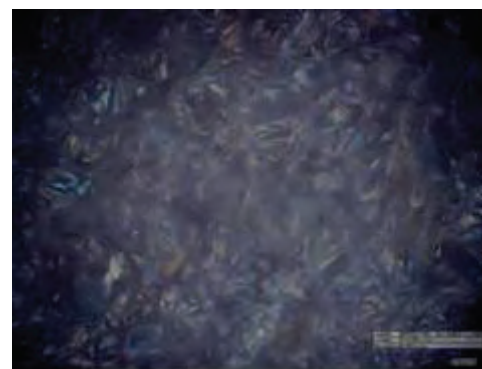
3. Characterization of Sunflower Pith

Photos of the cross section of sunflower pith and expanded polystyrene (EPS) produced by 3D digital microscopy are shown in Figure 2.



(a)

200µm



(b)

200µm

Figure 2 – Digital microscopy photos of the cross section of sunflower pith (a) and expanded polystyrene (EPS) (b).

These photographs show that these materials have a cellular structure. The average diameter of cells is of the order of 100µm for the EPS and 80µm for sunflower pith.

Figure 3 shows a surface topography of sunflower pith and expanded polystyrene (EPS). From these photographs, several peaks heights were measured relative to the lowest trough. We observe that the different measured values are in the range of 60 to 180µm for EPS, and of 80 to 200µm for sunflower pith. These values are similar for both materials.



(a)

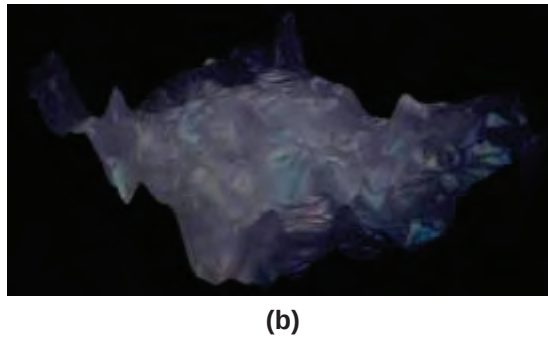


Figure 3 - Surface topography photos of the cross section of sunflower pith (a) and expanded polystyrene (EPS) (b).

From these results, we can say that the morphology of sunflower pith is comparable to expanded polystyrene. This result may explain the low density of sunflower pith. The air that is trapped inside cells may bring to the sunflower pith good thermal insulation properties.

In Figure 4, are presented the sorption-desorption isotherms of sunflower pith. These isotherms show that for a constant relative humidity, the moisture content corresponding to desorption is higher than that sorption. The water content at equilibrium at 90% RH is about 38% of the dry mass. The chemical nature of plant resources leads to different rates of moisture depending on the polarity of their functions. More the material has polar groups, more the formation of hydrogen bonds allow hydration. These results show that the sunflower pith is hydrophilic and can absorb a large amount of water.

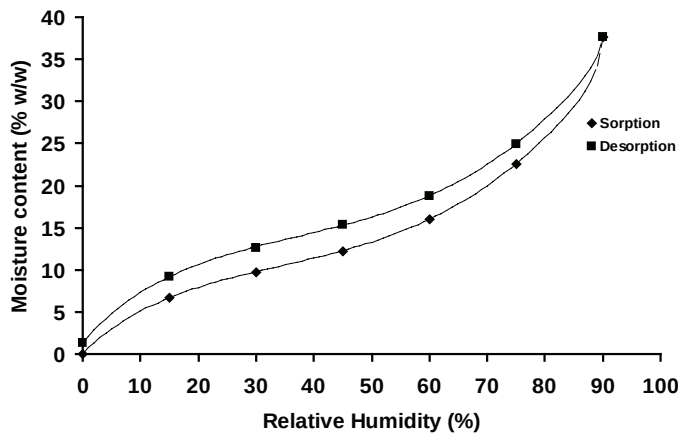


Figure 4 - Sorption-desorption isotherms of sunflower pith.

The thermal stability of sunflower pith was studied by thermogravimetric analysis. The TG and DTG curves are presented in the Figure 5. It displays several mass losses.

In agreement with the sorption-desorption results, the sunflower pith is hydrophilic in nature and it can absorb moisture. From this result, we can say that the first mass loss (equal to 11% w/w) corresponds to the evaporation of the water molecules. This is a general behavior observed in various cellulose based matters [15]. This is clear from the DTG curve. Below 200°C, the degradation of sunflower pith is lower even though a slight degradation of lignin and hemicellulose occurs at slow rate. However, at higher temperatures, that is between 200 and 550°C, the degradation rate is faster and a major weight loss occurs because of the degradation of cellulose, hemicellulose, and lignin ($T_{\text{donset}} = 230^\circ\text{C}$). To avoid degradation of the sunflower pith, the implementation must be done at temperatures below 180°C.

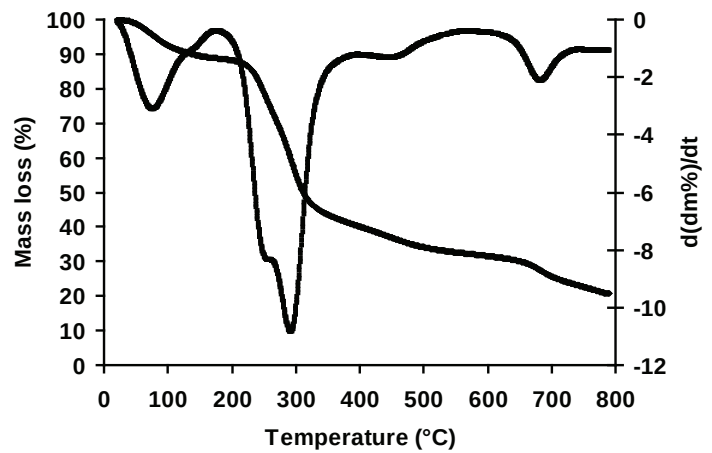


Figure 5 - TG and DTG curve of sunflower pith.

The thermal conductivities of sunflower pith particles (SPP), measured for temperatures 10, 25 and 40°C are shown in table 1. For similar densities, the thermal conductivity of these particles increases with temperature measurement (difference ranging from 4-5 mW.m⁻¹.K⁻¹ between 10 and 40°C). This conductivity decreases slightly with decreasing particle size.

Table 1 - Thermal conductivity of sunflower pith particles.

Materials	Thermal conductivity (mW.m ⁻¹ .K ⁻¹)			Density (kg.m ⁻³)
	10°C	25°C	40°C	
SPP (2mm < d < 5mm)	37,00	39,50	42,00	20
SPP (1mm < d < 2mm)	36,50	38,50	41,00	20
SPP (d < 1mm)	35,00	37,00	39,00	22
SPP (d < 200µm)	35,50	37,30	39,20	25

4. Core Preparation

The core material is made with sunflower pith particles finely ground less than 200 μm . The SEM photos of these particles are shown in figure 6 (a) and (b).

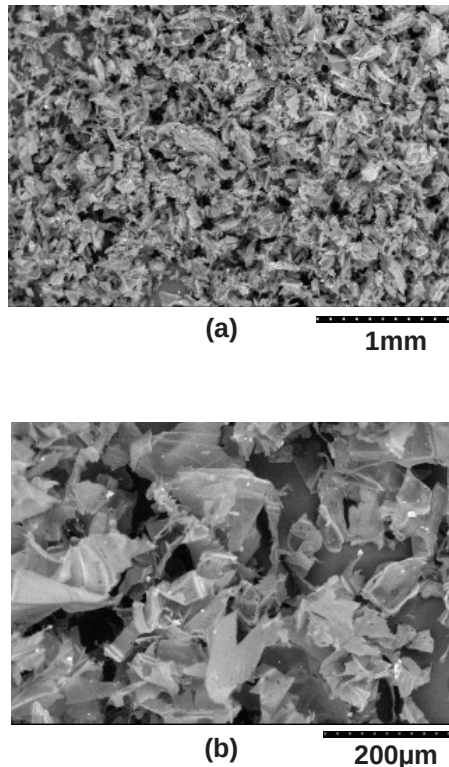


Figure 6 - Scanning electron micrograph of sunflower pith particles: (a) x40 (Mag: 1mm) (b) x200 (Mag: 200 μm).

From figure 6(a), we observe that these particles have no distinct form. For greater magnification (Figure 6(b)), different sizes and shapes are observed. The cells of the sunflower pith are not well distinguished.

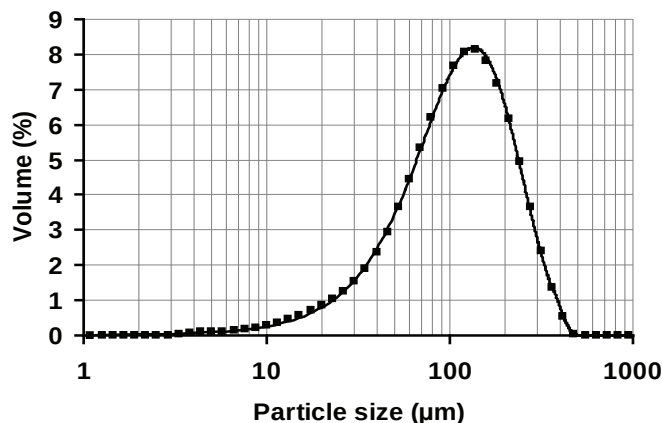


Figure 7 – Particle size distribution of sunflower pith particles.

The particle sizes distribution curve is shown in figure 7. This curve shows the broad distribution of particle size of sunflower pith:

- 50% of particles with diameters less than 100 μm .
- 37% of particles with diameters between 100 and 200 μm .
- 12.5% of particles with diameters between 200 and 360 μm .
- 0.5% of particles with diameters between 360 and 480 μm .

To achieve our plate, sunflower pith particles were moistened, thermo-compressed and then dried in an oven. The plate thus obtained is shown in figure 8.



Figure 8 - Sunflower pith plate wrapped in aluminum foil.

5. Results and Discussion

An analysis by X-ray microtomography was performed on the materials Sunflower pith and fumed silica. The 2D sample rotation gives different X-Ray pictures (different angles). All those pictures are then collected and re-built to form a 3D reconstruction. Thus the inner structure of the sample can be 3D-observed and inspected (Figure 9).

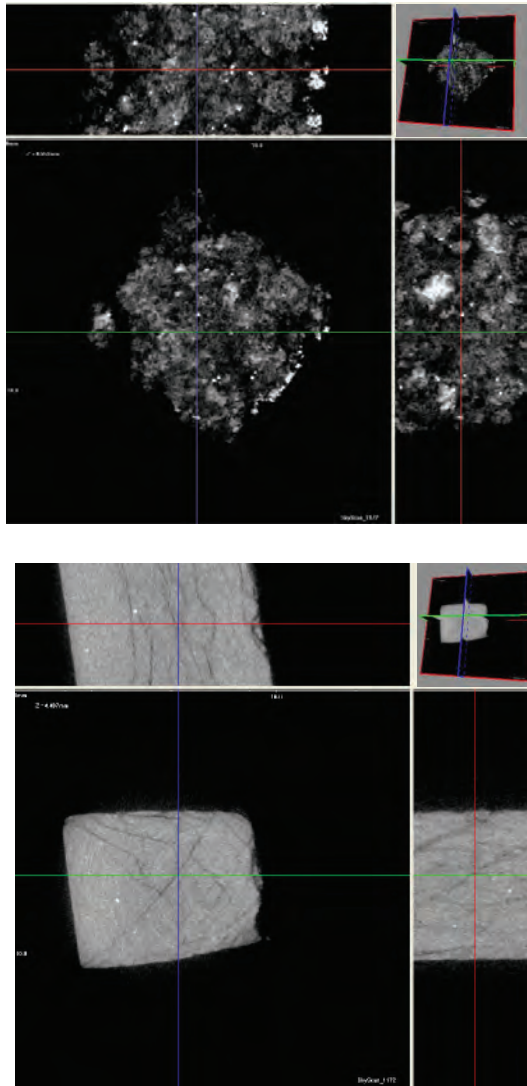


Figure 9 - 3D-projection of X-ray microtomography of sunflower pith plate and fumed silica plate.

We see huge disparities in terms of porosity for sunflower pith material. Low density areas are visible in this material (density $\approx 80\text{kg.m}^{-3}$). By cons, the silica fume material is more homogeneous and denser (density $\approx 250\text{kg.m}^{-3}$). The pores of this material are not visible (resolution limit of $10\mu\text{m}$).

Table 2 - Thermal conductivity of sunflower pith plates (SPPL) and fumed silica plate (FSPL).

Materials	Thermal conductivity at 20°C ($\text{mW.m}^{-1}.\text{K}^{-1}$)		Density (kg.m^{-3})
	1 bar	2.10^{-3} bar	
SPPL ($2\text{mm} < d < 5\text{mm}$)	43.50	31.50	60
SPPL ($1\text{mm} < d < 2\text{mm}$)	42.00	27.00	65
SPPL ($d < 1\text{mm}$)	43.20	23.50	80
SPPL ($d < 200\mu\text{m}$)	42.00	21.00	80
FSPL	21.00	10.50	270

To reduce the thermal conductivity of a material, one solution is to remove the gas, creating a vacuum in a sealed envelope. The thermal conductivities obtained for the different sunflower pith plates and fumed silica plate, at ambient and 2mbar gas pressure, are presented in Table 2.

From the results of this table, we observe that the various sunflower pith plates (SPPL) have similar thermal conductivities, varying between 42 and $43.5\text{mW.m}^{-1}.\text{K}^{-1}$, for densities ranging from 60 to 80kg.m^{-3} . Fumed silica plate has a lower thermal conductivity equal to $21\text{mW.m}^{-1}.\text{K}^{-1}$ for a density 270kg.m^{-3} .

The measures carried out under vacuum of 2mbar show a decrease in the thermal conductivity of sunflower pith plates, ranging from 31.5 to $21\text{mW.m}^{-1}.\text{K}^{-1}$ for sunflower pith particle sizes ranging from $2\text{mm} < d < 5\text{mm}$ to $d < 200\mu\text{m}$ (decrease from 28 to 50%). Fumed silica plate presents a decrease of about 51%. The thermal conductivity thus obtained is equal to $10.5\text{mW.m}^{-1}.\text{K}^{-1}$ against $21\text{mW.m}^{-1}.\text{K}^{-1}$ initially.

Thus, the vacuum sunflower pith plates lead to decreased thermal conductivity. This decrease is larger when we reduce the particle size of the sunflower pith plate.

The small pore size of silica fume or aerogels reduces the conductivity of the gas even at ambient pressure [16]. This explains the result obtained for the fumed silica plate ($21\text{mW.m}^{-1}.\text{K}^{-1}$). For sunflower pith plates, pore size is larger, which gives higher thermal conductivities at ambient pressure of about $42\text{mW.m}^{-1}.\text{K}^{-1}$.

The specific conductivity of a porous material depends on its pore size distribution, the conductivities of solid and gas phases and radiative properties of the material. In reality the main influence is due to gas phase transport property depending itself on the gas pressure (Figure 10) [6]. From this figure, and at the gas pressure equal to 2mbar, we note that the thermal conductivity obtained for the sunflower pith plate ($d < 200\mu\text{m}$) is comparable to PU foam.

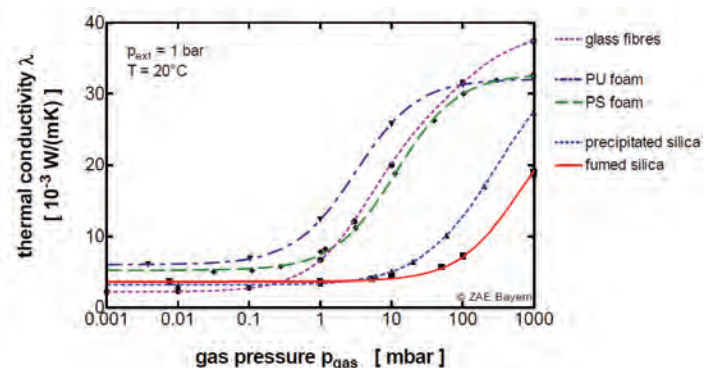


Figure 10 - Thermal conductivity of different core materials [6].

6. Conclusions

The morphology (cellular structure) and the low density of sunflower pith are comparable to expanded polystyrene.

From the thermal stability study, the sunflower pith showed general behavior observed in various cellulose based matters.

The vacuum insulation behavior of sunflower pith plate, at the gas pressure equal to 2mbar, is comparable to PU foam. The result can be improved by sealing in a barrier film under higher vacuum.

This work has shown that there is a potential to develop sunflower pith as an alternative core material for vacuum insulation panels.

7. Acknowledgements

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Developing 60 Year Lifetime Metallized VIP Laminates – Challenges and Solutions

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1. Introduction

Minimal thermal bridge is the primary reason why the VIP industry often selects metallized PET laminates over Al foil based solutions. But even the best metallized laminates known today cannot meet the barrier, chemical and mechanical demands of 60 years in construction applications, particularly in wet and warmer climates.

The most important parameters influencing the lifetime of VIPs are Oxygen and Nitrogen permeation rates, together with MVTR, permeation through the seals, and the resistance of the different polymeric layers to chemical degradation. The article describes the relative importance of each of these parameters, and the solutions Hanita is developing in order to achieve the goals of 60 year panel life with fumed silica cores in construction applications, and 15 years for refrigerators with cheaper glassfiber cores. These solutions include the substantial reduction in OTR and NTR levels resulting from minimizing mechanical defects (the Starry Night effect), and applying innovative multilayering technologies, such as those used in advanced transparent barrier solutions. The development of a novel high resistance adhesive layer is also discussed.

2. Developments

A necessary condition for developing ultra-high barrier laminates is to have a fast and extremely reliable way of measuring the permeation rate of the different atmospheric gases into the evacuated space. Part of the article is therefore devoted to a description of mVIP, a super sensitive technology which allows very accurate and fast OTR and NTR measurements.

2.1 Simple Thermal Bridge calculator

When laminates with Al foil are used in the production of VIPs, the rate of heat transfer from the warm side of the panel to its cold side via the envelope can be significant, and sometimes

even larger than that transferred through the body of the panel. To illustrate this effect, Hanita developed a simple Excel tool⁽¹⁾ to calculate the effective thermal conductivity of combinations of core materials and envelope laminates. By comparing the insulation performance of vacuum panels with different Al-foil envelopes to panels with metallized envelopes, it is easy to calculate the effect of the extra heat conductivity through the envelope containing Al foils, and its negative impact on the overall thermal insulation performance of the panel. This calculation is based on the comprehensive research of the thermal bridge effect made by the Swiss Research Institute in Zurich, EMPA⁽²⁾. During this research, the EMPA team calculated the effect of the thermal bridge by modifying the thermal conductivity λ of the panel in the standard formula for calculating the amount of heat transferred through a panel. With the modified $\lambda_{\text{effective}}$ the overall amount of heat transferred from the warm side to the cool side in a second can be calculated by the standard formula (the product of $\lambda_{\text{effective}}$ multiplied by the surface area of the panel (A) multiplied by the temperature difference (ΔT) and divided by the thickness (P) of the panel). In summary:

$$\text{The amount of heat transferred through a panel} = \lambda_{\text{effective}} \times A \times \Delta T / P$$

As an example, this calculator tells us that for panels of 50 X 50 X 2cm produced with high quality glassfiber core material and standard metallized laminate, the $\lambda_{\text{effective}} = 4\text{mW/Km}$, while for an identical panel produced with a laminate containing standard 6.3 μ thick Al foil, the value of $\lambda_{\text{effective}}$ is 9.3mW/Km, 2.35 times larger. The practical implication of this is that directly after evacuation, the thermal insulation efficiency of these specific panels is 2.35 times better when metallized laminate is used.

This simple example shows us why metallized laminates are so important for the VIP industry, and why it is vital to produce them with the required barrier properties to enable VIPs to serve as legitimate thermal insulation solution in buildings.

2.2 Metallic VIP (mVIP): A swift and sensitive OTR and NTR measuring technique

One major problem in developing ultra-high barrier laminates is the measurement of the slow permeation rates of oxygen and nitrogen molecules. There is no commercial equipment for measuring nitrogen permeation available, and the OTR of high barrier laminates is well below the detection level of any existing measuring device. The standard way of measuring the sum of OTR and NTR is to produce VIPs and to calculate the pressure build up rate from the measured rate change of the thermal conductivity of the panels. The problem with this technique is that in order to be able to measure significant changes in thermal conductivity, the measurements should be taken over many weeks or even months. This technology suffers from a high degree of inaccuracy, since the results have some dependence on the exact positioning of the panels between the hot and the cold plates, and because the density of the core may vary from one sample to another.

A more accurate process for the measurement of the permeation rates of oxygen plus nitrogen into VIPs was developed in the past by several research groups⁽³⁾ by connecting Spinning Rotor Pressure Gauges (SRG) to the envelope of standard VIPs using vacuum tight epoxy adhesives. In order to allow easy, accurate and fast OTR and NTR measurements, Hanita started a few months ago to develop an improved version of this technique under the framework of the European FP7 project NanoInsulate⁽⁴⁾.

In order to make the sample preparation process fast and easy, Hanita developed a simple and leak-less vacuum tight adaptor based on rubber O-ring sealing that enables sample preparation in less than 5 minutes. A photograph of the system can be seen in Fig.1.

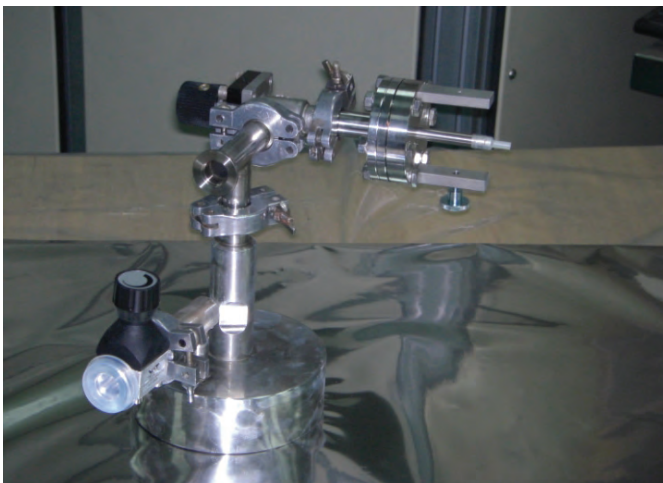


Fig. 1 Photo of the Hanita's mVIP

Since the pressure build up rate of a known VIP is inversely proportional to the free volume in the evacuated part of the VIP, reduction of the free volume can accelerate the pressure build up. This can easily be done by replacing the standard porous core material with a metallic plate, resulting in a reduction of the free volume. For example, the free volume of a 30 X 30 X 1cm VIP with standard porous core material is around 900cm³. By replacing the core material with a metallic plate of identical dimensions, the free volume can be reduced to 9cm³. It is important to note that this small evacuated free volume can be measured in situ very accurately using the basic law of ideal gases. By reducing the free volume 100 times, the pressure build up is accelerated 100 times. Preliminary tests with this newly developed mVIP system provided strong indications that in less than 1 hour, very accurate measurement of the permeation rate can be performed. This extremely high sensitivity will allow us to measure very accurately the NTR and OTR of all types of existing and newly developed VIP laminates, including laminates that contain Al foils. It will also allow very accurate measurement of the tiny side permeation through seals constructed from different seal solutions, or to measure the dependence of the side permeation on the seal's width. Because each SRG measurement head is relatively inexpensive, one central control unit of the mVIP system will allow the simultaneous measurement of dozens of samples.

Another very important feature of the mVIP system is the fact that the NTR and the OTR are being measured when the laminated is mechanically stressed, reproducing actual VIP conditions. This is extremely important, because there are strong indications that the permeation rate through the mechanically stressed areas along the edges, corners and folds is substantially higher than that through the non-stressed laminate.

2.3 Chemical robustness

In real life, the degradation rate of a VIP can be faster and in some cases much faster than expected taking into account the normal permeation rates of the atmospheric gases. This is especially true when the panels are exposed to elevated temperatures and high humidity for long periods of time. Under such environmental conditions, the degradation processes of the polymeric layers of the laminates can cause disintegration of the laminate structures, increasing permeation rates and even leading to puncturing. The parts most vulnerable to these hydrolysis degradation processes are the thin adhesive layers between the polymeric films of the laminate structure.

Recently, several VIP producers adopted an aggressive ageing test called the Accelerated Lifetime Test (ALT). In this test, the panels are exposed to 12-hour long cycles of temperature changes fluctuations from -30°C to 80°C and 65% RH. After 9 days, the

panels are kept for 3 days at room temperature and the change in the thermal conductivity of the panels from the initial value is measured. The panels are also visually inspected for delamination and creasing. This 9 day long procedure is repeated twice more. Usually, with standard lamination adhesives, all panels fail after the first 9 day cycle.

Hanita has developed a new type of lamination adhesive that keeps the panels completely intact even after four 9-day ALT cycles. More field tests simulating the conditions in building walls are required for investigating the degradation processes of the polymeric layers under real life conditions. However, it appears that the new adhesive can provide the necessary confidence that vacuum panels can function well for 60 years in buildings, even in warmer and more humid climates.

2.4 Minimization of the OTR and NTR

High barrier metalized laminates contain PET films coated with Al layers laminated together. The Al layers are deposited by a fast roll to roll vacuum thermal deposition processes, and have a thickness of around 100nm. They do not form a continuous layer but rather a polycrystalline structure. TEM micrographs of this polycrystalline structure of Al layers on thin PET film are shown in Fig.2. Note the dense network of grain boundaries which is responsible for most of the permeation of water molecules.

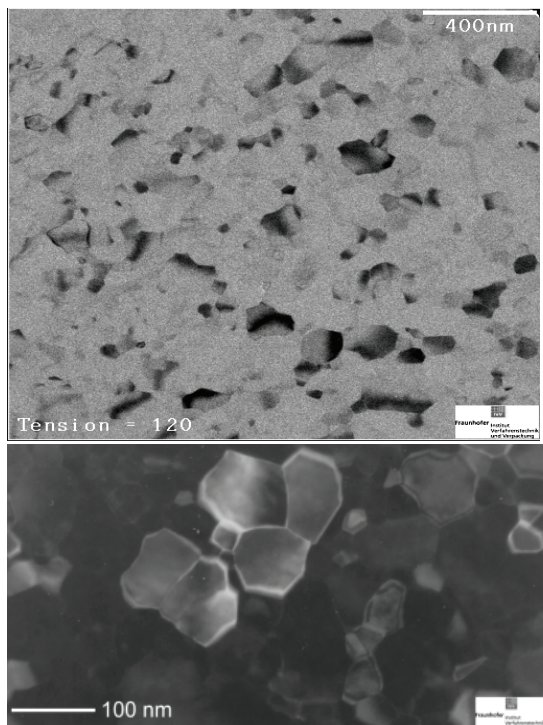


Fig.2 TEM micrographs of vacuum deposited Al layers on thin PET film. The layer has polycrystalline structure with grain size between a few tens of nanometers to a few hundreds of nanometers. (Courtesy of the Fraunhofer Institute, IVV)

Unfortunately in real life the Al layers are not perfect and contain many micron size pinholes that look like a star-studded sky when the film is back-illuminated in a dark room. Fig.3 shows a photograph of this “Starry Night” phenomenon.



Fig.3 Starry Night – A photograph of Al layer deposited on thin PET film and containing tens of microns size pinholes. In high quality metallized films the overall surface area covered by the pinholes is less than 2%. However they are considered to be the main route for oxygen and nitrogen permeation.

Some of the pinholes are created as a result of irregularities and dust particles on the surface of the substrate, but the vast majority of them are produced by mechanical damage that occurs while the metalized film is running on the production lines and in the rewinding process. The most common metalized laminates have a typical MVTR value of about 0.01g/m²day and OTR lower than 0.0005 CC(std)/m²day bar. Since the volume of 1 gram of moisture vapor in standard conditions is about 1200 CC we can see that for that for these laminates the permeation flux of water molecules is 4 orders of magnitude faster than that of oxygen molecules. One possible explanation for that huge difference in the permeation rates is that water molecules can permeate easily through the grain boundaries between the Al crystallines of the metalized films. While O₂ and N₂ molecules can permeate only through the pinholes.

Reduction of the OTR and NTR can be achieved therefore in three ways: reducing the pinholes density, plugging the pinholes with high barrier lacquers and creating structures of several Al layers with thin organic layers separating between them (the Torturous Path effect). All three approaches are investigated in the framework of the FP7 European project NanoInsulate. The main goal of this project is to develop efficient and cost effective VIP solutions for thermal insulation of buildings.

In the first year of this project substantial OTR and NTR reduction was achieved. As part of the war against pinholes, Hanita developed new production procedures that reduces by more than half the transfer rate of both the oxygen and the nitrogen. The

comparison of the permeation rate of nitrogen molecules plus oxygen molecule into VIPs produced with standard laminate and with laminate produced with newly developed production procedures is shown in Fig 4. The permeation rate was calculated from very careful measurements of the change rate of the thermal conductivity of the panels. These measurements, as well as the panel production, were performed by VaQtech, one of the industrial partners of the NanoInsulate project.

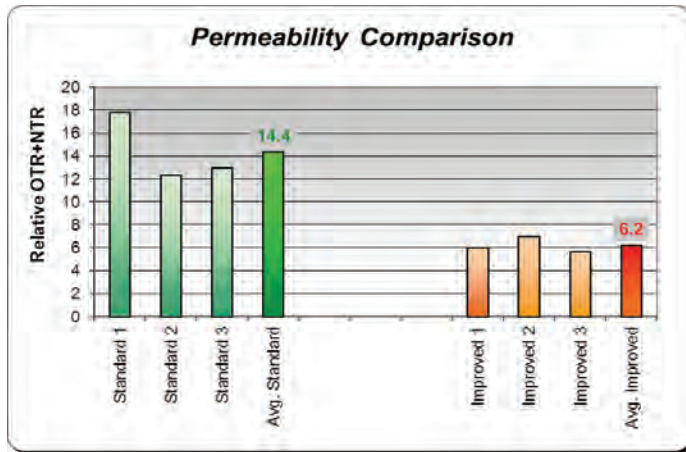


Fig.4 Relative permeation rates of oxygen plus nitrogen through standard laminate and through laminate produced in newly improved production processes. The permeation rates were calculated from the change rate of the thermal conductivity of evacuated panels.

Surprising OTR reduction of a metallized film was also achieved by coating the Al layer with a few micron thick layer of high barrier lacquer. In a set of tests, Hanita's standard metallized PET film was coated with two new types of Ormocer lacquer by the IVV and the ISC Fraunhofer institutes. After coating the measured OTR was less than 0.01CC(std)/m²daybar. This is probably the lowest OTR ever measured for a single vacuum metallized Al layer on polymeric film manufactured by a roll to roll process. It is also at least twice as good as the typical OTR value of Hanita standard laminate with one Al layer, which is 0.055CC(STD)/m²daybar. The Ormocer layers were developed and specially modified for metallic Al layers by ISC, while the OTR measurements were performed by IVV, the academic partner of the NanoInsulate project.

3. Conclusions

The results of the intensive R&D efforts by Hanita in the last year have proved that substantial OTR and NTR reduction can be achieved by improving the production processes of the laminates, and by integrating modified Ormocer layers into the laminate structures. Together with the newly developed robust adhesive

layers, the goal of a 60 year VIP lifetime in buildings seems to be very realistic. These R&D efforts will continue intensively in-house, and also in the framework of several international co-operation projects.

The completion of the development process of the mVIP measuring system will enable a much shorter evaluation time for the new developed laminates, as well as gathering valuable information on different permeation mechanisms that are presently unknown.

Acknowledgement

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Vacuum and Nanotechnologies for the Thermal Insulation Materials of Beyond Tomorrow – From Concept to Experimental Investigations

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Abstract

As the world's attention to and demand for energy savings and efficiency are continuously increasing, several strategies are employed for reaching the desired goals in this respect. One key strategy is to improve the energy efficiency of buildings, and thus their thermal insulation resistance. With increasing requirements for thermal insulation, the building envelopes are increasing in thickness far beyond what is considered as an appropriate and practical thickness. One crucial strategy to limit the building envelope thickness and still be able to achieve a satisfactory high thermal resistance, is to develop high performance thermal building insulation by application of vacuum and nanotechnologies. This work presents the conceptual principles for the high performance thermal insulation materials of beyond tomorrow, i.e. advanced insulation materials (AIM) like vacuum insulation materials (VIM), gas insulation materials (GIM), nano insulation materials (NIM), dynamic insulation materials (DIM) and NanoCon. Possibilities and restrictions with respect to miscellaneous theoretical considerations concerning thermal transport by solid state conduction, gas conduction, gassolid interactions, radiation and convection are addressed. Then different strategies for manufacturing some of these AIMs are explored, including membrane foaming, gas release and templating. Finally, some initial investigations and attempts to produce these AIMs in the laboratory are presented.

1. Introduction

The demand to improve energy efficiency of buildings is increasing as the energy use in the building sector accounts for a significant part of the world's total energy use and greenhouse gas emissions. In this respect the thermal insulation of buildings

plays an important role, where one major objective is to develop new and robust insulation materials and solutions with as low thermal conductivity values as possible. Applying traditional thermal insulation materials requires ever increasing thicker building envelopes. This is not desirable for several reasons, e.g. space issues with respect to economy and floor area, transport volumes, architectural restrictions and other limitations, material usage and existing building techniques. Recent studies [1] show that energy efficiency measures are the most cost-effective ones, whereas measures like e.g. solar photovoltaics and wind energy are far less costeffective than insulation retrofitting of buildings.

Stateoftheart thermal insulation materials and solutions like vacuum insulation panels (VIP) [23] and aerogels [4] may represent the best thermal insulation today with respect to very low thermal conductivity values. However, both VIPs and aerogels have their drawbacks. The VIP solution, which attains a considerably lower thermal conductivity than the aerogels, does not represent a robust solution as air and moisture over time will penetrate the VIP envelope and thus increase the thermal conductivity due to loss of vacuum. Adaption and cutting of VIPs at the building site can not be performed without loss of vacuum and thermal resistance, and any perforation of the VIP envelope increases the thermal conductivity from the pristine nonaged value of typical 4 mW/(mK) to about 20 mW/(mK). Furthermore, both VIPs and aerogels are very costly solutions compared to traditional thermal insulation. Nevertheless, in areas with a high living area market value per square meter, a reduced wall thickness (e.g. by use of VIPs) may involve large area savings and thus a higher value of the real estate.

Conceptual principles for the high performance thermal insulation materials of beyond tomorrow, i.e. advanced insulation materials (AIM) like vacuum insulation materials (VIM), gas insulation materials (GIM), nano insulation materials (NIM),

dynamic insulation materials (DIM) and NanoCon, have been presented earlier [2,57]. This work summarizes the conceptual ideas of the AIMs, and explores some possible strategies for actually making them, including membrane foaming, gas release and templating. Finally, initial investigations and attempts to produce AIMs in the laboratory are presented.

2. The Concepts of Advanced Insulation Materials

2.1. Thermal Transport and Conductivity

The total overall thermal conductivity λ_{tot} , i.e. the thickness of a material divided by its thermal resistance, is in principle made up from several contributions:

$$\lambda_{\text{tot}} = \lambda_{\text{solid}} + \lambda_{\text{gas}} + \lambda_{\text{rad}} + \lambda_{\text{conv}} + \lambda_{\text{coupling}} + \lambda_{\text{leak}} \quad (1)$$

where λ_{tot} = total overall thermal conductivity, λ_{solid} = solid state thermal conductivity, λ_{gas} = gas thermal conductivity, λ_{rad} = radiation thermal conductivity, λ_{conv} = convection thermal conductivity, $\lambda_{\text{coupling}}$ = thermal conductivity term accounting for second order effects between the various thermal conductivities in Eq.1 and λ_{leak} = leakage thermal conductivity. Each of these thermal contributions must be minimized in order to reach as low thermal conductivity as possible. The leakage thermal conductivity λ_{leak} representing an air and moisture leakage driven by a pressure difference, is normally not taken into consideration since insulation materials and solutions are supposed to be without any holes that would enable such a thermal leakage transport. The coupling term $\lambda_{\text{coupling}}$ can be included to account for second order effects between the various thermal conductivities in Eq.1, and may be quite complex. Theoretical approaches to thermal performance of vacuum insulation panels (VIP) usually assume this coupling effect to be negligible [8]. Generally, another coupling term might also be included in Eq.1, i.e. the interaction between the gas molecules and the solid state pore walls. However, as we will see later this last coupling term is included through a factor in the expression for the gas conductivity as given in Eq.2 for the Knudsen effect. The solid state thermal conductivity λ_{solid} is related to thermal transport between atoms by lattice vibrations, i.e. through chemical bonds between atoms. The gas thermal conductivity λ_{gas} arises from gas molecules colliding with each other and thus transferring thermal energy from one molecule to the other. The radiation thermal conductivity λ_{rad} is connected to the emittance of electromagnetic radiation in the infrared (IR) wavelength region from a material surface. The convection thermal conductivity λ_{conv} is due to thermal mass transport or

movement of air and moisture. All these thermal conductivity contributions are driven by or dependent upon the temperature and temperature difference.

2.2. Vacuum Insulation Materials and Gas Insulation Materials

A *vacuum insulation material* (VIM) is basically a homogeneous material with a closed small pore structure filled with vacuum with an overall thermal conductivity of less than 4 mW/(mK) in pristine condition. The VIM can be cut and adapted at the building site with no loss of low thermal conductivity. Perforating the VIM with a nail or similar would only result in a local heat bridge, i.e. no loss of low thermal conductivity. A *gas insulation material* (GIM) is basically a homogeneous material with a closed small pore structure filled with a lowconductance gas, e.g. Ar, Kr or Xe, with an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition. That is, a GIM is basically the same as a VIM, except that the vacuum inside the closed pore structure is substituted with a lowconductance gas. For further details it is referred to Jelle et al. [6].

2.3. Nano Insulation Materials and the Knudsen Effect

The development from VIPs to nano insulation materials (NIM) is depicted in Fig.1. In the NIM the pore size within the material is decreased below a certain level, i.e. 40 nm or below for air, in order to achieve an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition. That is, a NIM is basically a homogeneous material with a closed or open small nano pore structure with an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition. The low gas thermal conductivity in NIMs is caused by the Knudsen effect where the mean free path of the gas molecules is larger than the pore diameter. That is, a gas molecule located inside a pore will hit the pore wall and not another gas molecule. The resulting gas thermal conductivity λ_{gas} versus pore diameter and pressure for air is depicted in Fig.1 based on the following simplified expression taking into account the Knudsen effect [2,6]:

$$\lambda_{\text{gas}} = \frac{\lambda_{\text{gas},0}}{1 + 2\beta K} = \frac{\lambda_{\text{gas},0}}{1 + \frac{\sqrt{2}\beta k_B T}{\pi d^2 p \delta}}, \quad (2)$$

$$K = \frac{\sigma_{\text{mean}}}{\delta} = \frac{k_B T}{\sqrt{2}\pi d^2 p \delta}$$

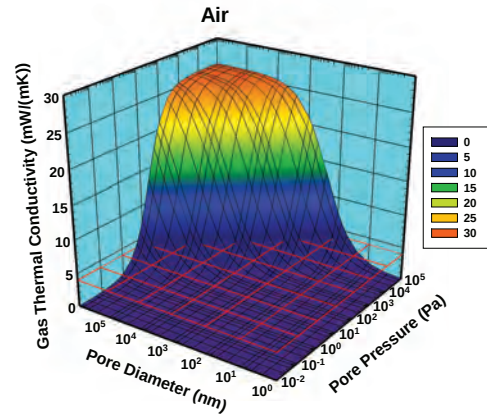
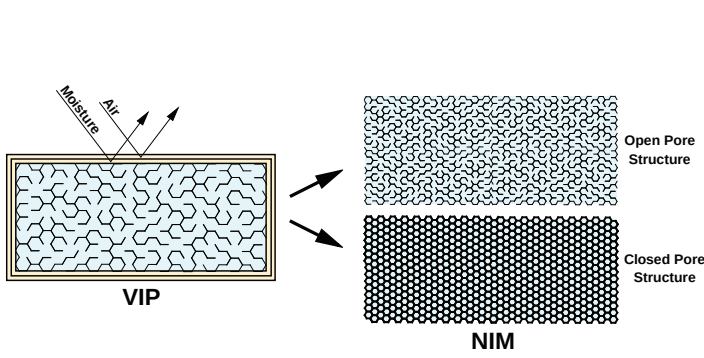


Fig.1. The development from VIPs to NIMs (left) and the effect of pore diameter and pressure on the gas thermal conductivity (Eq.2) for air (right) [6].

where λ_{gas} = gas thermal conductivity in the pores (W/(mK)), $\lambda_{\text{gas},0}$ = gas thermal conductivity in the pores at STP (standard temperature and pressure) (W/(mK)), b = coefficient characterizing the moleculewall collision energy transfer efficiency (between 1.5 – 2.0), k_B = Boltzmann's constant $\gg 1.38 \cdot 10^{-23}$ J/K, T = temperature (K), d = gas molecule collision diameter (m), p = gas pressure in pores (Pa), d_p = characteristic pore diameter (m) and σ_{mean} = mean free path of gas molecules (m). The radiation and solid state lattice conductivity in the NIMs has to be kept as low as possible in order to obtain the lowest possible overall thermal conductivity.

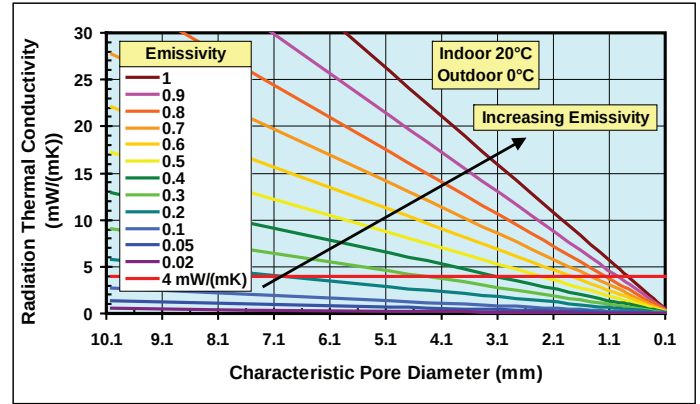


Fig.2. The radiation thermal conductivity versus pore diameter for various emissivities of the inner pore walls. From Eq.3 [6].

2.4. Radiation Effects in Small Pores

Applying the StefanBoltzmann relationship it may be shown that the radiation thermal conductivity decreases linearly with decreasing pore diameter, where the emissivity of the inner pore walls determine the slope of the decrease, according to the following relationship [6]:

$$\lambda_{\text{rad}} = \frac{\pi^2 k_B^4 \delta}{\theta \hbar^3 c^2 \left[\frac{2}{\varepsilon} - 1 \right]} (T_i^4 - T_e^4) \quad (3)$$

where λ_{rad} = radiation thermal conductivity in the pores (W/(mK)), $s = \pi^2 k_B^4 / (60 \hbar^3 c^2)$ = StefanBoltzmann's constant $\gg 5.67 \cdot 10^{-8}$ W/(m²K⁴), k_B = Boltzmann's constant $\gg 1.38 \cdot 10^{-23}$ J/K, $\hbar = h/(2\pi) \gg 1.05 \cdot 10^{-34}$ Js = reduced Planck's constant (h = Planck's constant), c = velocity of light $\gg 3.00 \cdot 10^8$ m/s, d = pore diameter (m), ε = emissivity of inner pore walls (assumed all identical), T_i = interior (indoor) temperature (K) and T_e = exterior (outdoor) temperature (K). That is, the smaller the pores, and the lower the emissivity, the lower the radiation thermal conductivity will be Fig.2.

However, various works [911] describe a large increase in the thermal radiation as the pore diameter decreases below the wavelength of the thermal (infrared) radiation (e.g. 10 μm), where tunneling of evanescent waves may play an important role. Note that in Fig.2 the radiation thermal conductivity is only plotted down to a pore diameter of 0.1 mm (100 μm), which is about 10 times larger than the mean infrared wavelength at room temperature (10 μm). The work by Mulet et al. [9] and Joulain et al. [10] indicate that the large thermal radiation is only centered around a specific wavelength (or a few). That is, this might suggest that the total thermal radiation integrated over all wavelengths is not that large. The work by Jelle et al. [6] elaborates more on these thermal radiation issues. These topics are currently being addressed in ongoing research activities.

2.5. Dynamic Insulation Materials

A *dynamic insulation material* (DIM) is a material where the thermal conductivity can be controlled within a desirable range. The thermal conductivity control may be achieved by being able to change in a controlled manner (a) the inner pore gas content or concentration including the mean free path of the gas molecules and the gas surface interaction, (b) the emissivity of the inner surfaces of the pores and (c) the solid state thermal conductivity of the lattice. Two models exist for describing solid state thermal conductivity. That is, the phonon thermal conductivity, i.e. atom lattice vibrations, and the free electron thermal conductivity. One might ask if it could be possible to dynamically change the thermal conductivity from very low to very high, i.e. making a DIM? Furthermore, could other fields of science and technology inspire and give ideas about how to be able to make DIMs, e.g. from the fields of electrochromic materials, quantum mechanics, electrical superconductivity or others? The thermal insulation regulating abilities of DIMs give these conceptual materials a great potential. It is referred to Jelle et al. [6] for further details and elaborations concerning DIMs.

2.6. NanoCon

With decreasing thermal conductivities of insulation materials, new solutions should also be sought for the loadbearing elements of the building envelope. Using concrete as an example, one might envision mixing NIMs into the concrete, thereby decreasing the thermal conductivity of the construction material substantially, while maintaining most or a major part of the mechanical strength and loadbearing capabilities of concrete. Hence, a new material is introduced on a conceptual basis (Jelle et al. [7]): *NanoCon* is basically a homogeneous material with a closed or open small nano pore structure with an overall thermal conductivity of less than 4 mW/(mK) (or another low value to be determined) and exhibits the crucial construction properties that are as good as or better than concrete. In the above definition of *NanoCon*, a homogeneous material is stated, although the first attempts to reach such a material might be tried by piecing or mixing several different materials together, i.e. with a final material product which on a nanoscale is not homogeneous. For example, joining NIM and carbon nanotubes in one single material might enable a very low thermal conductivity due to the NIM part and a very large tensile strength due to the carbon nanotube part. In this respect it should be noted that the extremely large tensile strength of carbon nanotubes (63 000 MPa measured and 300 000 MPa theoretical limit) surpasses that of steel rebars (500 MPa) by more than two orders. As a comparison, concrete itself (without rebars) has a tensile strength of 3 MPa and a compressive strength of 30 MPa.

3. The Aim of the Initial Experimental Attempts

The current materials that most closely resemble these ideal nano insulation materials are silicabased aerogels, which are commercially available as nanoporous materials with an open pore structure. Their thermal conductivity in air is typically around 13 mW/(mK) due to the Knudsen effect. They are used as core material in VIPs (4 mW/(mK)), contained in insulating blankets (14 mW/(mK)), and as loose, hydrophobic granules for spraying into building crevices (17 mW/(mK)). A very interesting aspect with aerogels is that they can be produced as either opaque, translucent or transparent materials, thus enabling a wide range of possible building applications. Aerogels have a relatively high compression strength, but are very fragile due to their very low tensile strength, and are easily broken down by abrasion processes. Our aim is to develop new thermal insulation materials with even better properties than aerogels. The main target is lowered thermal conductivity, with improved mechanical properties. In the first attempts, the aim is to be able to control the nanoscale structure of the material. Silica is chosen as a model material, since various silica precursors are available and their chemistry is quite wellknown. At a later stage, similar methods may be developed for other materials, e.g. titania and alumina.

4. Experimental Laboratory Production Methods

Three different methods for producing nanoporous hydrophobic materials were investigated, i.e. membrane foaming, gas release and templating. In all cases, hydrolysis and condensation of silane precursors may be used to form the solid network. This is the same reaction that is used for production of aerogels and may be depicted as:

Hydrolysis:



Condensation:



4.1. Membrane Foaming

In membrane foaming, the idea is to produce foams with nanoscale bubbles, followed by condensation and hydrolysis within the bubble walls to obtain a silica nanofoam. In the process, gas is pressed through a membrane to obtain bubbles with controlled size as depicted in Fig.3. Hydrolysis and condensation of precursors at the bubble-liquid interface should result in formation of gas capsules. This method was previously used to obtain nitrogen-containing capsules with titania-polypyrrole composite shells. Their diameter was in the range 15 μm as shown in Fig.3. Initial experiments indicated that preparation of silica nanofoams might be difficult to accomplish. This was supported by theoretical considerations. The gas pressure must be very accurately adjusted; if the pressure is too low, no bubbles will be formed and if it is too high, a continuous gas stream will result. The size of the bubbles may be decreased by decreasing the pore size of the membrane and adjusting its surface properties to obtain a high contact angle with the solvent, i.e. the solvent should be repelled from its surface. Furthermore, the solvent density should be rather high and its surface tension low. It should in principle be possible to design a reaction system that fulfills these requirements, so that production of nanosized bubbles is viable.

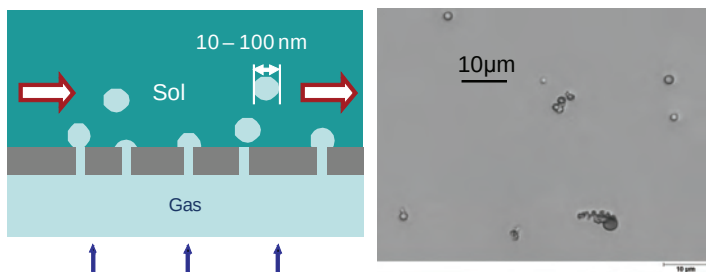


Fig.3. Preparation of gas capsules by membrane emulsification. Left: Aim of experiment. Right: Micronsized capsules obtained by Yang et al. [12].

For the production of a solid nanofoam, the liquid foam must be stable long enough for the reactions in Eqs.46 to proceed. Furthermore, if the foam is to be of interest as an insulator, its walls must be thin. Otherwise, the solid contribution to the overall thermal conductivity will be too high. Wall thicknesses of about 20 nm may be achieved if surfactant bilayers are used to stabilize the walls and the applied solvent has low viscosity and is rapidly drained from the wall interior. It is possible to achieve this in waterbased systems. However, the reactions in Eqs.46 are generally performed in alcohol solutions like ethanol or isopropanol. No surfactant was found that could stabilize nanofoams long enough, thus this line of work was so far abandoned.

4.2. Gas Release

The gas release method would require simultaneous formation of nanosized gas bubbles throughout the reaction system, followed by hydrolysis and condensation (Eqs.46) to form a solid at the bubble perimeter. Bubble formation could be achieved by either evaporation or decomposition of a component in the system. This method is similar to the process described by Grader et al. [13], where crystals of $\text{AlCl}_3(\text{Pr}_2\text{O})$ were heated to produce foams with closed cell structures. In this case, the crystals themselves decomposed. Upon further heating, the remaining solid dissolved in the generated solvent. Then a polymerization reaction occurred at the temperature of solvent evaporation. The solvent bubbles were trapped within the polymerizing gel, forming a stable foam with pore sizes 50300 μm after completion of the reaction. The gas release process entails several challenges. To obtain nanosized bubbles with a sufficiently narrow size distribution, the temperature must be the same throughout the liquid phase. In ordinary reaction conditions, this would be difficult to achieve. Further, the reaction to form the solid shell must proceed very rapidly if the shell is to be formed before the bubbles grow too large. This would require very reactive chemicals, and their application would require strict control of humidity both in the working environment and in the solvents used. Due to these practical difficulties, work in this direction was at the moment terminated.

4.3. Templating

In the templating process, a nanoscale structure in the form of a nanoemulsion or polymer gel is prepared, followed by hydrolysis and condensation by Eqs.46 to form a solid. This procedure is used for preparing e.g. catalysts and membrane materials. Our approach is to prepare hollow silica nanospheres, followed by condensation and sintering to form macroscale particles or objects. For thermal insulation materials, we would like to have a small pore size, combined with a small wall thickness. Assuming a pore diameter of 100 nm and a wall thickness of 15 nm, the solid volume fraction of the particle would be 54 %. With cubic close packing (ccp) of monosized spheres, the solid fraction of a “nanosphere compact” would be 41 %. In practice, the sphere packing will always be less efficient than ccp, thus lower solid fractions are envisaged - as is also desired. Several methods for nanosphere production are given in the literature. The current work is based on the work reported by Du et al. [14], who used the method for preparing antireflection coatings. The method is described in more detail by Wan and Yu [15], and their schematic depiction of the synthesis process is shown in Fig.4.

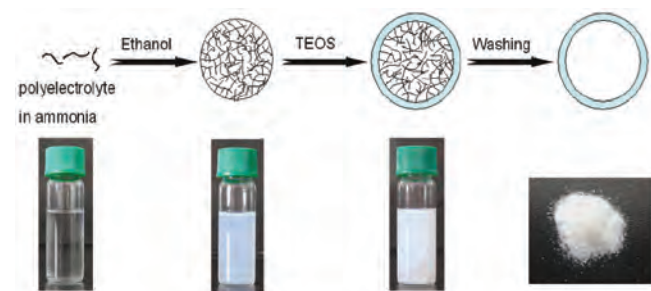


Fig.4. Schematic diagram showing the formation mechanism of hollow silica spheres [15].

Synthesis starts with dissolving the polyelectrolyte polyacrylic acid (PAA) in ammonia, followed by addition of ethanol to form an emulsion. The droplet size in the emulsion increases with increasing concentration of polyelectrolyte in the solution. The next step is gradual addition of tetraethoxysilane (TEOS), which reacts with water at the droplet surface and forms a solid silica shell. When the sample is washed with water, the polyelectrolyte diffuses through the shell, and after drying, hollow silica nanospheres are obtained.

5. Experimental Details of Templating Process

An initial templating experiment was conducted. First, 0.27 ml of PAA (polyacrylic acid, MW ~ 5 000, 50 % aqueous solution, Polysciences) was dissolved in 4.5 ml 25 % NH_4OH solution (Merck). An emulsion was formed by adding 90 ml of absolute ethanol (Kemetyl) was added during magnetic stirring at a rate of 760 rpm. TEOS (tetraethoxysilane, purum ($\geq 98.0\%$), Fluka) was added in five 0.45 ml portions, with at least one hour between additions. The total time of addition was 22 h. The sample was diluted with water to twice the volume and centrifuged at 10 000 rpm for 10 min. The supernatant was removed and the particles were redispersed in water. This cleaning procedure was performed four times. The particle size of the nanospheres in water was measured using a Malvern Zetasizer Nano ZS. The particles were dried and investigated by scanning electron microscopy (SEM), using backscattered electrons (BSE) in a Helios Nanolab[®] instrument. To further determine whether the spheres were hollow, they were subjected to focused ion beam (FIB) cutting.

6. Initial Nanosphere Manufacturing Results

The produced spheres had a reasonably narrow size distribution, with an average particle size of 190 nm measured by the Malvern Zetasizer. SEM images showed that most particles had diameters between 90 and 400 nm, with most around 200 nm (Fig.5), which is well in agreement with the size measured in water.

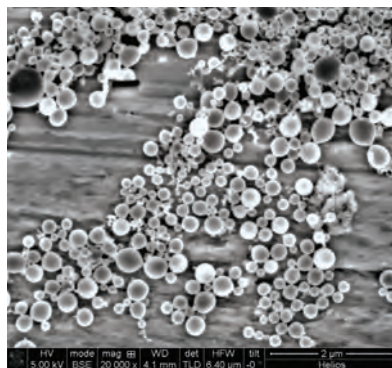
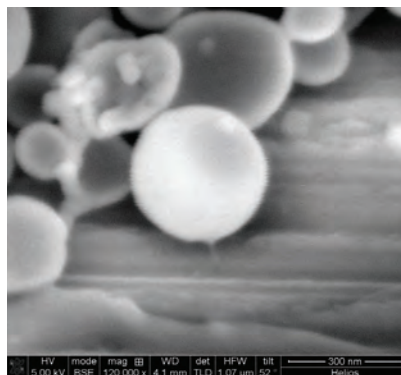


Fig.5. SEM image (BSE) showing an overview of the nanosphere sample, where the scale bar is 2 μm .

In Fig.5 the spheres show up as circles with dark centers and light edges. This is due to the atomic contrast in BSE images. SiO_2 is shown lighter than void areas. If the particles were dense SiO_2 spheres, they would also have light centers. Thus, this image is the first indication that most of the spheres are indeed hollow. Images of separate particles before and after FIB etching are shown in Fig.6. For convenience, relatively large spheres were chosen for the FIB experiments. It is clearly seen that the ion beam removes material from the sphere surface, showing an empty interior. Eventually, the sphere is slightly deformed. If the walls of the sphere are thin, the sphere collapses after etching. The rectangular hole in front of the particle in Fig.6 (middle and right photos) is a result of ion beam etching of the sample holder.



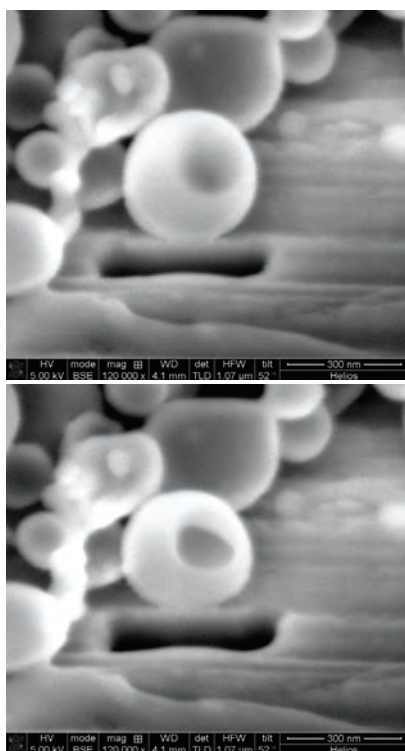


Fig.6. SEM image (BSE) showing an unetched sphere (left), as well as the same sphere after a little etching (middle) and after more extensive etching (right). The scale bar is 300 nm in all images.

7. Conclusions

The conceptual principles for the high performance thermal insulation materials of beyond tomorrow are presented, with a special focus on nano insulation materials (NIM). Different preparation methods for nanoscale insulation materials were evaluated. Initial experiments for preparing silica nanospheres showed that we are able to prepare hollow silica nanospheres by a templating process. The sphere size is in the desired range, and further work will focus on controlling particle size and wall thickness, and obtaining narrower size distribution. Thermal conductivity of the asprepared powder will be measured. For application as thermal building insulation, the sample surface should be modified to obtain hydrophobicity. Development of partial densification and agglomeration processes is also required to allow practical handling of the material.

Acknowledgements

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LockPlate System ETICS/* with integrated VIP Experience from building practice

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/ External thermal insulation composite systems*

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Requirements for the Future

Insulation of the building envelope is by far the most important action for reducing the energy needs of the built environment. Meeting the 20-20-20 target of the EU will need very performing solutions, both for new built as well as for existing buildings. The higher the desired heat resistance, the thicker the insulation layer gets. Traditional insulation materials need 30 cm and more to meet the passive house or zero energy standards. Especially for the post-insulation of walls and floors in existing buildings, this space is often not available. [1]

Intelligent ETICS with VIPs

The new LockPlate system requires less than 10 cm thickness to realise U-value of less $0.15 \text{ W/m}^2\text{K}$, whereas most traditional insulation materials would require 30 cm or more. The system is especially interesting for low energy retrofitting of existing buildings, but can also be used for new constructions. [2]

The Smart Way? VIP Inside of ETICS!

The LockPlate system is an innovative ETICS based on VIPs embedded in EPS in its core. The EPS envelope serves as a mechanical protection for every VIPs. *Fig. 1.* To reduce the thermal bridge effect on VIP edges in their joints (each VIP is wrapped up in an aluminium foil bag to seal the vacuum) the base VIP's are overlapped with another plate, also with embedded VIP. *Fig. 4.* And more, because of the EPS frame around VIP, the panels can be fixed to the wall with fasteners without having to perforate the VIP. [3] *Fig. 15.*

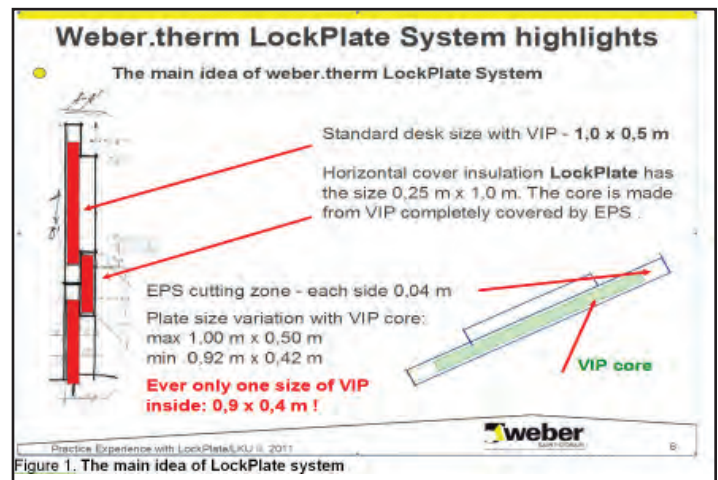


Figure 1. The main idea of LockPlate system

What Does VIP Stand For?

Vacuum Insulation Panel (VIP) has rated thermal conductivity (λ value) of around 0.007 W/mK [4], which makes them 5 to 6 times thinner than traditional insulation materials. The core material usually exists in shape of an open cell materials or fumed silica, e.g. VIPs are covered with a multi-layer barrier film to eliminate gas and moisture permeation. VIPs are typically evacuated at inside pressure below 5 mbar. Heat transfer by conduction, convection and radiation is dramatically reduced thanks to the very small pore sizes of the core material, the vacuum and added opacifiers. However, the very thin barrier film is very sensitive. Consequently, the VIP is quite fragile.

What Has Especially Been Targeted?

- Maximizing mechanical VIP protection during transportation and at the building site to avoid any damage. *Fig. 4, 5.*
- Minimizing heat flux transfer in the VIP joints - so called edge effect. *Fig. 6.*

- VIP size adjustment directly at the building site with no plate size limitation.
- Optional mechanical anchoring by fasteners, which is useful even at retrofitting. *Fig. 15, 16.*
- Minimizing the number of VIP size typologies. *Fig. 3*
- LockPlate System is ETICS in combination with VIP designed as one layer system with overlapping plate. *Fig. 5, 6.*

LockPlate System in the Building Practice

The LockPlate system components are produced in a limited number of standard sizes (0,5x1m and 0,5x0,5m for the base layer ("Panel") and 0,25x1m for the second layer ("Lock"). *Fig. 4.* This enables fast production and prompt delivery. The choice of three plate types has been made for the reason of covering every possible shape of façade. This fact is made easier because every plate has on its perimeter a cutting zone that enables easy plate size modification directly on site. *Fig. 1.* A software tool LockPlate Planner [5] is available for a tailor made lay-out of the panels on the façade. *Fig. 3.* The resulting output is a layout list for every façade, as well as a printout of plates required for production. Thus, possible errors in counting plates for the façade are being minimized. Those areas of the façade that cannot be covered by the base plates can still be overlapped by LockPlate in second layer. *Fig. 10 - 13.* This way, basically almost all shapes of façade can be properly insulated with this system. The whole LockPlate system must be applied by licensed contractors.

LockPlate at a Glance...

- Relatively thin system with very high insulating performance
- Intelligent combination of two materials and entire VIP protection by EPS
- Smart prefabrication and design software tool
- Easy plate size modification on site
- Mechanical fixation of ETICS components as usual
- Sharp thermal bridge effect reduction on VIP edges
- Verified solution from building practice
- Applicable for retrofitting and also for new building

The LockPlate System combines current applications of ETICS at building sites with the only difference that it contains embedded VIP.

This fact is a guideline of further treatment ETICS with integrated VIP because the VIP itself must be protected from mechanical perforation and because the use of VIP requires a balance about its positioning on the façades. As already mentioned, LockPlate System offers the solution of above stated problems.

Conclusion

Released intention is meeting requirements for passive houses by taking in account suggestions coming from not only designers but mainly from investors and housekeepers.

The reason is that replacing thick standard ETICS by the thin LockPlate System offers the possibility to create more inside room [6].

The LockPlate System itself has been tested at different sites where we were focussed on meeting the following targets [7, 8, and 9]. *Fig. 17.*

- Planning LockPlate System on the wall. *Fig. 10*
- Mass production of LockPlate elements and sustainably keeping their quality
- Simple application at the site while utilisation all technological steps incl. mechanical anchoring. *Fig. 11, 12 and 15*
- Appropriating the best way of communication with not only architects but also with other professions at the site

By

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Appendix

Figure 1. The main idea of LockPlate system

Figure 2. Principle of wall layering

Figure 3. LockPlate Planner

Figure 4. LockPlate composition

Figure 5. LockPlate set up

Figure 6. LockPlate filled in surface

Figure 7. Façade assessment

Figure 8. Window frame - horizontal overlapping

Figure 9. Window frame - vertical overlapping

Figure 10. Window sill insulation

Figure 11. Window sill – set up

Figure 12. Window sill insulation - overlapping

Figure 13. Plinth part

Figure 14. Construction connection

Figure 15. Mechanical fixation by fasteners

Figure 16. Scaffolding fixation in the system

Figure 17. Final coating

Appendix

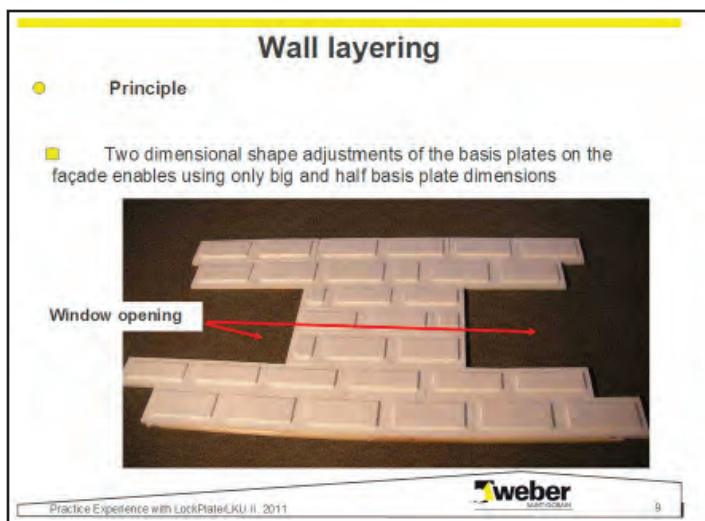


Figure 2. Principle of wall layering

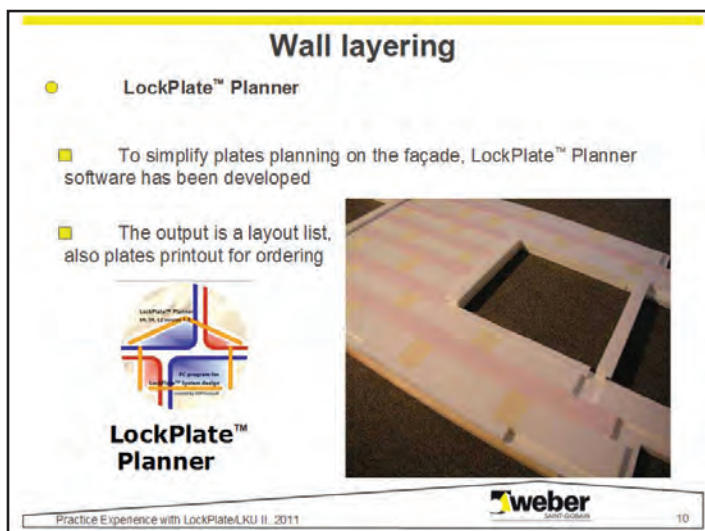


Figure 3. LockPlate Planner

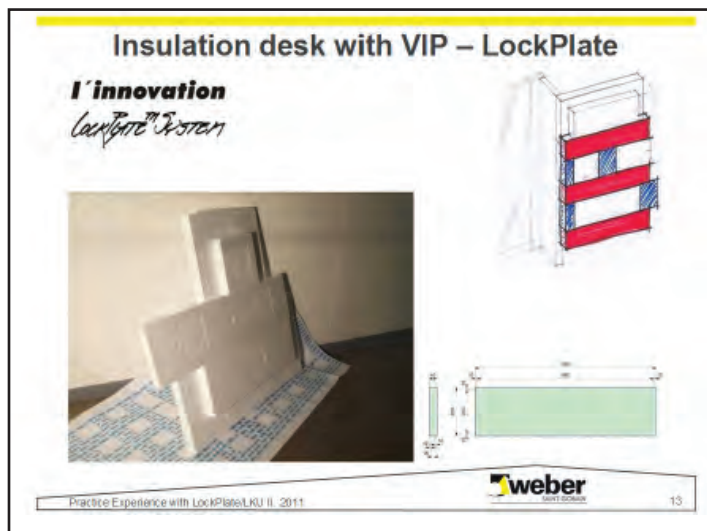


Figure 4. LockPlate composition



Figure 7. Façade assessment



Figure 5. LockPlate set up



Figure 8. Window frame – horizontal overlapping

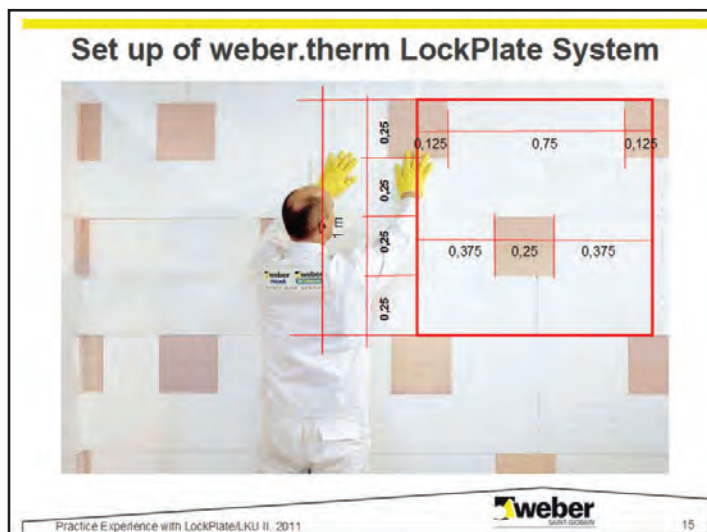


Figure 6. LockPlate filled in surface



Figure 9. Window frame – vertical overlapping

System on the window sill

- Window sill
- It is easy to use overlapping LockPlate to set up insulation layer in window sill part, e.g.



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Figure 10. Window sill insulation

System on plinth part

- Plinth part
- System on the plinth part can be completed with other high efficient insulation desks, phenol board, e.g. Water tightness must be guaranteed in the whole set up.



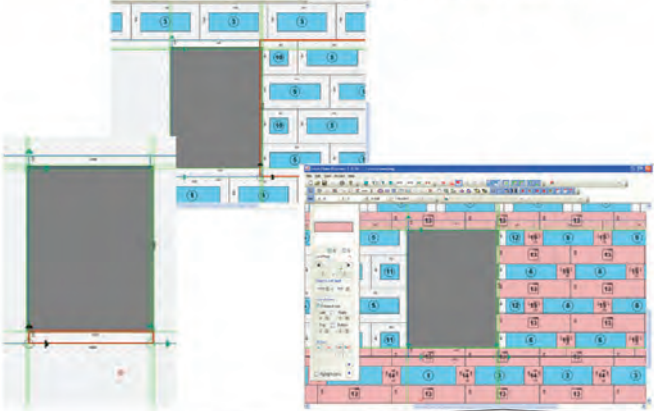
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Figure 13. Plinth part

System around the window frame



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Figure 11. Window sill insulation – set up

System connection to other construction

- Construction connection
- The system is easy to be connected to other constructions. In this case the system connection between wall insulation and wooden part is shown.



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Figure 14. Construction connection

System on the window sill

- Window sill
- The LockPlate fits exactly the gap under window sill and thus the system gets smooth and thermal bridge is completely eliminated



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Figure 12. Window sill insulation - overlapping

Fastener technique

- Fastener
- Mechanical anchoring is not a problem. On the contrary, the short fasteners can be applied around plate perimeter and finally all fastener heads are covered with LockPlate and no thermal bridges occur



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Figure 15. Mechanical fixation by fasteners

Various openings through the system

- **Scaffold hook**
 - Sectile EPS frame around the plate enables positioning scaffold hooks, e.g. Different anchoring techniques can be applied



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Figure 16. Scaffolding fixation in the system

Rendering on LockPlate system

- **Final coating**
 - Final coating on weber.therm LockPlate system doesn't differ from rendering on classical ETICS. The same application is required and can be carried out by trained & certified craftsmen trained with VIP ETICS.



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Figure 17. Final coating

Technical Session 7

Advances, Challenges and Opportunities – II

*(Session Chair – Dr. Samuel Brunner,
EMPA, Switzerland)*

Barrier Development and Evaluation Methodology

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1. Introduction

Vacuum insulation is now a rapidly expanding market and technical advances are being made quickly. One of the most important components of vacuum insulation is the barrier film. The function of the barrier and associated heat seals is to slow the increase in panel internal pressure which is directly related to the panel's thermal performance. A better barrier opens up markets that require slower decrease in performance (longer life) and potentially high temperature applications. Over three years were spent developing a more advanced barrier film and it has been used on hundreds of thousands of panels. From this development and use experience, many of the important things learned are presented in this paper.

2. Variables That Affect Performance Versus Time

The temperature and humidity on each side of the panel versus time during the transportation, storage, product manufacture and end use affect the atmospheric gas diffusion rate and the water vapor transmission rate. It should also be remembered that the diffusion through the heat seals should be determined and incorporated into the calculations. The panel dimensions need to be considered. The panel dimensions affect the seal length to panel area. The most important panel dimension is the panel thickness. The change in panel performance is linearly related to the panel thickness. A panel with twice the thickness will have half the rate of decrease in performance since the diffusing gases will go into twice the volume so the pressure rise is half. The last item is the potential damage to the barrier that can occur at any stage of the panel's life from panel manufacture through the end of the panel's useful life.

3. Accelerated Life Testing

Barriers have been for sometime at the performance where producing actual panels and testing them versus time to determine the degradation rate requires very long time and therefore is not

very useful in barrier development. It might take half a year or more before being able to get some idea if a new barrier design is beneficial. This approach was particularly a problem in the new barrier development since the research was to develop a barrier that was many times superior to the existing barriers and would take many times longer.

Mocon Oxygen Transmission Testing

Years ago, MOCON developed a Super OX-TRAN test that was stated to test down to 0.0005 cc/m²-day-bar. One of the problems is that virtually all the barrier films for vacuum insulation measure below the minimum that the MOCON test can measure. Thus it is not able to give any feedback to say if a new barrier design is improved. Some of the other issues are:

1. MOCON measures only oxygen, other gases such as nitrogen, water vapor, and out gassing from the barrier or core is not measured.
2. The Super OX-TRAN test is a steady state test. Thus it will miss transient effects that might occur immediately after evacuation. It also means that there is an inherent fixed sensitivity. Running the test longer does not increase sensitivity.
3. The Super OX-TRAN test also does not measure the diffusion through the panel heat seals.

Accelerated High Temperature and High Humidity Testing

Some organizations have used a high temperature (85° C) and high humidity (85% RH) test of full thickness test panels. If the actual application is at high temperature and humidity, this test may be a good test but most vacuum panels are used at low temperature and many are used in refrigerator or freezer walls where the relative humidity is, by design, very low. In most cases it is best to not think in terms of relative humidity but to think in terms of vapor pressure. Relative humidity is the water vapor weight in the air divided by the maximum amount the air could hold. This water vapor weight changes drastically with temperature and therefore also the vapor pressure changes

drastically with temperature. The water vapor pressure at 85° C and 85% relative humidity is about 49400 Pa. The water vapor pressure in the wall of a typical refrigerator is less than 94 Pa. This is over 500 times higher. In addition to this, the barrier diffusion rate will also increase with temperature. The exact rate is unknown but it may double for every 10° C. Between 25° C and 85° C there are six 10° increments so there might be a 64 times increase in the diffusion rate. Multiplying both together results in about 33,000 times increase. One week of this condition could be equivalent to about 634 years in a refrigerator wall. Therefore, this test was not very beneficial in the barrier film development.

Minimum Volume Accelerated Barrier Test

For the above reasons, the researchers began developing an accelerated barrier test. It was not desired to accelerate the diffusion or out gassing due to higher temperature or higher external pressure since the diffusion and out gassing mechanisms might change. The approach chosen was to utilize an extremely small internal volume (very thin panel) incorporating the panel's normal surface area and seal length. It was also decided not to try to measure the gas diffusion rate but to directly measure the panel thermal performance change (by ASTM standard conductivity testing) since this is the actual property of interest. This test captures all the degradation mechanisms that result in decrease in panel performance. It also has one more large advantage. As the test proceeds, the effect of any out gassing can be seen and the longer the test runs the more accurate the prediction. A few months of testing can predict the panel performance 10 or 15 years in the future and longer testing can provide an even longer forecast. This test allowed the evaluation of many different barrier designs. Without this test, the development would not have been possible.

4. Additional Development Tools

To rapidly investigate the many barrier design options, the barrier diffusion was modeled using computer Finite Element Analysis (FEA). With this technique it is not possible to predict the exact diffusion rate but it provided valuable insight.

5. Additional Considerations

Currently there are two major approaches to barrier films. The barrier can contain an aluminum foil layer or the barrier contains no aluminum foil.

Barrier with Aluminum Foil

1. The aluminum foil is an outstanding barrier but it can have pin holes created in the manufacturing rolling process or pin holes can be created sometimes when the barrier is folded over to tape the seal edges or other manipulation. The pin holes can lead to a catastrophic loss of vacuum but most barriers incorporating aluminum foil also incorporate a metalized film laminated to the foil. This mitigates most of the issue with the pin holes since it is no longer a through path. However there is still one major disadvantage to barriers containing aluminum foil. Heat flows along the aluminum foil and travels around the edge of the panel to the other side. This heat effectively by-passes the vacuum insulation. On very large panels this reduction in panel performance could be 20 to 25%. However on narrow or small panels the performance reduction of the vacuum panel can be about 30% to 55% or even more in extreme situations.

Barrier with No Aluminum Foil:

1. Barriers with no aluminum foil have a difficult task to create an outstanding barrier. Typically multiple vacuum metalized layers are laminated together. Sometimes chemical barrier materials are added. It is difficult but not impossible to arrive at a design that has outstanding performance and because there is no foil layer, there is no edge heat transfer that would reduce the panel performance.

6. Panel Failure

During the final evaluation and real world trial use, it is important to investigate any panel failures and determine where, why, and how the failure occurred. Once the cause is understood, a design to mitigate the problem can be developed and tested.

Helium Leak Testing

The first objective is to find the failure location on the panel. Often the panel is pressurized with helium and a “sniffer” is slowly moved around the panel until the helium is found. The “sniffer” can be based on a mass spectrometer or at less cost a detector based on the substantially different thermal conductivity of helium is used. It is a time consuming process to find the leak or in some cases multiple leaks. The areas of the leak are circled with a marker for further investigation.

Backlight Dark Room Approach

An alternate approach to finding the leaks is to remove the panel core and light the interior of the barrier pouch while in a dark room. A pin hole can sometimes be spotted. This approach is not as sensitive as the helium leak test but it is usually faster and provides the location of the leak.

Optical Microscope

Once the failure area has been found, an optical microscope can be used to try to better understand the failure. Fig. 1 is an example of the optical microscope approach. The optical microscope was of marginal benefit in the research.



Fig. 1. Optical microscope (back lit) of a barrier where there was a physical hole.

Scanning Electron Microscope (SEM)

The scanning electron microscope can be the most revealing method of understanding a failure. It can be used at very high magnification but most often it was used at magnifications about the same as could be achieved with an optical microscope. The great advantage of the scanning electron microscope was the very large depth of field (everything was in clear focus). Fig. 2 is an example of a failure location. The detail is so great that the researcher can start to build an understanding of the situation that must have caused the failure. In this case you can see the laminate layers and make assumptions as to which layers failed first.

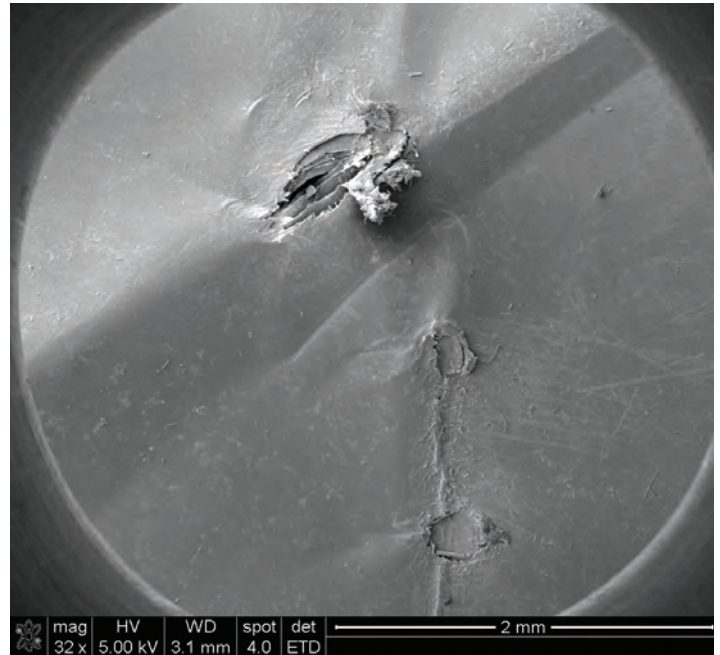


Fig. 2 is a scanning electron microscope picture of a failure.

Vacuum panel barriers can fail for many reasons. The most common reason is the barrier comes into contact with something sharp such as the corner of a steel cabinet. Generally vacuum insulation barriers should be viewed as fragile. Anything sharp will cause failure. Other failures can be caused by high stress areas such as corners and folds of the barrier. Still other panels may fail caused by items that are not really barrier failures. Moisture still left in the panel can cause reduced performance. The panel may be out of the acceptable dimensions. The panel may be damaged in shipment to the customer.

7. Conclusions

The technology to produce improved vacuum insulation barriers is increasing every day. This author expects that barrier performance will significantly improve over the next ten years. Also the abuse resistance of the barriers will improve. The better barriers will result in opening new markets and expanding existing markets. The industry is at a very steep part of the sales and technology curve and barrier technology will lead the way to success.

High Performance Steel Cladding Systems Using Vacuum Technology

R.G. Ogden, S.X. Wang, C.C. Kendrick

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1. Introduction

In the next decade, building regulations will require much higher standards of energy efficiency and improved thermal performance of building envelopes. Many conventional cladding systems will struggle to achieve the required standards. Those that can achieve the standards will see their physical thicknesses increase considerably, possibly to a level where their use may unacceptably compromise the net to gross area ratios in buildings, as well as construction density (the number of buildings constructed in a given site area).

New, more highly performing insulation materials and techniques will be required that deliver improved performance at minimum thickness. As a result, a range of advanced cladding concepts based on vacuum insulation are under investigation [1-3]. Research has demonstrated that vacuum cladding systems are unlikely to be economic for U-values of 0.2 and higher, as these are within the practical ability of conventional insulation materials. However, where U-values lower than 0.2 are required, and certainly where U-values are required in the range 0.15 to 0.05, very significant benefits can be achieved due to: a) the relative physical thinness of panels (circa. 15%-25% of conventional solutions), b) economies arising from the consequent space saving and c) the inability of competing materials and solutions to offer viable cost effective solutions.

This paper investigates a novel steel cladding system using vacuum technology in terms of thermal modelling. The results revealed the panel can deliver low U-values.

2. Concept of the Panel

Atmospheric pressure exerts a compressive force of about 10 tonnes per square metre. In order to prevent vacuum panels from collapse, powders or foams are commonly used to fill the cores of conventional flat vacuum panels to resist crushing. These fill materials however compromise thermal performance by introducing heat transfer paths through panel. To avoid these effects, a solution has been developed that features a pressure resistant oval steel core, which is illustrated in Fig. 1. Key features for this panel are: the hollow shape used to resist crushing, no

outgas from fill materials, the vacuum core has polyurethane applied to the outside to form a finished panel that is rectangular in shape. Thin steel sheets are applied to the outside surfaces for protection. The vacuum largely eliminates convective heat transfer as well as thermal conduction, so that only radiative heat transfer remains. Low emissivity treatments on the casing surfaces reduce radiative heat transfer to a low level.

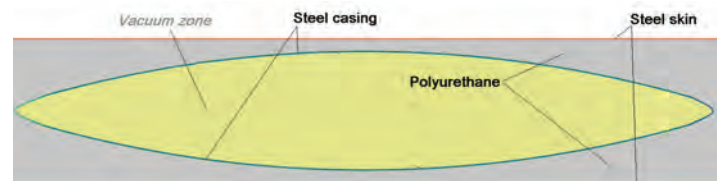


Fig. 1: Concept of a new vacuum panel

3. Thermal Modelling

In order to investigate the thermal performance of this new vacuum panel, thermal modelling was conducted by means of two-dimensional finite difference analysis using BISCO software from Physibel. The boundary conditions of fixed temperature apply on each side (top and bottom in this paper) of the panel. Heat flow through the panel across these two temperature zones was calculated and therefore the equivalent U-values were obtained. Different combinations of parameters were selected for the modelling, such as panel width, full panel thickness, core casing materials and emissivity of the inner surfaces. The following sections will discuss how equivalent U-values change due to combined variations of geometrical dimensions, materials and surface properties.

3.1 Low emissivity inner surfaces

The surfaces surrounding the vacuum zone were originally treated with shiny low-e treatment with emissivity of 0.05. For a further reduction of radiation between them, a value of 0.03 was modelled as well and compared with emissivity of 0.05, detailed in Fig. 2. The emissivity of a material (usually written ϵ or e) is

the relative ability of its surface to emit energy by radiation. It is the ratio of energy radiated by a particular material to energy radiated by a black body at the same temperature. Emissivity is a dimensionless quantity. A true black body would have an $\epsilon = 1$ while any real object would have $\epsilon < 1$. In general, the duller and blacker a material is, the closer its emissivity is to 1. The more reflective a material is, the lower its emissivity. As a reference, highly polished silver has an emissivity of about 0.02.

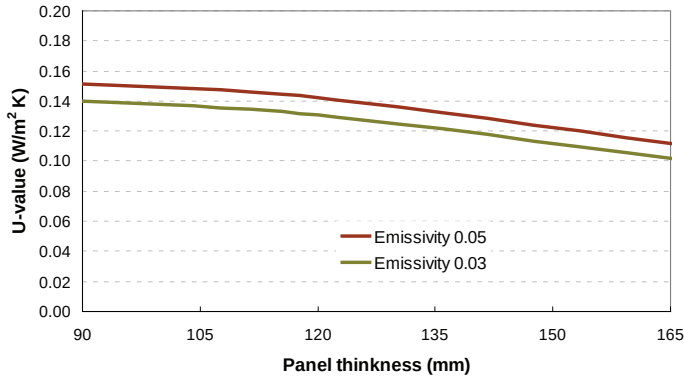


Fig. 2: U-value comparison between two low-e surfaces

Taking two infinite parallel plates (same properties) as an example, the net radiation loss rate can be obtained if the Stefan-Boltzmann Law is used:

$$q = \epsilon \sigma A_c (T_h^4 - T_c^4)$$

Therefore, heat exchange is proportional to emissivity of the surfaces. In this study, about 7% reduction of U-value was obtained while using a 0.03 emissivity value instead of 0.05.

3.2 The relationship between panel width and thickness, and thermal performance

Increasing the width of panel requires greater load carrying capacity in the casing and since the geometry of the arch becomes flatter, that is a lower rise to span ratio, stability is more difficult to achieve. Wider panels however have a better thermal performance as edges have less effect on the whole panel. As can be seen from Fig. 3, the U-value changes from about 0.11 to 0.07 when doubling the width of a 165 mm thick panel.

Panel thickness also has a strong influence on U-values. Increasing a panel from 90 mm to 165 mm thick while using 600 mm width, reduces the U-value by 30%.

Acknowledging these variables, panel U-value changes from about 0.15 to below 0.07 when the panel shape changes from the thinnest narrowest to the thickest widest. This is illustrated in Fig. 3.

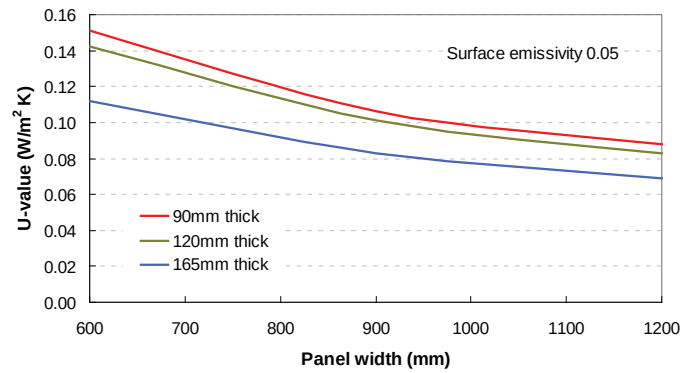


Fig. 3: U-values vs panel dimensions

3.3 Comparison with whole PUR composite panel

A comparison between this vacuum panel and polyurethane composite panel was made on the basis of different panel widths and thicknesses and assuming the casing being made from stainless steel with a surface emissivity of 0.05. The results are shown in Fig. 4.

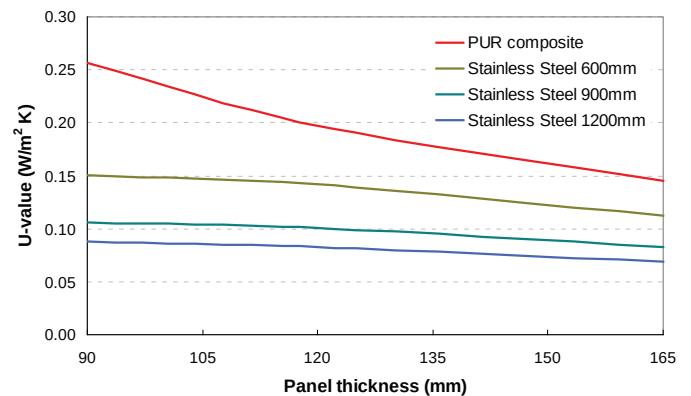


Fig. 4: Compare with polyurethane composite panel

Comparing this vacuum panel with PUR composite panels, a greater difference in U-values can be observed in the case of thinner panels. Taking a 600 mm width panel as an example, the U-value of this panel is almost half that of the PUR composite panel when 90 mm thickness is selected. However, for panel thickness of 165 mm, the U-values for both panels are much closer. Accordingly, there is more benefit in using this new vacuum panel when a thin wall is required.

3.4 Effect of individual parameters

Fig. 5 shows the U-value changing with the individual parameter changes. The base case shown in the figure is the panel 600 mm wide, with 0.05 emissivity, carbon steel casing. The other bars except 'Best' in Fig. 5 present the U-values when only one change to the base case is made as described. The last, 'Best' shown in the graph assumes all of these changes combined, i.e. the panel with: 1200 mm width, 0.03 emissivity and stainless steel casing. The percentage figures on top of the bars stand for U-value reduction rate for each case comparing to the base case.

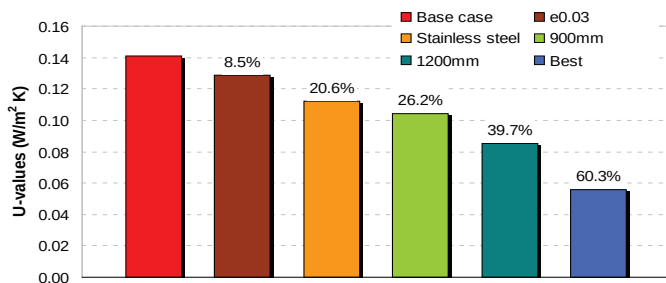


Fig. 5: U-value vs individual parameter change

Increasing the panel width is the best method for improvement, with almost a 40% reduction of U-value. The overall best case yields in excess of a 60% U-value reduction in comparison with the base case.

4. Conclusions and Further Developments

The concept of a novel vacuum panel was introduced in this paper. It is an innovative idea for making VIP without supporting fillers that usually provide stiffness for conventional VIPs, such as powders or foams. The advantages of this concept compared with conventional VIPs include:

- Absence of filling materials. There is no thermal conduction through the space, and no outgas, which is normally released from filling materials.
- Low-e treatment on surfaces surrounding the vacuum chambers. This reduces the radiative heat transfer.

Two-dimensional thermal modelling was carried out on this concept to obtain equivalent U-values of whole panel, a criterion for panel performance estimation and panel selection. The modelling results showed that low emissivity surfaces contribute to reducing radiative heat transfer between surfaces in an effective way. In addition, the equivalent U-value of the whole panel can reach as low as 0.056 W/m² K when the best scenario for this

panel was selected. Compared with polyurethane composite panels with the same overall external dimensions, the new vacuum panel provides greater U-value reduction when thinner panels are required.

It is anticipated that further work will be carried out on this concept and will concentrate on investigating the joint design, psi value and establishing a whole façade thermal performance based on this concept.

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CSI Elevated Temperature Conductivity and Rapid Conductivity Test Method

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1. Introduction

Century Super Insulation (CSI) being developed for building construction applications 1) provides an *effective* R56.8 US (10 RSI or 0.10 U) from a panel less than 1.5" (40mm) thick; 2) maintains R-value over the 50 to 100 year service life of the building without refitting; 3) survives both the construction and normal service environments; and 4) will prove affordable and practical to the builder contractor or owner.

CSI VIP (vacuum insulation panel) is comprised of a proprietary glass microfiber core encased within a durable hermetically welded stainless steel foil vacuum envelope. The core microfibers are constructed from borosilicate glass containing no submicron fibers. Panel sizes for construction are projected to be standardized at 18" (450mm) width and available in lengths from 18" (450mm) up to 72" (1830mm). Expected volume pricing of Century is planned to be below \$4.40/ft² (£29/m²).

This paper presents information on CSI elevated k factors and a new rapid k test.

The CSI construction designs provide for a very wide service temperature range of from cryogenic up to 800 degrees Fahrenheit (427°C) mean temperatures. This temperature range is possible due to the robust materials used in its construction and process. Predictions for the high temperature thermal conductivities (k) of CSI are presented in this paper. A high quality mass production process has been developed for CSI which provides the economy of scale necessary to drive the panel cost and price to attractive levels. One crucial item identified early on was the need for a fast accurate portable test method for thermal conductivity. None existed. The rapid 100% inspection method under development now for CSI thermal conductivity quickly determines this important property at the point of manufacture. In addition, the test is simple and straightforward enough that it can be used out in the field during CSI installation. Monitoring of CSI panels over time within the insulation envelope is also possible. The basics of the method rely on the heat transfer property of thermal effusivity, or the unsteady exchange of heat from a hot object to

the CSI panel. Initial test results are provided in this paper for four stainless foil clad VIP panels. The data predict the true ASTM C 518 or ASTM C 177 thermal conductivities at the room mean temperature condition.

The results presented here show that CSI has excellent high temperature properties, best in class. The new effusivity test method shows high promise as a rapid and accurate method for the determination of center of panel thermal conductivity of CSI panels. In addition, the new test method also holds promise as a predictor of thermal conductivities at cryogenic through elevated mean temperatures.

2. Estimated CSI Elevated Temperature Thermal Conductivity Performance

2.1 Thermal Conductivity of Commercial Glass Microfibers vs. Temperature and Density

No high temperature test data for CSI are available at this writing. Thus, the exercise focused on finding suitable atmospheric pressure product data and estimating performance using expected behavior under vacuum at elevated temperatures.

The internet was searched for thermal data on this subject at atmospheric pressure. The results are shown for one manufacturer, Johns Manville in Figure 1. The data were given in tabular form for a product called Microfelt B, which are the data points shown in bold, and a product called AA Microlite which are the other lower density points shown. The binderless Microfelt is closest to the glass fiber of the CSI product in fiber diameter and density. However, the densities shown for Microfelt B are lower than CSI designs which will typically range between 14 lb/ft³ and 18 lb/ft³.

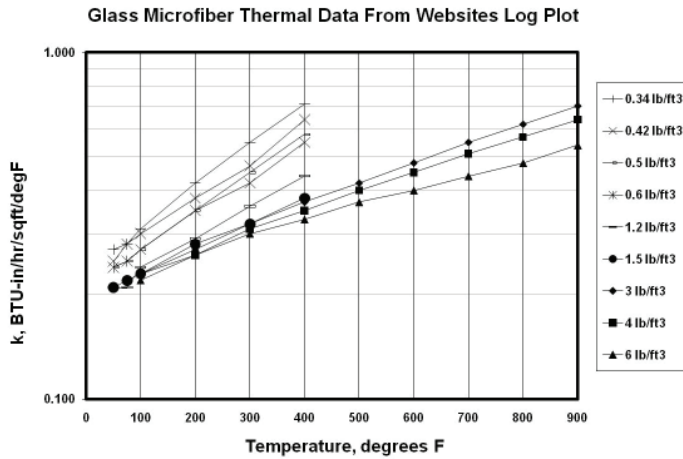


Figure 1. Response Plot k Versus Temperature at Atmospheric Pressure

The data were plotted as log k versus temperature from the author's experience that k versus temperature is typically a linear function for glass fiber mats. This is seen to be the case for these data. What was needed next was a method to perform the extrapolation to the heavier glass fiber core mats such as used in CSI.

2.2 Microfiber Slope Analysis

To accomplish this extrapolation, first the linear fit slopes of each of the microfiber products were calculated through data analysis. The slopes of the data reflect the change in k with temperature. These slopes are plotted against mat density in Figure 2. The results of this curvefit show that the change in k with temperature (slope) reduces with increasing mat density. This trend is consistent with glass fiber mats in general. From the physics the slope should diminish rapidly as mat density increases. The reason for this trend is that the radiation conductivity component extinguishes faster than the solid conduction component increases.

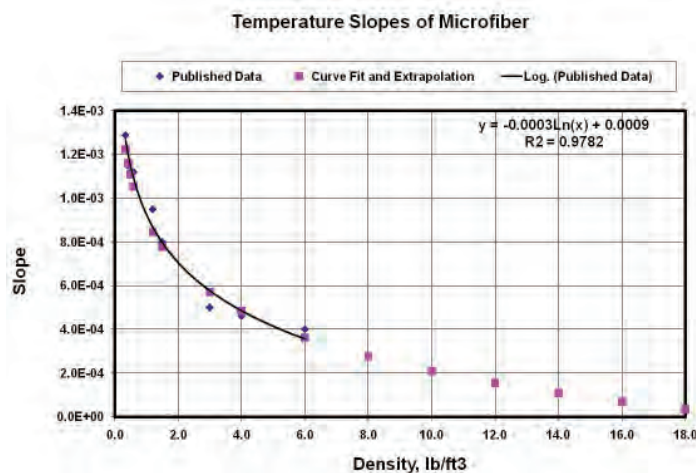


Figure 2. Slope Curvefit for Atmospheric Pressure Microfiber Data

2.3 Combining Slope Data into Mathematical CSI k Performance Model

The next step in the process was to combine the slope information learned from the published microfiber data with the author's proprietary mathematical model of CSI at ambient mean temperature and at or below 0.01 Torr pressure. The slope at the limit of the published data was used and is considered conservative for this analysis.

The results of this process are shown in Figure 3. Note that by using the slope information of Figure 2 combined with the room temperature math model, the thermal conductivity trend of the CSI panel is seen to increase with mean temperature. This is an expected result. Further, it appears that the lower density CSI has better (lower) thermal conductivity than the higher density CSI. The explanation for this is that at the higher CSI densities the solid conduction k component of the mat begins to come into play more predominantly. The bold data points are consistent with the typical densities of CSI panels.

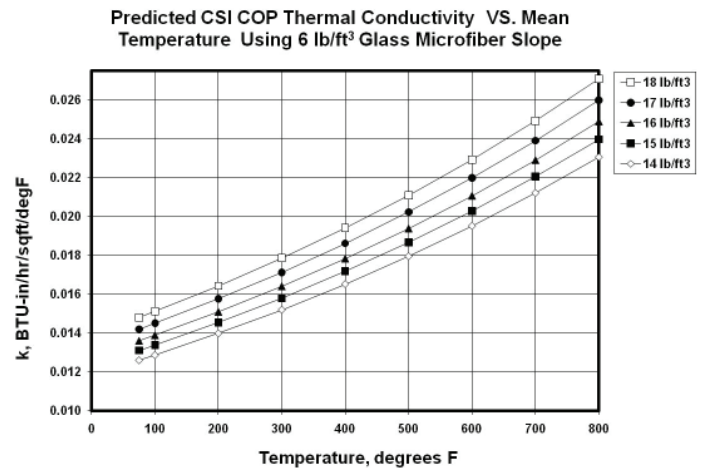


Figure 3. Expected Thermal Conductivity of CSI versus Mean Temperature and Density

These predicted results need to be confirmed using high temperature k factor data. Sufficient data will be gathered and reported on once sufficient panels are available for this purpose.

3.0 Rapid Thermal Conductivity Test Method Development

3.1 History of Method

This method came about from the author's auspicious observation that a very hot metal foil skinned VIP once evacuated and sealed could be easily handled by bare hands with *no pain* right out of the oven. The only explanation for this behavior is that the heat within the low thermal conductivity hot VIP transferred very slowly from the VIP into the author's higher thermal conductivity skin. By reversing the direction of the heat transfer the author postulated that it might be possible to infer the thermal conductivity implicitly by studying the resulting unsteady state temperature profiles at the hot surface/VIP interface. Clearly a precise quantity of heat energy from a high conductivity massive object transferred into the CSI panel over time at known room temperature would be needed to form the foundation of the method. Whether this method would be sensitive enough to forecast the very low thermal conductivities of CSI panels was unknown.

The author over the years has explored many novel steady state thermal methods in pursuit of a fast k test but none were found to have the level of precision necessary to be able to predict the property consistently or accurately. Proven steady state methods such as ASTM C 510 or ASTM C 177 are precision methods but take a great deal of time, hours to get a sufficiently accurate result. That fact precludes testing 100% of the panels and reliance on statistical methods must be used.

The method of choice explained here is an unsteady state method and borrows from the theory of thermal effusivity of two objects. There is a great deal of mathematics involved that is beyond the scope of this paper. Suffice it to say that the method described appears to show a reasonable agreement at this early stage of development. What follows is a brief explanation of the hardware and some test results.

3.2 Hardware System

The heart of the system is the heated puck. The body of the puck is fashioned out of 2 aluminum disks connected with a plastic ring to provide an inner volume. This volume is filled with a high temperature Thermolyne Briskheat 418 W heating strip coiled up to provide heat to the bottom disk. The disks are instrumented with fast response K type thermocouples to monitor temperatures. An insulated handle is attached to the top of the puck to allow it to be placed either on top of the foam rest during heat up recharging or on the test panel.

The puck is connected to a precision Partlow MIC 6124101 heat controller through an SCR relay. Puck setpoint temperatures are controllable to within 1 degree with this setup. The output of the puck and controller are monitored, recorded to data files, and controlled with a LabVIEW VI program written for this test method. A National Instruments cDAQ -9174 is employed to interface between the puck and computer. An NI 9213 thermocouple module provides the interface between the thermocouples and the cDAQ. Figure 4 are some photo shots of the system shown while testing a panel.



Figure 4. Rapid Thermal Conductivity Tester

3.3 Test Samples

Four vacuum panel samples were subjected to the new test using the hot puck method; Panels 250A, 250B, 250C, and 250D. Panel 250A refers to a 17" (432mm) x 21" (533mm) stainless foil skinned panel with known thermal conductivity (resistivity R/in 74.2 US). Panel 250B is the same size as 250A but with unknown thermal conductivity. Panel 250C was a much larger panel 21" (432mm) x 35" (890mm) also with unknown thermal conductivity. Finally panel 250D was a small panel of size 250A with known thermal conductivity (resistivity R/in 4.5 US). Panel 250D was a ventilated panel.

3.4 Procedure and Temperature Signals

The basic procedure was unchanged in testing the 4 test sample panels. First, the puck was allowed to heat up and stabilize before and between runs until within + or - 2 degrees Fahrenheit of setpoint 250 degrees Fahrenheit. The puck was placed on a thick piece of urethane foam to provide isolation. The data system was started once this criterion was met. Temperature data was recorded every second for approximately 1 minute at this stage of the test. The purpose was to have a record of the stability of the heat energy in the puck.

Once the temperature was stabilized the puck was quickly placed on the top surface of the specific test panel. Care was taken to align with the center of the panel. The weight of the puck was sufficient to provide good thermal contact with the flat stainless steel foil surface. Once the puck was placed onto the panel surface the power to the puck was switched off. The data system continued to record temperature data for an additional 300+ seconds. Total test event time was approximately 400 seconds. Figure 5 shows the thermal history for each of the tests.

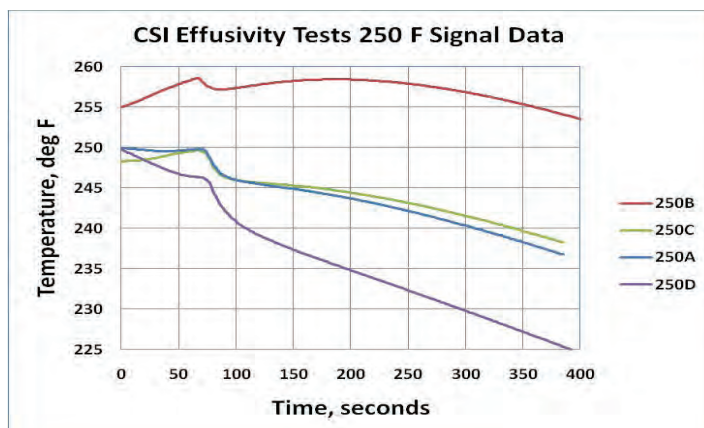


Figure 5. Temperature History Data for Four Stainless Foil Panels

It is apparent from examination of the data of Figure 5 that there are differences and similarities between the various panels. Two are widely divergent and two are close together. One would expect a negative slope for any panel tested since the heat from the puck must travel into the panel and ambient surroundings via a combination of radiation, conduction, and convection. The ventilated panel 250D appears to have the highest negative slope and thus is absorbing heat quickest from the heated puck (turned off). It has the worst thermal conductivity performance. Panel 250B shows a situation where the panel absorbs heat very slowly compared to the others indicating it may be the best of the lot. Panels A and C show a similar trace. This may infer that their thermal conductivity is also similar since they are of identical construction, only different lengths and widths.

It is also apparent from these data that the stability of the puck is slightly different for each test. Observe the data between 0 and 75 seconds. For example, the pucks for 250B and 250C appear to be increasing in temperature at the start of the test whereas 250A is stable and 250D is decreasing. The impact of this instability on the test is as yet unknown. Better control of the puck temperature prior to the start of the test is an area to be explored.

To block that effect from the data analysis the temperature history data was replotted with the data from 0 to 100 seconds removed. This is shown in Figure 6. The straight line slopes from these data were calculated and are plotted as shown.

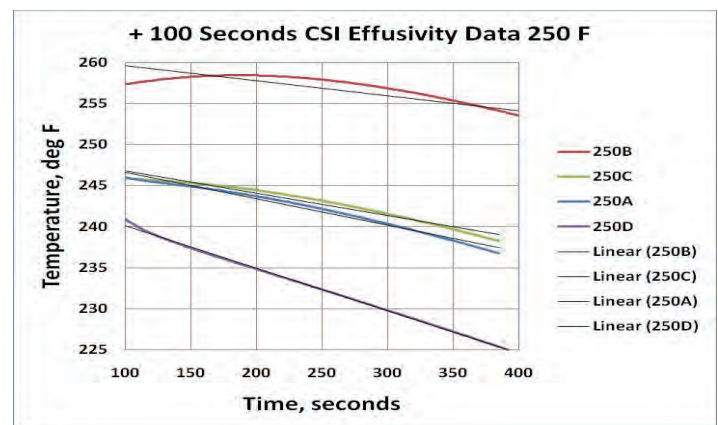


Figure 6. Temperature History Data at 100+ Seconds

3.5 Data Reduction and Analysis

Finally, in order to show the power of this rapid method the approximated cooling slopes from each test were compiled along with the thermal data from the two known test panels 250A and 250D. Since it was unable to determine curvature for this limited data set, a simple linear fit of the data was made. The results are given below in Figure 7.

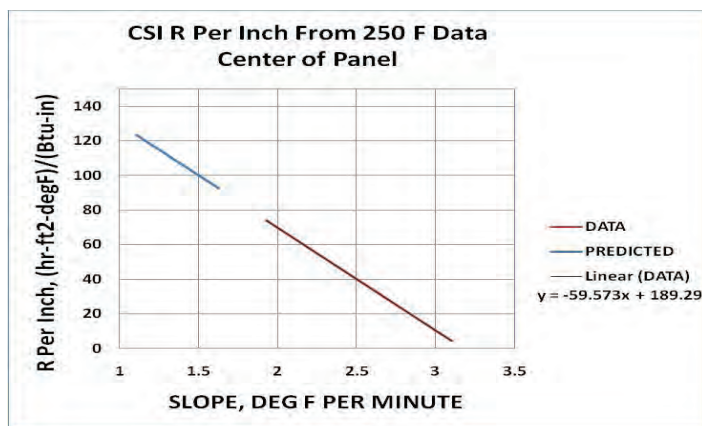


Figure 7. Estimated R per Inch from Effusivity Data

Based on the test results shown it is reasonable to assume that panel 250C has an R per inch of 92 US while panel 250B has an R per inch of 123 US. Further repetitive testing of panels is required to establish full confidence in this method. However, these early results show promise.

The total test time excluding the puck heat stability portion is under 300 seconds, or 5 minutes. This is close to being an acceptable time frame for rapid k testing with routine traceable calibration to the proven test methods, ASTM C 518 and/or ASTM C 177. It is very likely that even faster test times are possible given some tuning of the puck design and heat control system.

It should also be quite possible to use variations of the puck method to estimate thermal conductivity for CSI panels at many other temperatures.

4. Conclusions

Century Super Insulation (CSI) is currently being developed primarily for buildings and construction applications. CSI is also a very versatile VIP platform that can be designed into a variety of difficult applications where conventional VIP cannot be used.

CSI VIP current design is compatible with any climactic condition from very cold to very hot. This paper also shows that there is great potential for using CSI at extreme temperatures. The predicted elevated temperature performance of CSI panels is best in class. This implies that thermal protection and energy savings covering a wide range of temperatures between cryogenic and high temperatures are possible.

The rapid thermal conductivity test method shows great promise. It will be an essential part of the process of manufacturing CSI panels and allow 100% quality control.

5. Acknowledgements

The primary author wishes to acknowledge the efforts of three individuals. Much gratitude goes to teacher wife Mary Chris for her outstanding teaching of common sense during this exercise. Sustainable Architect co-author daughter Samantha Rusek provided quite heated and invaluable discussion on the benefits of the puck method for testing CSI in the building environment. Finally, sister Carolyn deserves credit for her unwavering commitment to CSI.

6. Appendix of Conversion Factors

Density 1.0 lb/ft³ = 16.0179 kg/m³

Pressure 1.0 Torr = 133.322 Pa

Temperature 75.0 deg F = 23.89 C

Delta Temperature Δ 1.0 deg F = 0.555 K

R-Value 1.0 R (US) = 0.1761 RSI

U-Value U (US) = 1/R (US) and U (SI) = 1/RSI

Resistivity 1.0 R per inch = 6.9348 mK /w

Thermal conductivity 1.0 Btu-in/(hr ft² deg F)
= 0.1442 w/(m K) = 144.2 milli-w/(m K)

Quality Control of Vacuum Insulation Panels: Measurement of Internal Pressure and Moisture Content in High-Volume Manufacturing

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Abstract

As vacuum insulation panels have gained acceptance in higher-volume applications, the interest in efficient product validation techniques has grown. While laboratory evaluations often involve long-term calorimetric study, inspections for product acceptance typically rely on visual inspection and pressure measurement. Pressure measurement is an important tool for quality control, since handling, storage conditions, installation practices, as well as manufacturing defects can lead to vacuum decay at various rates. As a high-volume manufacturer of silica-core VIPs using a variety of barrier films, Nanopore has developed efficient methods for reliable measurement of pressure and moisture content. In this paper, we will present empirical product validation data from the manufacturing process and discuss the challenges associated with prevailing quality control methods.

1. Introduction

The advantage of Vacuum Insulation Panels (VIPs) as thermal insulation has become well known: Compared with traditional materials such as fiberglass or polyurethane foam, the insulating value (R-value) of a VIP may be as many as twelve times higher. It is also generally understood that while most insulation degrades over time, a VIP presents a special case in that its continuing performance depends upon the integrity of its internal vacuum.

As the internal pressure of a VIP rises to atmospheric pressure, whether because the envelope has been breached, or in consequence of the slow permeation of gas over time, its thermal conductivity will rise to an ultimate value near 18 mW/(m.K). In this condition, it remains superior to free air (as well as polyurethane foam and fiberglass) because of the Knudsen diffusion effect associated with the very small pores of the silica core. Nevertheless, such a VIP will have lost 80% of its insulating value.

While many factors contribute to VIP performance (size, density, pore size distribution, opacity, etc.), most of these are fixed

during the manufacturing process. The fragility and perishability of a VIP are determined solely by the continuing performance of its vacuum barrier envelope.

2. Selection of the Vacuum Barrier

Among VIPs intended for long-term service, the vacuum barrier will usually incorporate metal layers in order to retard transmission of gas and water vapor. Improvements in VIP longevity thus occur at the expense of effective thermal conductivity due to heat conduction through the barrier at the edges of the VIP. In the context of product validation testing, manufacturers and system designers routinely confirm the effective conductivity of specific VIP configurations. (Effective conductivity as a function of VIP dimensions and barrier linear thermal transmittance has been studied extensively by others.) It is interesting to consider two panels identical in size: one fiberglass-core VIP encapsulated using a six micron aluminum layer and one silica-core VIP encapsulated by a multi-layer laminate containing only ~0.3 microns total metal. By testing the panels successively as components of a closed system (incorporating a phase-change material), we may detect the shift in performance as shown below (Fig.1).

Temperature Profiles

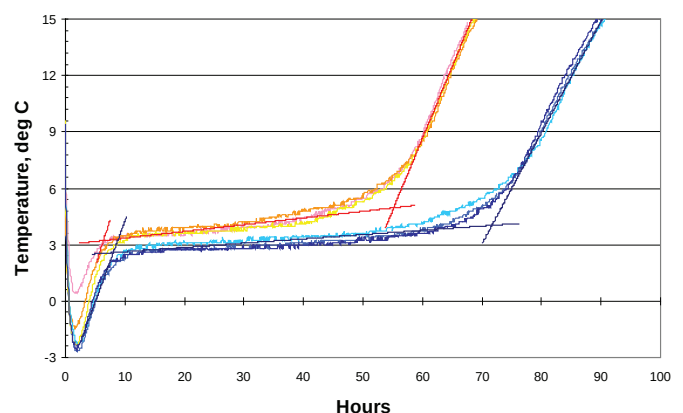


Figure 1: Time to Temperature Profiles: FG=fiberglass, NPI=silica

Because dimensions, differential temperature and heat of fusion are known, the time required for phase change can be used to calculate the effective thermal conductivity. (Extrapolated line segments aid in determining the elapsed times.)

Although the fiberglass VIP has a lower center-of-panel conductivity, its effective performance is degraded dramatically by the thicker aluminum layer of its barrier film (see Table 1). A barrier's contribution to effective conductivity increases with the ratio of perimeter to area, such that it becomes dominant for very small VIPs. For this reason, many VIPs intended for use at moderate temperatures employ a multi-layer thin-metallization laminate in spite of the higher associated gas and water vapor transmission rates.

Table 1

Thermal Conductivity, mW/(m.K))	Fiberglass Core in High-Metal film	Silica Core in Low-Metal film
Center-of-Panel value measured by ASTM C518	2.21	3.69
Effective VIP Thermal k, system analysis	8.20	4.88

3. Quality Control Measures

While a variety of machine and process control methods are employed during VIP manufacturing, the fragile nature of the vacuum barrier necessitates rigorous post-production quality control. Handling, storage conditions, installation practices, as well as manufacturing defects can each affect the rate at which the product vacuum will decay. Generally, the non-destructive methods used to detect failures in the vacuum barrier may involve: bench testing for internal VIP pressure, product quarantine to allow a sufficient interval for detection of VIP pressure increase, visual inspection, high-temperature exposure, or monitoring by product validation sensors (e.g. thermocouples, pressure transducers, thermal gauges, etc.) incorporated into the finished product. A typical pressure testing apparatus is described in Figure 2:

The VIP is placed in a vacuum chamber and pumped down under controlled conditions.

When the chamber pressure falls below the internal VIP pressure, the envelope film will lift away from the VIP core. With care, the pressure at which the film lifts can be repeatedly measured to within a fraction of one mbar, so that this may comprise a satisfactory measurement of VIP pressure.

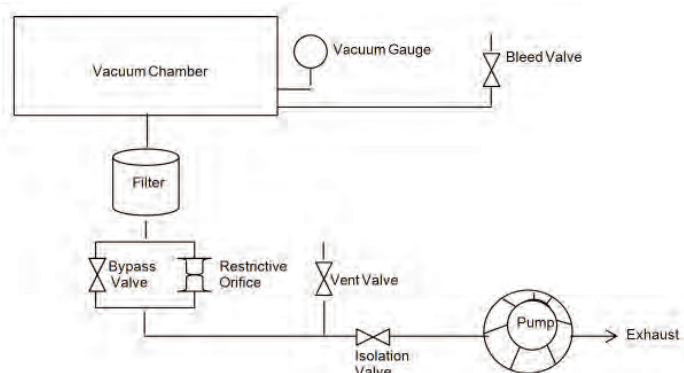


Figure 2: Schematic of Pressure Test Apparatus

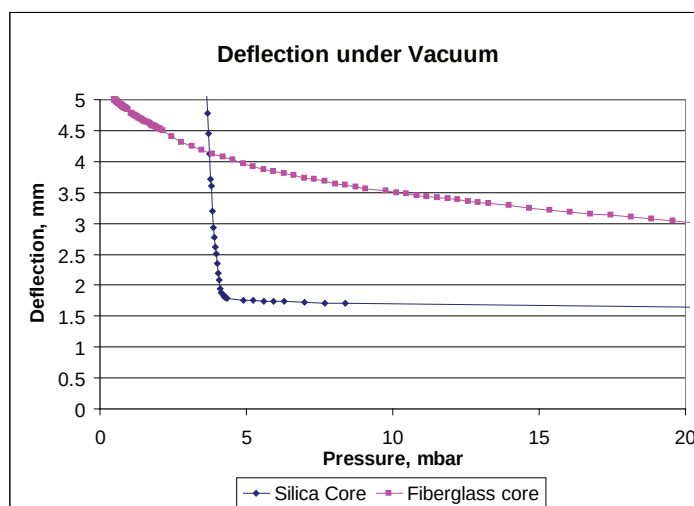


Figure 3: Silica VIP film lift at 4.1 mbar; Fiberglass VIP film lift not apparent

While pressure testing via the film-lift method is indispensable to quality control of most silica-core VIPs, the usefulness of the technique with other core materials is often limited. Figure 3 illustrates the difficulty in measuring the internal pressure of a fiberglass VIP. Whereas film lift from the silica core is quite distinct, the low modulus and low pressure of the fiberglass core combine to prevent detection of film lift in the range of interest (which for fiberglass VIPs extends well below 1 mbar). Of course, the use of getters may further complicate pressure testing, as any pressure rise will be a function of the getter absorption rate as well as the barrier leak rate.

In practice, product quarantine times must be combined with pressure testing to insure that smaller leaks are detectable. Small leaks tend to be associated with defective heat seals, however when appropriate engineering controls are in place, such leaks remain highly detectable. The heat seal shown in cross-section below (Figure 4) contains a 50 micron capillary which would generate a pressure rise sufficient to be detectable within a matter of hours.

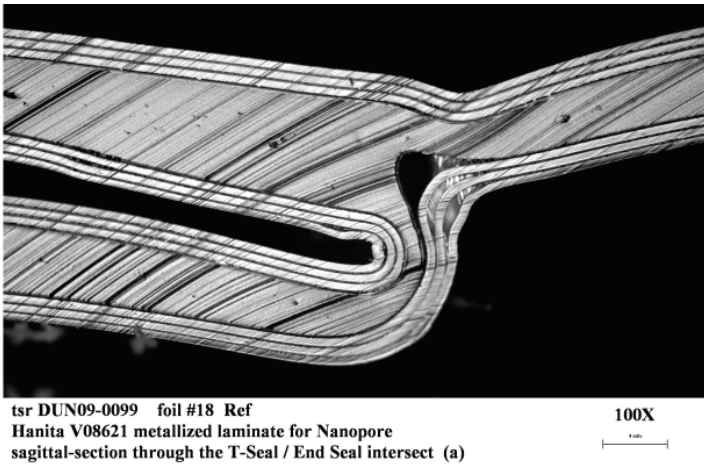


Figure 4: Cross-sectional micrograph of a defective seal

Since heat seal leaks are easily prevented by machine-level process controls, the more common mode of film failure results from puncture, abrasion, or excessive local stress. Usually such failures appear as pinholes (as shown, Fig. 5).

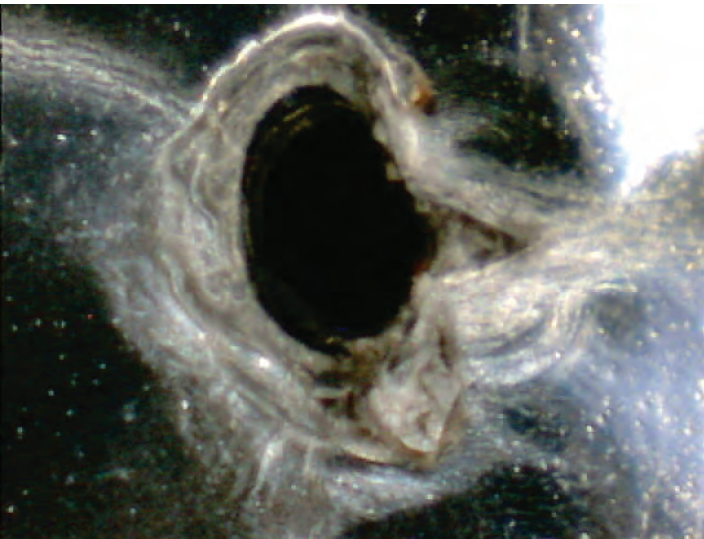


Figure 5: photograph of 400 micron pinhole

As pinhole leaks tend to be large, it is sometimes assumed that, once a sufficient quarantine time has passed, they may be detected by visual inspection alone. However, the restriction of air flow between layers of compressed film can become a complicating factor.

An illustrative experiment uses hypodermic tubing to form a calibrated leak. The 100 micron internal diameter tubing is cut to standard lengths and embedded into the vacuum seal of several VIPs. In some, the tubing reaches the core, while in others it is separated by a length of flap under vacuum. Because the two layers of barrier film are under compression by atmospheric pressure, the effective flow rate is reduced by nearly two orders of magnitude (shown below, Fig. 6).

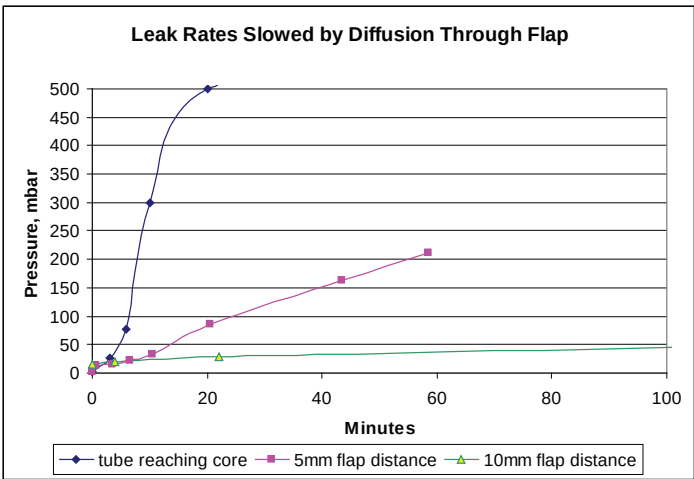


Figure 6: Leak rates depressed by travel between film layers

In this example, the VIPs under test are less than one half liter in volume. Under the same flow conditions, the pressure of the largest VIPs in common commercial usage would be expected to rise at a rate 50 times slower. If we take the 100 micron orifice separated from the core by a 10mm flap length to represent the worst-case for detection, then we can predict the necessary quarantine hold times as a function of VIP size and detection sensitivity (see below, Table 2).

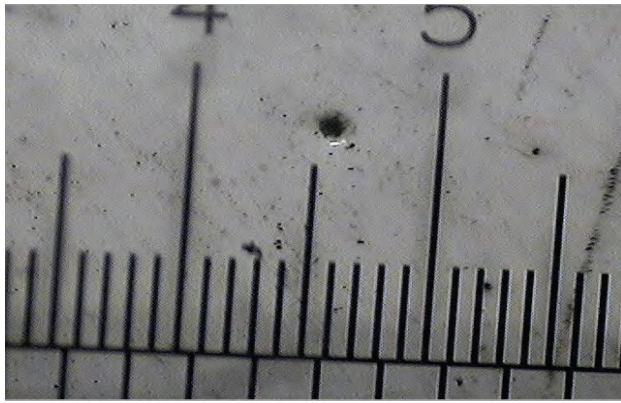
Table 2

<u>VIP size</u>	<u>Volume, liters</u>	<u>Minutes to film lift: detection @ 1mbar sensitivity</u>	<u>Hours to film lift: detection @ 10mbar sensitivity</u>	<u>Days to visible loose film ~800mbar</u>
10x200x200mm	0.4	1	1	1
25x400x400mm	4.0	10	4	10
25x800x800mm	16.0	40	17	40
25x900x900mm	20.3	51	21	51

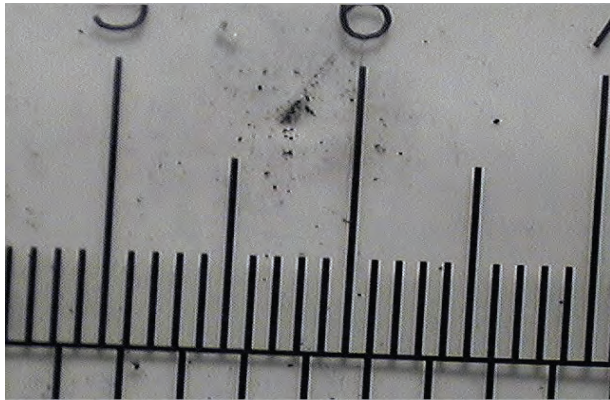
It is unfortunate that most trauma does occur at the corners of a VIP where barrier film flaps are present. In manufacturing practice, it is often apparent that the quarantine wait times suggested by Table 2 are not overly conservative.

These realities have important implications for the end-users of VIPs. It is sometimes assumed that once a lot of VIPs passes a quality control inspection for pressure, any subsequent film failures will be large enough to be easily detectable. But if the user relies solely on visible relaxation of the film, even large leaks may not be readily detected without extended observation times.

A further complication is presented by partial-puncture defects (below, Fig.7)



Open hole – vents within hours



Closed hole – stable for months

Figure 7: 100 micron puncture defects

In the worst case, such a defect may reseal itself almost completely, only to reopen when film tension is increased (as by thermal contraction at low temperatures). Visual inspection is certainly capable of identifying larger punctures, but smaller defects (as those shown) are typically located only by destructive testing. Hence, prevention of such defects by secondary packaging or encapsulation (and avoidance of sharps throughout the product lifecycle) is of the highest importance.

4. Temperature Effects

Assuming that VIPs under study are known to be dry and are measured under consistent conditions, temperature effects can usually be ignored. However, product validation often involves elevated temperatures that may complicate pressure analysis. When significant water is present, VIP pressure becomes a strong function of temperature (as shown, Fig.8).

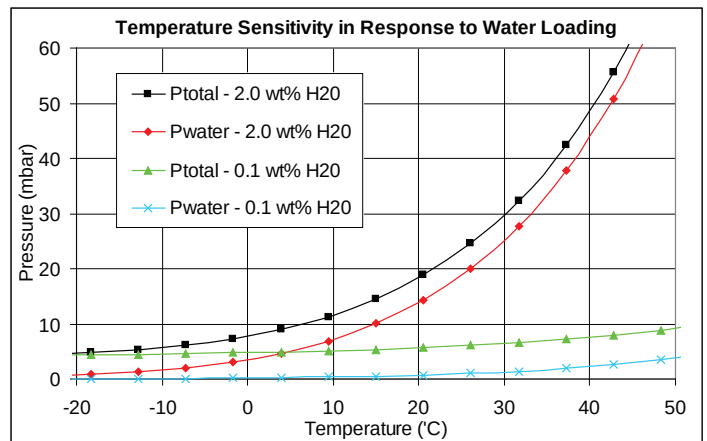


Figure 8

Since VIPs accumulate moisture as they age, consistent temperature control becomes more important for older VIPs. If sufficient care is taken to establish equilibrium at multiple levels, the ideal gas law and Antoine equation can be used to calculate the partial pressure of water.

As films are exposed to higher temperatures, they will tend to relax and conform to the shape and texture of the core. The effect is often noticeable in pressure testing, and for thinner VIPs, this may even prevent visual detection of failures at ambient pressure.

Whenever approaching the maximum operating temperature of a laminated film, the risk of delamination should be considered. Especially with prolonged exposure at higher humidities, such failures as shown in Figure 9 begin to emerge. Typically, the seal layer will remain intact so that the subsequent pressure rise will be limited only by the gas transmission rate of the seal layer.

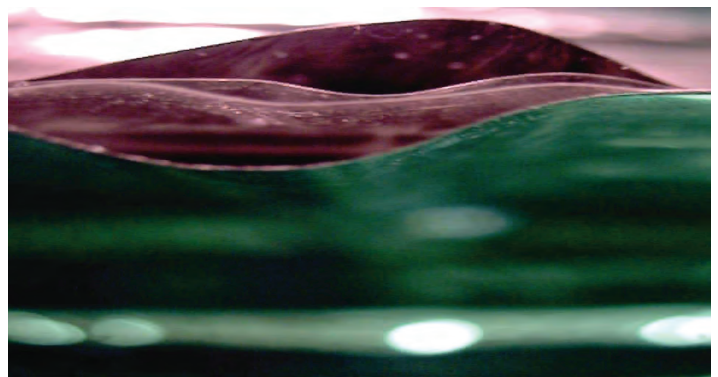


Figure 9: De-lamination of multi-layer film at VIP's outside edge. The transparent layers are the polyethylene heat seal layers which have pulled away from the metallized outer layers

4. Conclusion

Product fragility is likely to remain one of the barriers to the acceptance of vacuum insulation for some time to come.

While preservative packaging and secondary encapsulation reduce fragility, a forthright explanation of VIP failure modes is essential to customer education. Suppliers must be prepared to recommend sampling plans and quarantine periods appropriate to each new application.

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Poster Sessions

On Getters for Vacuum Insulation Panels

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Keyword: Getter; Vacuum Insulation Panels; Thermal Conductivity; Service Life

Abstract

Getter or desiccant is an indispensable component of Vacuum Insulation Panels (VIP), especially for those VIPs whose core is made of hydrophobic material like glass fiber, PU-foam etc. These core materials may release gases and water vapor that could permeate through high barrier multilayer foil film and heat seal layer. By adding getters and desiccants, residual gases and water vapor can be absorbed so as to keep the vacuum degree in long term. Thus the thermal insulation performance of VIPs would be improved and its service life would be prolonged.

Conventional evaporable and non-evaporable getters must be activated above 400°C. However, high barrier multilayer foil film can not be heated in high temperature. Therefore, conventional getters are unavailable. According to sorption mechanism, two kinds of getter alloy have been investigated in this paper: Ba-Li alloy and TiZrV alloy. The sorption performances for O₂ and N₂ have been tested by means of a constant volume method.

According to VIP fabrication process and vacuum environment inside VIP, two kinds of getters have been prepared: one is tablet-shaped getter in which the alloy powder is directly pressed; and the other is tablet-shape alloy getter coated with calcium oxide. All handlings were carried out under argon atmosphere in a glove box. Selecting Calcium Oxide desiccant as contrast sample and making VIP samples by using these three kinds of getter, their thermal conductivity have been measured and tracked.

1. Introduction

In general, VIP has two kinds of core material: fumed silica and glass fiber. Fumed silica is a kind of nano-porous materials that has very strong adsorption characteristics for gases and water vapor. While as a kind of hydrophobic material, the getter is required to be added to the core material of glass fiber in order to absorb gases and water vapor which releasing from glass fiber itself. These gases and water vapor could permeate through high barrier multilayer foil film and heat seal layer[1,2].

Through preparing getters with two different chemical compositions and structures, their sorption properties and influence on thermal conductivity of VIP have been studied in this paper.

2. Experimental Sections

2.1 Getter Preparation

2.1.1 The preparation of Ba-Li alloy getter

According to Ba-Li binary phase diagram, Ba-Li alloy includes two kinds of intermetallics, namely BaLi₄ and Ba₁₉Li₄₄[3-7]. In this paper, The BaLi₄ was synthesized from Ba metal (>99.5wt.%) and Li metal (>99wt.%). Due to the extreme sensitivity of the Ba and Li metal in air, all handlings were conducted in a glove box with purified argon (Ar> 99.999%, H₂O<0.5ppm, O₂<0.5ppm). they were heated to 400°C and held for 60 minutes at this temperature in a closed iron crucible, followed by cooling to 250°C. Then the smelt was cast into a mortar, after solidifying and cooling to room temperature. The BaLi₄ alloy was ground into powder with a grain size of less than 45 mesh.

The metal surface is coated with a layer of paraffin oil that need removing before used, because barium and lithium are active metals.

1g Ba-Li alloy powder was compacted into alloy pieces of Φ10mm×4mm in a glove box with purified argon, numbered as No.1 getter. The No.1 getter was wrapped with 5g calcium oxide desiccant and then compressed into composite getter of Φ20mm×7mm, numbered as No.2 getter.

2.1.2 Preparation of Ti-Zr-V Getter

The Ti-Zr-V porous getter was fully activated at 450°C for 40 minutes in a glove box with purified argon[8], and then was wrapped with 5g calcium oxide desiccant and compressed into composite getter of Φ20mm×7mm, numbered as No.3 getter.

Calcium oxide desiccant powder was packaged in permeable Du Pont membrane whose dimension is 70mm×140mm, numbered as No.4 getter.

2.2 Preparation of Test Specimens for Vacuum Insulation Panels

The preparation process of VIP is as follows: Firstly, the core material that was made of glass fiber of diameter 2~5 μm was dried for 2h at 200°C. Secondly, The high barrier multilayer foil film of structure PA(15 μm) / metalized PET(12 μm) / Al(7 μm) / PE(50 μm) was cut, heated and then sealed into an envelope of size 200mm×300mm and a thickness of 10mm. Then, the core material was bagged into the envelope, evacuated to $2 \times 10^{-2} \text{Pa}$, heat sealed to make VIP samples by respectively using these-above four kinds of getter.

2.3 Testing Apparatus

The thermal conductivity of VIP was measured by Thermal Conductivity Testers from EKO INSTRUMENTS CO., LTD at 25°C and <40RH. The cold side temperatures is $T_c = 5^\circ\text{C}$ and hot side is $T_h = 35^\circ\text{C}$.

The test apparatus, leakage rates $< 1.5 \times 10^{-4} \text{PaL/s}$, background vacuum $> 1 \times 10^{-4} \text{Pa}$, has been designed and manufactured in laboratory. The sorption performances of No.2 getter and No.3 getter for O_2 and N_2 have been tested by means of the constant volume method at 25°C and <40RH.

3. Results and Discussion

3.1 The Sorption Performance of No.2 Getter and No.3 Getter

The tested results are shown in figure 1 – figure 4. In the beginning hours, the pressure decrease rapidly with time, which indicates that the sorption rates are faster in the beginning. As time goes by, the sorption rates begin to decline, and the pressure decreases very slowly. Finally, the sorption rates declines very slowly, and the getter is close to its full function capacity.

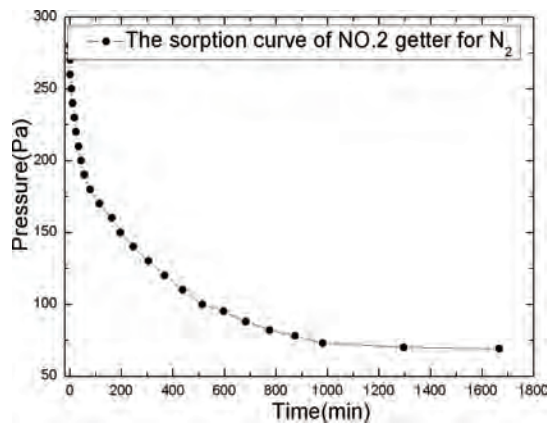


Fig. 1 N_2 Adsorption Curve of No.2 Getter

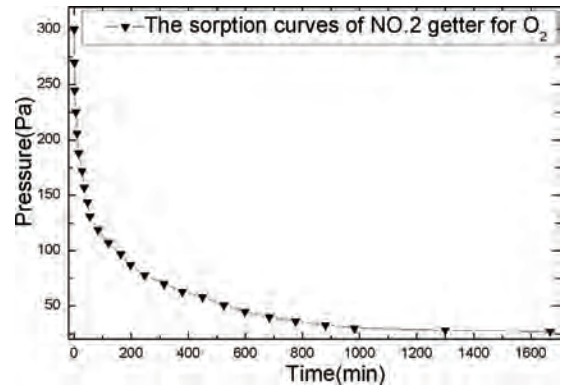


Fig. 2 O_2 Adsorption Curve of No.2 Getter

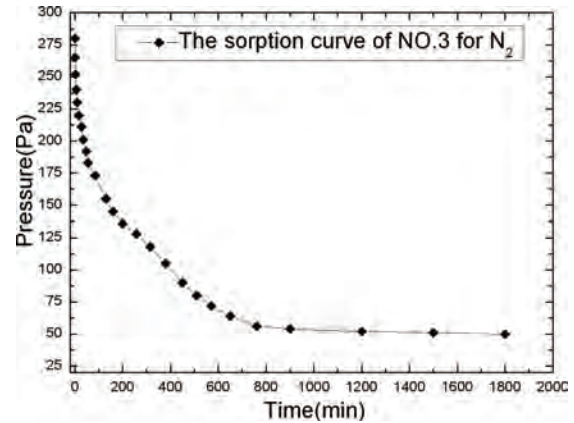


Fig. 3 N_2 Adsorption Curve of No.3 Getter

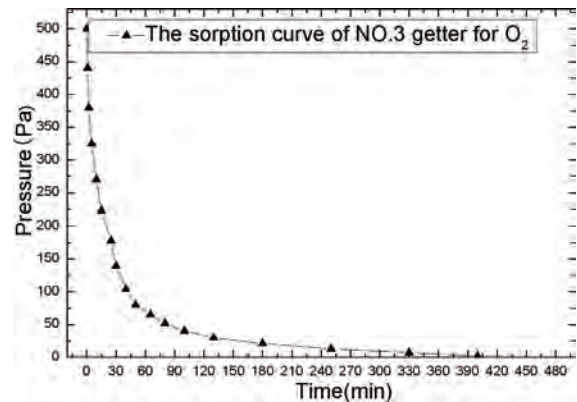


Fig. 4 O_2 Adsorption Curve of No.3 Getter

3.2 Tracking Test of Thermal Conductivity for VIP

Tracking test of thermal conductivity is shown in figure 5. It can be seen that the thermal conductivity of VIP with No.1 getter is 6mw/(m·k) at the beginning and then up to 12 6mw/(m·k) in two days, and thereafter it starts to go down to 2. 6mw/(m·k) after about a month. The main reason is that physical adsorption of gases and vapors on the surface of No.1 getter can not be eliminated completely during evacuating process. In the vacuum

environment, the gases and vapors are released under the affection of gas concentration gradient. When the gas concentration reaches to equilibrium, accompanied by a chemical reaction adsorption, the thermal conductivity reaches to the highest value. Then the getter physically absorbs the residual gases and performs chemical reaction, as a result, thermal conductivity declines to 2.6 mw/(m·k) in one month. As times goes by, the adsorption rates of getter starts to decline slowly. Because its adsorption rate is too slow to absorb the gases released from the core material as well as those gases and vapors that could permeate through high barrier multilayer foil film and heat seal layer, the thermal conductivity rises slowly and reaches to 3.4 mw/(m·k) after 13 months.

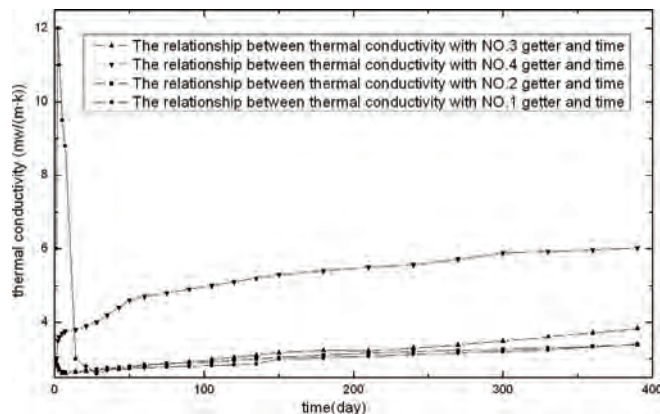


Fig. 5 tracking test results of thermal conductivity

The initial thermal conductivity of VIP with No.4 getter is 3.02 mw/(m·k) and rises fastly in the first month, and then is slowing down. This is because No.4 getter is desiccant, which doesn't absorb gases. However, during the earlier stage masses of gases are released from the core material, at the same time, there are the gases and vapors which permeate into VIP through high multilayer foil film. Therefore, thermal conductivity rises slowly first, while reaches to 6.0 mw/(m·k) after 13 months.

From the figure, both the initial thermal conductivity of VIP with No.2 getter and No.3 getter is 3 mw/(m·k), and followed by a downward trend. On the 21st day, both thermal conductivity decreases to the lowest. However, thermal conductivity of VIP with No.3 getter is still lower than that of No.2 getter. It may explain that during the first 21 days, the adsorption rate of getter is greater than the outgassing rate of the core material and the permeation rate of high multilayer foil film. From the 22nd day, the slow rising trend of thermal conductivity of VIP with No.3 getter is nearly the same as that of No.1 getter. The difference is the adsorption rate of No.3 getter is slower than that of No.2 getter. The main reason is No.3 getter has large activity and absorbs masses of gases at the beginning, which causes its activity reduces quickly. In contrast, No.2 getter is more stable.

4. Conclusions

The sorption performances of No.2 getter and No.3 getter for O₂ and N₂ are all excellent. As times goes by, the adsorption rates of getter become less and less. According to changes of thermal conductivity of VIP with No.1 getter, the fundamental design for getter structure should be "desiccation firstly and then sorption". The rising trend of thermal conductivity with getter is slower than that of desiccant. The service life would be prolonged by 1~2 times.

5. Acknowledgments

This work was supported by the Fujian Super Tech Advanced Material Co., Ltd. Research & Development Center.

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The Outlook of China VIP Industrial Development

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Abstract

The paper describes the development history and current situation of China's Vacuum Insulation Panel (VIP) industries, and relevant universities' and research institutions' research on VIPs. The issues related to personnel training are also discussed in this paper.

VIP industries in China have been developing rapidly in the past few years. The numbers of VIP manufacturers in China have increased continuously with the growth in production capacity as well as the manufacturing techniques. This paper aims to outline China's current VIP production capacity, quality, cost, and application issues/scopes. In addition, the outlook for future development of China's VIP industries has been objectively estimated.

1. Introduction

Due to the growing shortage of resources, energy and the deteriorating environment, environmental protection and energy conservation have become a global concern nowadays. Most countries attach great importance to energy saving and low-carbon economy. From Copenhagen to Cancun, climate change has become the global issue of common concern. The forbidden use of CFCs material and HCFCs transitional materials, and other environmental protection measures offer great impetus to the development of VIP technology. VIP is a relatively a new industry in China, and its foundation is poor. In the early 1990s, only a few research institutions and universities started exploratory research activities; and a small number of companies imported some VIPs from Germany and Japan for experimental application of VIP refrigerators.

2. Current Situation of VIP Research and Personnel Training

In China, the earliest research and development activities on VIP were started in 1997 and initiated by Lanzhou Institute of

Physics's researcher, Shi Fanglu. He and his colleagues considered to develop open-celled Polyurethane foam as the core material for VIP. Open-celled Polyurethane requires high density and high open-cell content.

Based on experiments, the final improved thermal conductivity could come to 0.006W/m.k. This research achievement was introduced in April 2003 in Polyurethane Industry Whole Store (ODS) International BBS. It drew participants' high attention and interests. While due to various reasons, this achievement was not able to be put into industrial production. In 2003, Professor Xulie and Doctor Yang Chunguang from Low-temperature Teaching and Research Section of Shanghai Jiaotong University started to study VIP technology. And their paper called "One High-efficient Insulation Technology-Vacuum Insulation Panel" was published in Vacuum Magazine. In 2007, the paper about adopting rigid open-celled Polyurethane foam as VIP's core material, written by Professor Han Houde and Doctor Kang Ankang from Shanghai Maritime University, was published. The paper aimed at discussing the influence Polyurethane and VIP inner vacuum level could have on VIP's insulation performance. The result turns out that this kind of VIP has good insulation property whose thermal conductivity could be lower than 10mw/m.K, as open-celled PU is the core material of VIP, its pore diameter is between 140 to 220 μ m, open-cell content is higher than 95%, its density is 45 to 60kg/m³, VIP inner vacuum level is lower than 10Pa. In 2010, Lanzhou Institute of Physics's Researcher Wang Xianrong guided Wen Yonggang's Doctoral paper "Vacuum Insulation Panel (VIP) Technology and Development". The paper further analysed the mechanism of micro-insulating, and tried to analyse those factors which could impact VIP's overall insulation property, heat bridge effect, VIP's service time etc. Above mentioned organizations have carried out relatively in-depth study on VIP. Besides, Xiamen University, Dalian Fisheries University, Beijing University of Science and Technology, Xi'an Jiaotong University and Yixing Beta Thermal Insulation Materials Inc. also have studied VIP.

Concerning personnel training, Lanzhou Institute of Physics (Belongs to Chinese Academy of Space Technology), Shanghai Jiaotong University, Xi'an Jiaotong University and Shanghai Maritime University has trained a batch of doctoral degree students. As the rapid development of VIP industry in China continues, more and more colleges and universities join in.

3. The Distribution of Production Enterprises

In 2003, only a few companies were involved in VIP business. SOMO Nano Advanced Materials Technology Co., Ltd. supplied a small number VIPs to Haier. At that time, Haier also produced VIP for their own use, while the core material was supplied by SOMO. Besides, Qingdao Gang Sen Plastic Co., Ltd., Qingdao IDXIN Ele. Appliance CO.,Ltd. produced some VIPs as well. While at that time, in China, in addition to Haier, who have used VIP in their products, only a few refrigerator companies started to do experiments for application of VIP on their refrigerators. Therefore, it could be said that the VIP market in China at that time was just a beginning, in a period of wait-and-see, not mature at all. Some VIP manufacturers even did exit the market. However, from 2007, the market began to be active, more and more top refrigerator companies in China tried to apply and use Vacuum Insulation Panel, moreover, many of refrigerator supporting parts manufacturers have gradually moved into VIP industry.

By coarse and general estimate, currently, there are dozens of VIP manufacturers in China mainly distributing in Fujian Province, An'hui Province, Jiangsu Province, Sichuan Province, Guangdong Province and Shandong Province. VIP productions in these areas account for the majority of VIP market. Among these, Fujian Super Tech Advanced Material Co., Ltd is specialised in manufacturing merely VIP. It was founded by Wang Kunming who started to organized his people to do R&D work

on VIP since 2004, and put into mass production from October 2007. As the matter of fact, in addition to Super Tech, many VIP manufacturers are refrigerator supporting parts manufacturers but not VIP specialized manufacturers. VIP is just one of their products.

VIP production enterprises distribution has the following characteristics: close to the refrigerator production base, such as Hefei, Shunde, Chengdu, Qingdao; close to the sea port to facilitate export trade; close to those provinces of rich energies, such as raw material of glass wool production plants which highly facilitate procurement. The supplying pattern of VIP is shown as below.

3.1 VIP production enterprises

Haier¹

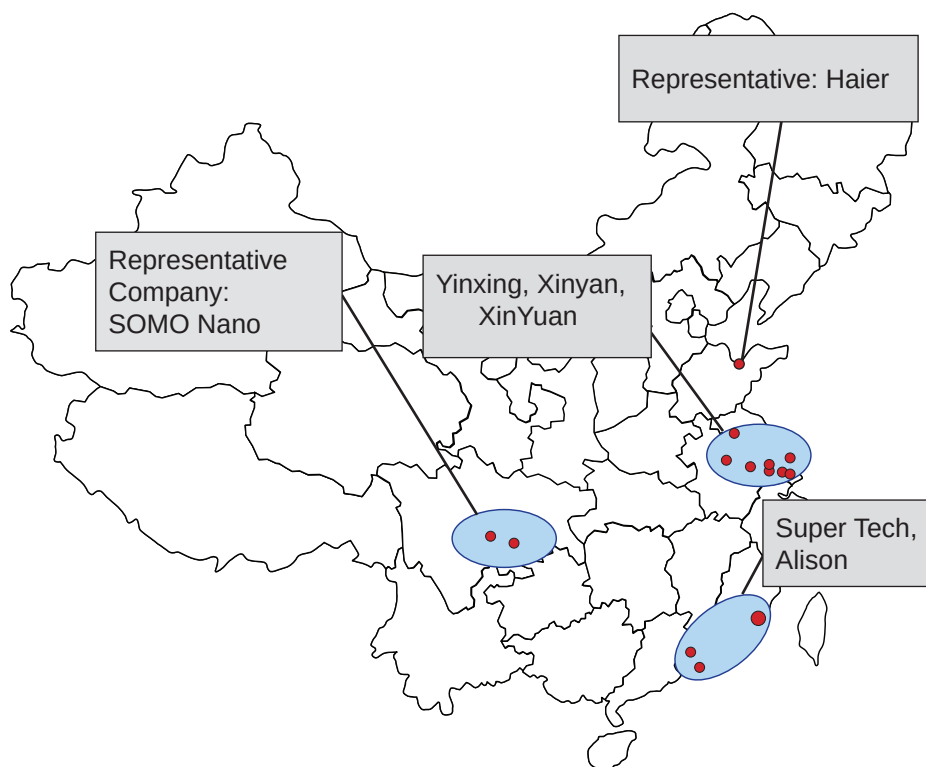
Haier imported 4 vacuum sealing equipments respectively from Japan and Korea to produce VIP for their own use. The core material and barrier film bag Haier used were supplied by SOMO Nano Advanced Materials Technology Co., Ltd. Its production method was wet process technique.

SOMO Nano Advanced Materials Technology Co., Ltd.

As a privately-owned company, SOMO Nano possesses 4 vacuum sealing machines to produce VIPs. SOMO Nano applies wet process production technique to produce core material and initial thermal conductivity of VIPs produced could reach to 0.0035w/m.K. SOMO Nano currently supplies finished VIPs and half-finished products to Haier.

Jiang Yin Xin Yuan Molding & Plastic Co.,Ltd.

Jiang Yin Xin Yuan Molding & Plastic Co.,Ltd. was established in 1994, it is mainly engaged in processing of plastic products. In 2005, it developed the Vacuum Insulation Panel. It has three production lines for VIP core material and the technique for core material production is dry process method. Thermal conductivity of VIPs produced could reach to 0.0035w/m.K. Currently, they have no equipments for thermal conductivity measurement. Xin Yuan mainly supplies hardware polyester plastics and VIP to Meiling company.



¹Information concerning the following mentioned companies is from the Internet, its authenticity is unverified.

Suzhou Xinyan Group Co., Ltd.

Suzhou Xinyan Group Co., Ltd. was established in 1998. It is a group company that specializes in producing high-grade decorative film and VCM metal composite panels; environmentally-friendly PET metal composite panels; marine fire protection materials; high-grade PCM roller plate, stainless steel hairline titanium plates, color crystal glass decorative panels. As it is known, it started to do R&D work on VIP in 2008. Its technique for core material production is wet process method. Thermal conductivity of VIPs produced could reach to 0.0030W/m.K. Currently, Germany NETZSCH testing equipment is being used to test thermal conductivity.

Chuzhou Yinxing Electric Co., Ltd.

Founded in 2001, Chuzhou Yinxing Electric Co., Ltd. is good at producing interior containers and other matched plastic parts for refrigerators. It started to produce VIP in 2009. Its technique for core material production is wet process method. Thermal conductivity of VIPs produced could reach to 0.0035W/m.K. Currently, Japan EKO testing equipment is being used to test thermal conductivity.

Jiangsu Xiuqiang Glasswork Co., Ltd.

Founded in 2001, the main products of Jiangsu Xiuqiang Glasswork Co., Ltd. are: appliance display glass, solar coated glass, TCO glass, LOW-E glass. As it is known, it began R & D on VIPs from 2008. It is mainly engaged in producing core material for VIPs by applying wet process method. Thermal conductivity of VIPs produced could reach to 0.0040W/m.K. Currently, Japan EKO testing equipment is being used to test thermal conductivity.

Suzhou Hongda Fangyuan Glass Wool Co., Ltd.

Suzhou Hongda Fangyuan Glass Wool Co., Ltd. is a manufacturer of centrifugal fibre glass. It imported the full set of production equipments and technology for producing centrifugal fibre glass from Owens Corning, United States of America. They had used recycled waste glass to produce centrifugal fibre glass since 2010. The diameter of its core material is between 3-5 microns which is produced wet process method. The thermal conductivity of its VIP is less than 0.004W/m.K.

Qingdao Kerui New Environmental Material Co., Ltd.

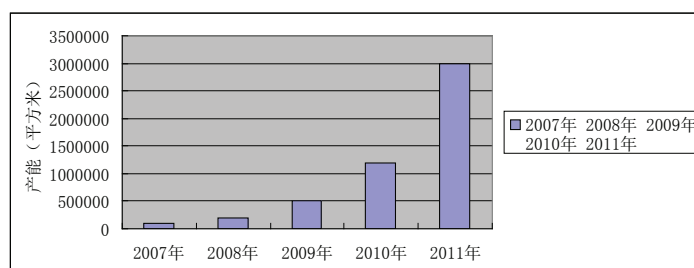
Qingdao Kerui New Environmental Material Co., Ltd. is specializing in producing building insulation material. Its main product is energy-saving mortar for building insulation. Its R&D work on VIP started from 2009, rock wool is chosen as its core material, the thermal conductivity is between 0.007-0.008W / m.K.

ALISON ASIA PACIFIC ELECTRON CO., LTD.

ALISON ASIA PACIFIC ELECTRON CO., LTD. is located in Yingde City of Guangdong Province and was set up in 2006. It is focusing on R&D, production and sales of the aerogel composite insulation material and VIP. Its details production capability is unknown.

Fujian Super Tech Advanced Material Co., Ltd.

Fujian Super Tech Advanced Material Co., Ltd. was founded in October 23, 2007 and located in Liancheng Industrial Area (covers an area of 86,667m²). It is one of the high and new tech enterprises in Fujian Province. Super Tech is a company integrating R&D, production and sales of VIP as one. It is specializing in producing only VIPs. Super Tech is dedicated to providing personalized service and systemic technique service to customers. With advantages of special core material ingredient, progressive production techniques and strict control on quality, its VIP insulation performance is better than industry average



in China. Certified and tested by China National Centre for Quality Supervision & Test of Plastics Products, the center of the panel thermal conductivity of Super Tech's VIP could reach to 0.0019W/m.K. The long-term plan on production output target is to rise up to 6million m²/year. Super Tech VIPs are sold not only in domestic market but also in Korea, Japan, USA, and some countries in Europe. Super Tech is the biggest VIP supplier and manufacturer in China who possesses 20 sets of vacuum machines.

Relying on independent R&D and technology transfer agreements, Super Tech has applied 15 national invention patents and utility model patents. Besides, through technology innovation and reformation, a series of advanced production machines and testing equipments are being originally designed. Hence, it could be said that, currently, Super Tech is the leading VIP manufacturing company in China.

3.2 Industry Production Capacity

2007	100000 m ²
2008	200000 m ²
2009	500000 m ²
2010	1200000 m ²
2011	3000000 m ²

Fig.1 Industry Production Capacity

3.3 Cost and Price

The material cost for VIP mainly consists of core material, barrier film bag and desiccant/getter. At present, most VIP manufacturers choose to use fiber glass cotton and by using wet process technique to produce core material for VIP. This could cause relatively higher cost, while VIP's quality is more stable. The thermal conductivity of VIPs could be lower than 0.002w/m.K. If Centrifugal fiber glass cotton is used, the quality would be relatively lower. Furthermore, the investment on getter production could be large and the whole production process is very strict.

With the rapid growing of VIP market and large-scale production, VIP price is decreasing gradually, for instance, the price of 10mm thick VIP is reduced from USD33.5/m² in the year of 2006 to USD 21.5/m² in 2011. And it could be estimated that there is still room for price dropping.

4. Application Perspectives

4.1 Application in Refrigerator and Freezer

Currently, refrigerator and freezer industry are the top two consumption markets for VIP, and these two markets are blooming now. The global economy is recovering and domestic and international market demand for refrigerator presents a strong growth momentum. In November, 2010, China's total output of refrigerator and freezer was 85.75million, an increase of more than 20% for the year. According to "the Refrigerator Industry White Paper 2009-2010", the retail market is showing rapid growth characteristics as well. In major cities of China in 2010, the overall sales volume and sales value have increased by 43.45% and 49.17% respectively.

In the coming years, it could be estimated that refrigerator and freezer industry would grow rapidly due to : (1)At present in urban households, there are more than 51% refrigerators that were purchased before 1994. Assuming the service life of

refrigerator is 10-12 years, these refrigerators would be replaced very soon. (2) With China's policy called "New Countryside Construction", farmers' income will increase gradually and substantially, therefore, in the next few years, there will be a massive demand of refrigerators in rural areas. (3)International refrigerator manufacturing industry is moving to China faster and China is becoming the world's refrigerator manufacturing center. China's output of refrigerator and freezer accounts for more than 40% of the world. (4)The top refrigerator manufacturers in China now are all increasing their investment to expand production capacity. Therefore, it is estimated that the output of refrigerator in next few years will maintain a growth rate of more than 10%.

4.2 Application in Refrigerated and Frozen Container

Refrigerated trains, refrigerated vehicles, refrigerated containers are required to use insulation material. Currently, China's refrigerated containers are mainly used in foreign trade transport, while for domestic trade, the popularity of cold chain logistics is very low. For instance, the annual output of refrigerated containers of China International Marine Containers is 100,000 sets, while the percentage of VIP used in this sector is less than 1%.

Statistics show that China's current consumption of refrigerated food is increasing by 10% per year. This growth in consumption of frozen foods is promoting the development of refrigerated transport industry.

5. Domestic Research & Development

Domestic research & development work on VIP mainly focuses on quality improvement, cost reduction and service life enhancement.

5.1 Core Material

Core material plays a very important role to the quality of VIP. Therefore it is important to select the core material very carefully. Firstly, select the core material from different kinds of fiber materials and then identify one or two fibers to produce core material by proper proportioning and mixing. By improving the production technique, based on quality assurance, this kind of core material could greatly reduce the production cost. Secondly, the reasonable and proper ingredient of core material could offer a possible and efficient way to solve the problem of waste treatment, environment protection and energy saving.

5.2 Barrier Film Bag

The structure of barrier film bag is varied and diversified, and it requires low penetration rate against Oxygen, Hydrogen and Nitrogen. In order to eliminate the edge effects of barrier film, more research and development is required to focus on different kinds of environmentally-friendly composite film without aluminum but of high barrier property.

5.3 Getter

Many experiments show that it is efficient to apply getter in VIP to prolong the service life of VIP. Currently, there are several professional getter manufacturers in China, and a number of VIP manufacturers have started researching and developing a kind of getter which does not require heating activation, which is very suitable in medium and low vacuum condition. Compared with the traditional high temperature getter, this type of getter performs well in absorbing air. Moreover, the material is non-toxic and environment-friendly.

5.4 Fast Testing Checker Equipment

In order to ensure effective quality control, 100% VIP productions are required to be inspected. The research on this issue is an ongoing phenomenon. The capacitive mini vacuum sensor is under development. However, the measure of degree of vacuum in VIP is a tough issue, as VIP cannot be opened and the vacuum chamber is small and narrow. Hence, the traditional measurement methods are not suitable. Nevertheless, taking Micro-Electro-Mechanical System technology to make the miniature vacuum gauge can effectively solve the problem.

5.5 The Transformation of Production Equipment

As the market develops rapidly, the demand to increase production intensifies. The existing manufacturing equipments already cannot satisfy production needs. The research and development on more advanced automatic VIP production equipments, including core material on-line molding, drying, cutting, automatic conveying, automatic vacuum sealing line etc., is becoming more urgent than ever. The production output can be greatly enhanced and subsequently the cost will come down. In addition, when the production efficiency is improved, lesser personnel is required in the manufacturing process.

5.6 Irregular Shaped VIP

Some irregular shaped VIPs are being put into a small-scale production stage. When the related market becomes mature, such VIPs can be considered to put into large-scale production. It is an important technical area for a company to do research and development on irregular shapes VIPs.

5.7 Research on Applications

In order to further expand the application fields of VIP, more and more research is being carried on how to how to apply VIPs properly. At present, the application techniques of VIPs differs between different refrigerator brands and in some cases they produce undesirable influence on insulation performance. Therefore, how to scientifically and correctly apply VIPs is a topic worth to be studied.

6. Conclusions

Vacuum Insulation Panel (VIP) is a composite insulation material, with innovative and high-end technology, that has great development prospects in China and elsewhere. In recent years, the trends to upgrade household appliances and stricter standards for energy-saving are generating more market demand for Vacuum Insulation Panel. Meanwhile, with improvement of VIP technology, its production cost is continuously reducing and this is a favorable impetus to the market.

With more and more importance attached to energy saving and emission reduction measures, governments of many countries are announcing stricter and mandatory energy efficiency standards for buildings and refrigerators. As long as VIP industry continuously keeps on reducing the cost through large-scale production and innovative technologies, the market demand for VIPs will keep on growing and subsequently VIPs will be considered as regular insulation materials in many cases.

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Linear Thermal Transmittance of Thermal Bridge at Building Envelops with VIPs

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1. Introduction

The energy consumption in buildings has recently increased and in some countries, it reaches almost 40% of the total energy use. Therefore, there are various efforts to minimize energy loss or maximize energy conservation in buildings, one of which could be improving thermal performance of building with high efficient insulations. The building envelope should be considered at first for this purpose as it seems to be more closely related to the building energy performance. There are various ways to improve the envelope's thermal performance, such as adding more conventional insulation to the envelope, and using the state-of-the-art insulation materials.

VIPs (Vacuum Insulation Panels) have been recently introduced to the building sector as a high insulating material. Their thermal performance is a factor of five to eight times better than that of conventional insulation materials, such as glass wool, rock wool, expanded polystyrene, etc. One of VIPs advantages in building application is it can make the building envelope thinner while maintaining the same or better thermal performance in conventional building practice. However, it should be more cautious in building application since it is more fragile and smaller than conventional insulation materials.

In particular, the heat loss is caused at the panel edges as the form of the thermal bridge effect, depending on adjacent materials and attaching methods. If heat loss increases through the thermal bridge, the thermal performance of the building envelope with VIPs could decrease. Therefore, it is important for the VIPs application in building envelope to prevent the thermal bridge.

The aim of this study is to analyze the thermal bridge effect of VIPs wall applications through the calculation of linear thermal transmittance, depending on the VIPs installation methods. For the study, four types of the building envelopes with VIPs were designed and the linear thermal transmittance at the VIPs connecting area was calculated using a computer simulation program, HEAT 2 and equations from an ISO standard. The linear thermal transmittances of the four types of building envelope were compared.

2. Building envelope with VIPs

2.1 Properties of VIPs

The VIPs used for this study use fiber glass as a core material in the core bag wrapped with multilayer films of nylon and aluminum. As the VIPs used for this study was made by a pilot plant for the experimental purpose, it doesn't have sharp edges. Therefore, the air gap might be caused between VIP panels so that more attention should be paid in applying the materials into building envelope. The size of the developed VIPs is 500 mm * 800 mm with 10 mm in thickness. The thermal conductivity at the centre of the VIP is 0.003 W/mK. However, the K value might increase by about 0.001~0.002 W/mK depending on the thermal bridge effect at the edges of the panel.



Fig. 1 VIPs

2.2 Building envelope design with VIPs

In order to analyze the thermal bridge effects for VIPs installation methods linear thermal transmittance at the VIPs jointing area, the four types of VIPs installation method for building wall were designed: Joiner Type, Wooden Lath Type, Anchor Type and Insulation Pin Type. The composition of the designed wall is as follows; 200 mm concrete, 25 mm glass wool, two layers of 10 mm VIPs, 25 mm glass wool and two layers of 9.5 mm of plaster board. In consideration of mechanical damage of VIPs in practice, VIPs were placed in between two layers of glass wool.

Figure 2 illustrates the elevation and cross sectional view of Joiner Type which uses thermo plastic of joiner as spacer and attaching material so as to minimize the area of thermal bridge. By adding flexible polyethylene to the connecting area, the Joiner Type can minimize the dimensional difference and air gap.

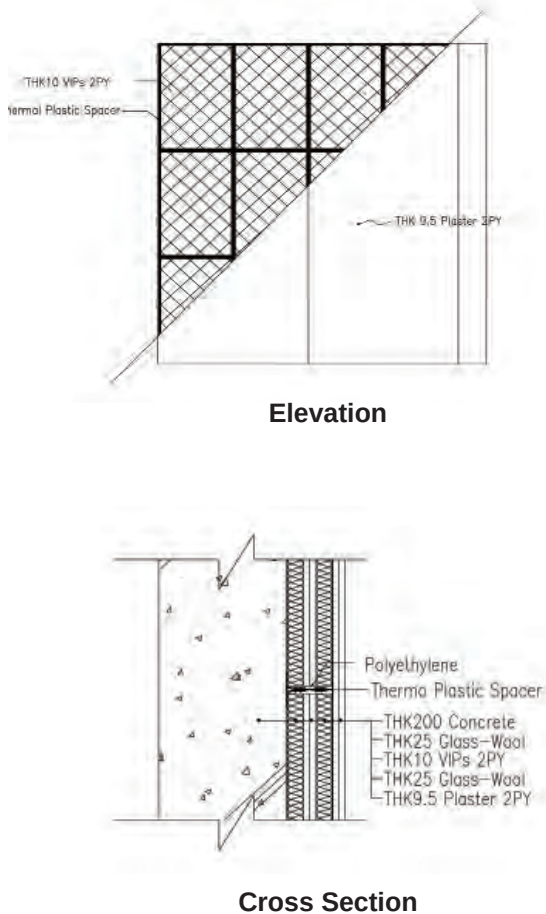


Fig. 2 Joiner Type details

Figure 3 illustrates the elevation and cross sectional view of Wooden Lath Type. This Type uses wooden laths for attaching the VIPs as a spacer.

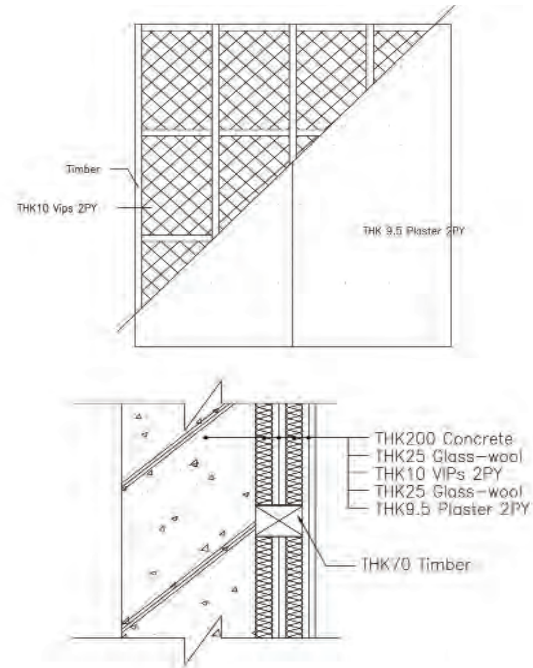


Fig. 3 Wooden Lath Type details

Figure 4 illustrates the elevation and cross sectional view of Anchor Type. This Type installs VIPs using anchors to concrete. The minimum number of anchor bolts were used to support for the VIPs installation in order to reduce the thermal bridge effects through the metal anchor bolt with higher thermal conductivity.

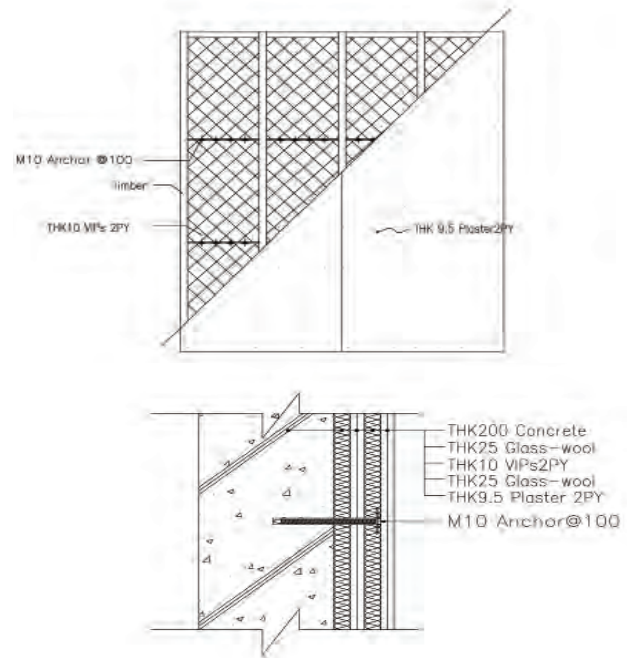


Fig. 4 Anchor Type details

Figure 5 illustrates the elevation and cross sectional view of the Pin Type. This type installs VIPs using insulation pins that were glued to the concrete surface. The air gap in between insulation pins was filled with polyurethane foam.

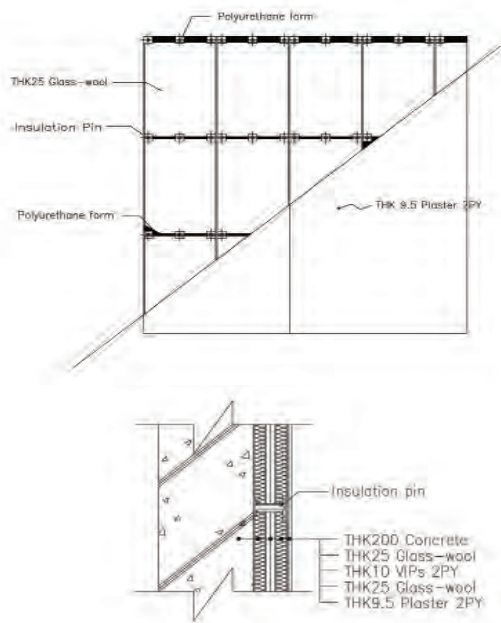


Fig. 5 Insulation Pin Type details

3. Calculation of Linear Thermal Transmittance

3.1 Calculation methods of linear thermal transmittance

The thermal bridge effect takes place at the area of poorly insulated or thermally unbroken in building components. The temperature of the inner surface of thermal bridging may be different from other part of the envelope, even though this could depend on the temperature difference between inside and outside. This temperature difference indicates the heat loss through the area that decreases the thermal performance of a building, and may also cause condensation problem.

Therefore, the thermal bridging should be taken into account for building energy performance, as introduced with a ISO standard(ISO 10211: 2007 Thermal Bridges in building construction-Heat flows and surface temperatures- Detailed calculations). It includes the calculation method of linear thermal transmittance at the thermal bridges in building envelope to evaluate its thermal insulation performance. In order to evaluate

the thermal insulation performance of building walls with VIPs according to the installation methods, we calculated the linear thermal transmittance of their thermal bridges.

The linear thermal transmittance can be calculated from the steady state two-dimensional heat flow that takes into account the heat losses that the one-dimensional calculation of U-values could not calculate. It can be defined as heat flow rate in the steady state divided by length and by the temperature difference between the environments on either side of a thermal bridge”(ISO 12011). The linear thermal transmittance can be calculated with the following equation(1). For the modeling, the length of neighboring walls to thermal bridge could be greater of 1m or three times the thickness of the flanking element concerned.

$$\psi = \frac{\Phi}{\theta_i - \theta_o} - \sum U_i l_i \quad (\text{Eq. 1})$$

ψ : the linear thermal transmittance (W/mK)

Φ : the total heat flow (W/m)

$\theta_i - \theta_o$: the temperature difference between the inside and outside environments(°C)

U_i : the thermal transmittance of the adjacent building element(W/m²K)

l_i : the length over which the value U_i applies (m)

3.2 Modeling method and thermal boundary conditions

For this study, HEAT 2 computer program was used to calculate the total heat flow(Φ) through the walls. 2-D geometrical model was used for two-dimensional calculations(Fig. 6). For the total heat flow(Φ) calculation, cut-off planes of each sides from the connecting area has the length of 1000 mm, the insulation thickness of 70mm including 20 mm VIPs and one dimensional heat transfer coefficient(U_i) of the wall was 0.118(W/m²K).

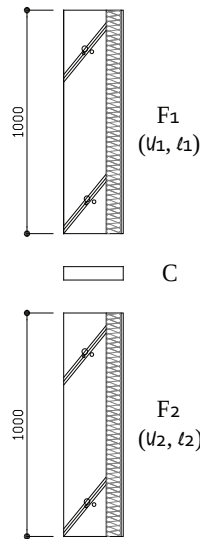


Fig. 6 Cut-off planes for a 2-D geometrical model (F_1 & F_2 : Neighboring wall to thermal bridge; C: Thermal bridge)

For the thermal modeling with HEAT 2, the thermal properties of the building material are illustrated in Table 1. The values refer to BS EN ISO 6946:1999 and DIN V 4108-4 with the exception of VIPs volumetric heat capacity for which we supposed the same values as glass wool. Table 2 shows the boundary conditions for the thermal modeling.

Table 1 Thermal properties of the wall component material

Material	Conductivity (W/mK)	Volumetric heat capacity (MJ/m ³ K)
Concrete	2.7	1.830
Glass wool	0.033	0.062
VIPs	0.005	0.062
Plaster board	0.431	1.360
Plastic	0.209	2.259
Steel Anchor	41.83	3.891
Wood	0.150	1.000
Urethane foam	0.041	0.105
Poly ethylene	0.033	1.000

Table 2 Thermal boundary conditions

	Temperature(°C)	Thermal resistance(m ² K/W)
Inner surface	20	0.13
External surface	-11.3	0.04

3.3 Results and analysis

The calculation results of linear thermal transmittance for the VIPs installation methods are illustrated in Table 3. In considering the characteristics of inconsecutiveness of the attaching materials, like anchors and insulation pins, separate ψ value calculations were made for the area with spacer and without spacer.

The Joiner Type has the lowest ψ value of 0.023 W/mK, followed by Wooden Lath Type with 0.073 W/mK, Insulation Pin Type with 0.074 W/mK and Anchor Type with 0.266 W/mK. However, the ψ values at the area without spacers for Insulation Pin Type and Anchor Type are 0.067 W/mK and 0.028 W/mK, respectively.

Table 3 Calculation results of linear thermal transmittance

Application Method	linear thermal transmittance (W/mK)	
Joiner Type	0.023	
Wooden Lath Type	0.073	
Anchor Type	0.266 (Anchor part)	0.067 (Air gap)
Insulation Pin Type	0.074 (Insulation Pin part)	0.028 (urethane form)

The results indicate that the Joiner Type with the lowest linear thermal transmittance value would be the best VIPs installation method for the wall in terms of its thermal performance. This fact might be due to the material of the high efficient thermal plastics, and this type of installation has an advantage in using thinner configuration of the material. Even though the connecting area of the Wooden Lath Type has the highest ψ value so that it has thermal disadvantage, it could be one of the easy installation options as they are easily available and cheaper

4. Conclusion

This paper analyzed the thermal bridging effects of VIPs installation methods with the calculated linear thermal transmittances. Four types of VIPs installation into wall were designed and the ψ values of linear thermal transmittance for types were calculated through 2-D thermal modeling and formula.

The results indicate that the Joiner Type ranks top in thermal performance with the lowest ψ values, followed by Wooden Lath Type, Insulation Pin Type and Anchor Type. Compared to the Joiner Type, the Anchor Type's linear thermal transmittance is ten-times higher so that it is expected more heat loss through the anchor attaching area. For Insulation Pin Type, the linear thermal transmittance of insulation pin area is similar to Wooden Lath Type. Due to the polyurethane foam stuffed in between

insulation pin and air gap between VIPs, the linear thermal transmittance was the second to Joiner Type.

In conclusion, the Joiner Type and Insulation Pin Type have relatively lower ψ values bridge than other installation types so that they are able to minimize the thermal loss of the building wall with VIPs. They are followed by Wooden Lath Type and Anchor Type. For the Anchor Type, the thermal bridge seems to be significant due to the high thermal conductivity of metal material, so that more cautious approach is required for VIPs installations to buildings.

It found that the VIPs attaching methods would have different thermal bridge effects that would decide the thermal performance of the components, as the conductivity of connecting materials for VIPs is different. Therefore, it is very important to choose an installation type to minimize the thermal bridge in application of VIPs to buildings.

In the future, the design of building envelope with VIPs should be developed in consideration not only of thermal performance but also of workability and economic aspects, and further study for optimal installation method is required.

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