



Benefits of vacuum insulation panels in building envelopes for warm-keeping

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Abstract

VIP is a new insulation material and it is highly employed in lots of country in Europe. Due to its basic construction principle, the structure can vary in a large range. This thesis gives a wide explanation on the structure and construction approaches which aims to tell the difference in thermal performance, space saving or maybe economic aspects. On the other hand, seeking the best insulation materials blindly may cause carelessness on the drawback. In the thesis, the drawbacks like thermal bridges and expansion deterioration also gave, and these aspects will warn people take care about the balance between lifespan and functions. In the end, developing on nowadays VIP material is keep going, new material comes out emerge in endlessly, thesis still give a brief introduction about it.

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1. Introduction

1.1 Background

Today's building population is using approximately 40 % of total energy consumption in the world (Luis P-L, et al, 2008). Therefore, the building sector is contributing to a vast amount of carbon dioxide (CO₂). Due to climate changes, caused by CO₂ and other green house gases, it is important to reduce this emission. Actions must be taken on buildings of today, especially older ones, in order to reduce emission when the building consumes energy for heating and cooling purposes, because with much energy consuming, the CO₂ will be released more and more.

1.2 VIP

A relative new product that can be used in the building envelope is vacuum insulation panels (VIP). This material insulates 8 times better than conventional thermal insulation materials, such as mineral wool and cellular plastics (EPS, XPS). This material is promising, since thin layers give good thermal performance if placed in building envelopes. By fit with this kind of material, the thermal comfort problems of some region like southern of China (around Chang Jiang river, not too far south, still in temperate zone) can be improved, because there is no heating supply (for example, indoor radiators) in southern in cold winter. Therefore, the CO₂ emission would be reduced after less energy used for heating.

Vacuum insulation panels (VIPs) are regarded as a high-performance thermal insulator which was designed in order to reduce energy use and CO₂ emissions. Since the thermal performance is improved, the raw material to generate thermal energy for buildings will be reduced which result in the reduction of CO₂. VIP can be applied in various aspects which include the following field such as buildings, refrigerators and cryogenic apparatus or devices. Most times the insulation performance of VIPs

always degrades with the number of years that it has been put to use or have been used. When looking at the initial thermal resistance of VIPs for refrigerator, this is said to be 5 times more than that of conventional insulation materials which have the same thickness. The core materials in VIP are kind of materials that can withstand the external atmospheric pressure and also will be able to be almost gas-tight envelope in order to maintain the inside vacuum and a getter or desiccant which can absorb various types of gas flow which are going into the panel. The core materials which are used in VIP must be porous and should always be easy to evacuate and also have a minimum solid conduction effect and due to all these factors, materials which are the form of bulk powders, foams and fibers are mostly used as the core material.

Therefore, the aim of this project is to do the research about the structure of the VIP, find the advantage in compare with conventional material. On the other hand, treat this material positively which means discover the drawback of VIP. In the end, the new development of VIP will also be studied.

2. Method

This thesis, broadly, is based on existing data and other resources by searching online in databases.

2.1 Data collection and analysis

Once a research problem has been formulated, the outcome is based on the data collection and analysis. To collect data, it can be divided into two parts, the primary data and secondary data (Walliman, 2005).

Normally, databases come from internet, company notes and libraries etc. Most part of this project by using the database “Science Direct”.

2.2 Research strategy

Research strategy is carried out to describe how it is intended to implement the empirical study (Biggam, 2008). Grounded theory is one of the research strategies. It is quite difficult theory to apply in practice, it is demanding in the sense that it does not follow the normal procedures for implementing a research project. In one word, the discussion and conclusion of the grounded theory based project is drawn from a clear research focus and go through the other literature review which can support the topic (Biggam, 2008).

3. Analysis from old building material aspects

As usual, the load bearing structures are constructed by a massive layer of concrete or brick or as frames of wood or steel. Thermal insulation is for massive layers seen as a covering extra layer and in the case of frames a filling material between frame structures.

In comments, the structure type is important for where the insulation material is placed, especially in new constructions. However, in old buildings, the extra insulation will be put on the inside or outside of the structure.

These are base materials which primarily have a load-bearing function, but also a climate protective function as wind, air barrier and precipitation. It is different with the VIP kind material – which have a totally different function (primarily thermal insulation). Like cellular plastics, VIP is also a building cover material. To acknowledge how great the VIP gets, the issue should be start with traditional material.

3.1 Extrusion polystyrene (these kind)

Insulation material of polymer products is widely used in construction material gaps

or as covering material. Recently, China government make the decision to process old building optimization, and the strategy is cover the old building with foam material. It is cheap and environmental friendly.

Old building walls do not have multi-layer materials, which by covered with foam the energy saving demand can be met. In detail, extrusion polystyrene (EPS=expanded, XPS=extruded) kind of materials have been developed as thermal insulation material for exterior wall because of its characteristics, such as low density of 28.8 kg/m³, high specific heat of 1213 J/kg K, and the extremely low thermal conductivity of 0.03 W/m K. Due to its great property, it can be constructed in every position, such as used as exterior insulation layer, interior insulation layer and middle insulation layer. The thickness of insulation layers commonly range from 25 to 100 mm. (Jinghua et al, 2008)

Some researchers processing a simulation work. They want to find the result of the ratio between heating consumption to the EPS.

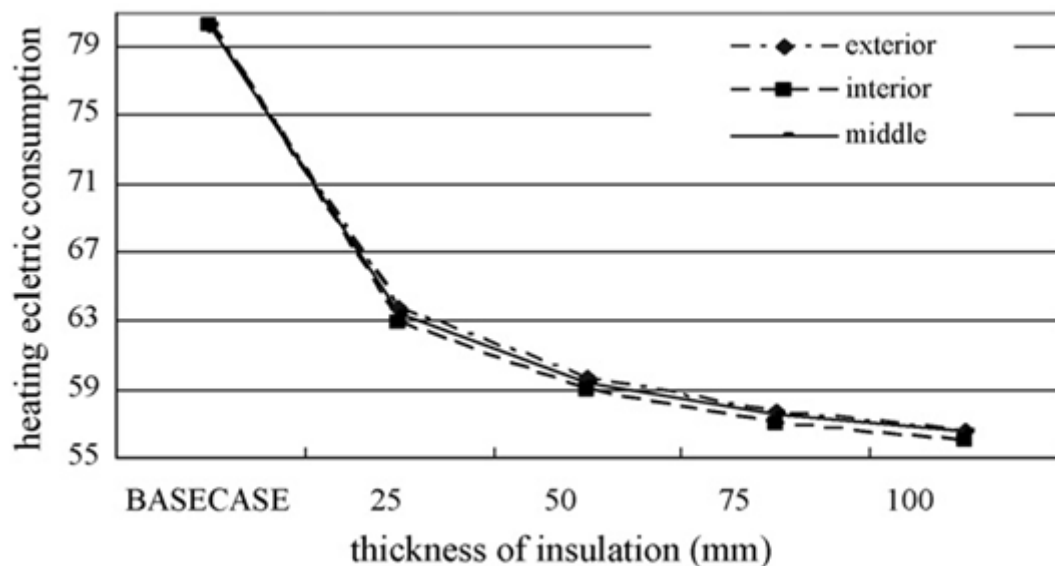


Figure 1 Effects of insulation thickness and position on heating electric consumption.

(Jinghua et al, 2008)

The experimental space is electrically heated. The position of EPS is also a kind of variables. It can be found from figure 1 that after the EPS over 25mm, the insulation property gets a better improvement. However, from the figure 1 it can be found wherever the position, the insulation functions are more or less the same. So for convenience covering work and defend thermal bridges, an exterior covering position is better. Obviously, the polymer cover increases the thermal comfort and decrease the heating consumption to some degree.

4. Research result of VIPs

VIPs material is not an invariable construction. It can be altered in terms of usage or environmental aspects. The detailed information of VIP will be introduced from its basic structure.

4.1 Basic construction

The VIP can be described as an evacuated open porous material covered with a multilayer envelope. The concept graph is shown in figure 2. Briefly speaking, the main components of a VIP are inner core, barrier envelope and getters and desiccants. The envelope could either comprise of thick metal covers or multilayer barrier of metalized polymeric layers to protected against environmental damage and handling stresses. The mixed getter or a desiccant is constructed inside the VIP core to adsorb gases or water vapors that penetrate into a VIP through envelope barrier. All these materials cover the core layer by layer, and the air will be extracted out to form a vacuum condition. Traditional non-vacuum insulation materials convection in material pores causes the dominant heat transfer across such materials. Because the pores with air gains better heat transfer, while pores without air (media) gains better insulation. The vacuum the better, because of the thermal energy requires media to transfer. However, in VIP this kind of heat transfer is suppressed because there is

vacuum cavity built inside the core material (Alam et al, 2011). The core material will be introduced later.

VIP material can be divided into two categories: sheet based VIPs or film based VIPs. These two types also called static VIPs. The reason is the vacuum can only be created when manufacturing which means it cannot be created again after the producing process complete. It also cannot be re-created for many years using. Sheet-based VIPs take advantage of metal material, so it shows better load bearing capacity and resistant to mechanical damages, but the drawback is heavier weight and a greater thermal bridging effect. On the other hand, even thinner ($100\sim150\cdot10^{-6}$ m), and lighter, the multilayered metalized polymer film envelopes can be easily damaged during handling. (Alam et al, 2011)

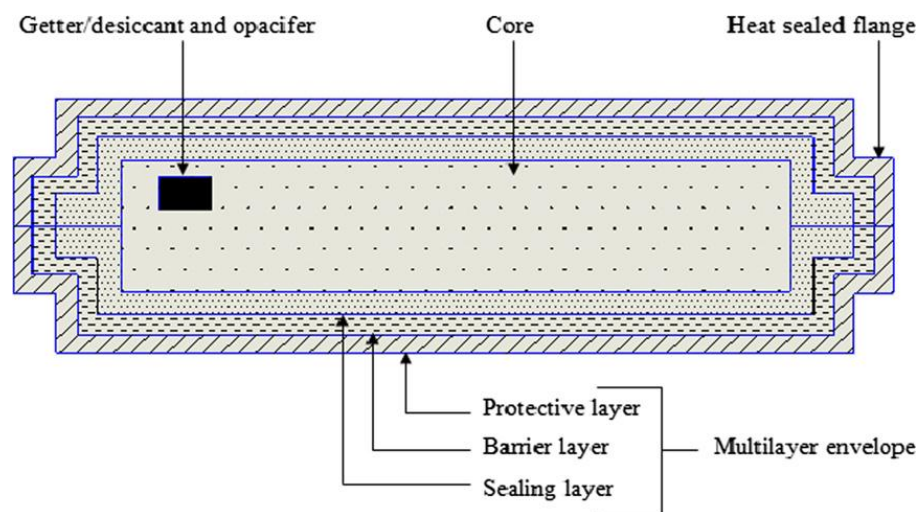


Figure 2 Concept graph of VIP material (Alam et al, 2011)

4.2 Core material

The core material is chosen on basis of necessary functions, it must be porous structure with suitable pore size. With this kind of fabric obtained, inner part could support the VIP envelope physically. Gaseous heat transfer should also be suppressed, so the core material is better to take small size porous materials such as open porous foams, powders or some kinds of fibers. (Alam et al, 2011)

4.2.1 Foam

Polyurethane (PUR) and expanded polystyrene (EPS) can be used as a core in VIPs. The pore size is ranged in $30\sim 250\cdot 10^{-6}$ m. These foams have low density ($60\sim 100$ kg/m³) so that in evacuated conditions a low thermal conductivity is obtained. According to J. Fricke's research (2009), the thermal conductivity value could range in $0.003\sim 0.007$ W/mK. A low gas pressure (lower than $1\cdot 10^{-4}$ bar) is also required to achieve a reasonable thermal resistance. However, too low pressure is not feasible, because it will influence the durability of the whole material; it is expected to be 100 years or longer for building applications. Clearly it would be difficult to achieve the lower thermal resistance value for taking foams in VIPs even with zero gaseous conductivity. On the other hand, foams always have higher fire toxicity, and it will release mainly carbon monoxide (CO), hydrogen cyanide (HCN) and other harmful emissions. Luckily, thermal conductivity of foams can be reduced by reducing the size of pores. Recently, rubber blended polypropylene and polyethylene nano/microcellular foam has been discussed by taking CO₂ pressure quench method. (Nemoto, T. et al, 2008) Nano/microcellular foams with improved structural arrangement are on developing, which are alternatives for VIP in core materials fabricate. (Alam et al, 2011)

4.2.2 Powder

Powder form materials are fumed or pyrogenic silica, silica aerogels and expanded perlite. They may build up the VIP core as a formation of individual or mixture. Fumed silica is a common one which is used due to its low thermal conductivity ($0.003\sim 0.006$ W/mK) and the requiring pressure in the range of $20\sim 100\cdot 10^{-3}$ bar. Its density is approximately $150\sim 200$ Kg/m³ and the pore size is $300\cdot 10^{-9}$ m. Fumed silica was first developed by Degussa AG in Germany in 1942 (Evonik Industries). Thanks to the low density and low thermal conductivity, fumed silica is a favorable core material for VIPs to achieve a satisfied thermal conductivity with value of 0.004

W/mK. (Alam et al, 2011)

Silica aerogels started to be developed by Kistler in 1931 which produced sodium silicate (Kistler SS& Caldwell AG, 1934). It is nanoporous materials as well with pore size of approximately 20 nm and a density with range of 3~350 kg/m³. The thermal conductivity is approximately 0.001~0.003W/mK in general and it can even achieve a value of 0.004W/mK at around 50 mbar which make it suitable for VIP applications. Silica aerogel also have great fire stable characteristics of nonreactive and nonflammable. However, the cost is high and wide use is not plausible.

Expanded perlite requires a low pressure of below 0.1 mbar to achieve the desired thermal conductivity; simultaneously it still is less effective than silica aerogel and fumed silica. Expanded perlite can be adopted only if it is in combination with fumed silica in different mass ratios. So this kind of mixture can be optimized to achieve a low thermal conductivity at a relative high pressure for a specified useful life of the VIP core. However, it is not expected to perform well at reasonable pressure. (Alam et al, 2011)

4.2.3 Glass fiber

Glass fibers can be also adopted as the core material of VIP panel for high temperature applications due to its low density and high thermal stability (>1000°C). It is reported that glass fiber has comparatively great radiative conductivity of 0.0007 W/mK and solid conductivity of approximately 0.0021W/mK at 300 K. The density is similar to fumed silica with a value of approximately 250 kg/m³. Its fiber diameter is 0.5~0.7*10⁻⁶m). Collectively these features results in a thermal conductivity of 0.0028W/mK requiring a suppression of the gaseous conductivity within 0.0012W/mK to achieve the qualified VIP core thermal conductivity of 0.004W/mK. A pressure of approximately 0.01*10⁻³ bar was required to suppress the gaseous thermal conductivity. The theoretical total thermal conductivity value of 0.0036W/mK for a glass fiber core at 0.1*10⁻³ bar is studied by some researchers (Alam et al, 2011). Some investigation found that a type of glass fiber based VIPs is

used for insulating hot water cylinders in industry. Glass fiber based VIPs are a great alternative material for isolation usage in domestic ovens, furnaces, concentrated solar power plants and fuel cell power plants. (Alam et al, 2011)

4.3 VIP envelope materials

The envelope (or say the cover) can not only protect the VIP from air and water damage but also support to against atmospheric pressure and handling stresses with a certain mechanical strength during transportation and installation. Envelope performance depends upon the multi-layer barrier properties and capability of resist the thermal bridging across the rims. Envelope materials are expected to have a certain water vapor transmission rate and a certain oxygen transmission rate to hold a useful lifespan of approximately 30~50 years for building applications. The combination of envelope could be polymers and thin metalized films or metal foils. These are currently adopted to produce VIP envelope. In general, the durability of multilayer film envelope of a VIP depends on environment temperature, relative humidity and size of panel. (Alam et al, 2011). The figure 3 shows the typical structure of the envelope.

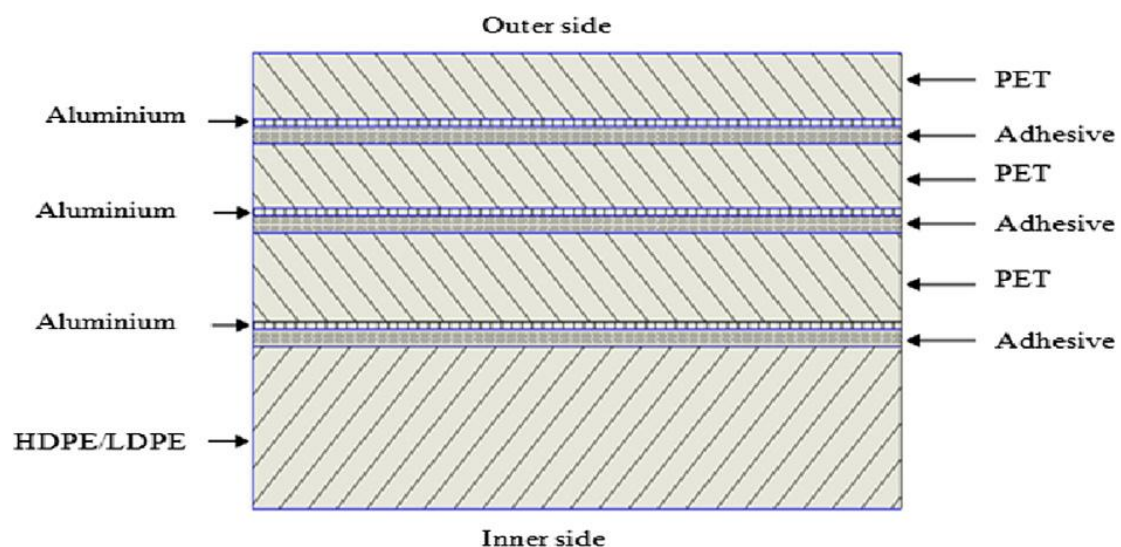


Figure 3 Typical multi-layer VIP envelop (Alam et al, 2011)

4.3.1 Protective layer

The protective layer is the outer one of envelope and it can protect the VIP from environmental damage and handling stresses which also acts as a substrate for barrier layer. Polyethylene terephthalate (PET) has a better barrier property which is used as protective layer currently due to its low cost. Other kinds of materials for the outer part of envelope is being discussed, for instance, taking Nylon 6 (Polyamide) to act as a protective layer in VIP envelope is employed by some researchers. Because of its high temperature application, heat pumps and water storage tanks are covered by this material due to its high melting point (225°C). The disadvantage of Nylon 6 is the high cost. (Alam et al, 2011)

4.3.2 Barrier layer

The middle layer in figure 3 is acts as a barrier layer to against air and water vapor transmission damage. It is formed by either an aluminum foil or metalized layers of polymers. The aluminum is attached to the polymeric substrate. The barrier layers numbers in a VIP envelope varies from one to three, but a single layer cannot functioning well while three layers structure is suitable due to its better barrier properties to against air and water vapor transmission damage. Polypropylene (PP) and polyethylene terephthalate (PET) are always being used as substrates. A research group investigated the use of metalized layer of ethylene vinyl alcohol copolymer (EVOH) and metalized layer of PET in VIP envelope (Araki K et al, 2009). They found that WVTR (water vapor transmission rate) and OTR (oxygen transmission rate) index were high if compared to the envelope with aluminum foil. It is also reported that the metalized layer of EVOH has better barrier properties than metalized PET in VIP envelope. However, because metal has high thermal conductivity, with it constructed in barrier layers the thermal bridging effect on edges of VIP would be enlarged. Silicon oxides (SiO_x) and silicon nitride (SiN_x) coatings could replace it to reduce the thermal bridge effect. However, SiO_x and SiN_x covered PET barrier for

VIPs has not been reported till now. Nevertheless, there is no doubt these two materials covered VIP have great potential and further investigation is required. Electro-spun Methyltriethoxysilane (MTES) nanofiber fabric has high thermal stability and super hydrophobicity which is also a potential barrier layer. (Alam et al, 2011).

4.3.3 Sealing layer

The sealing layer is the layer which closes the core material in the VIP. This layer performs the sealing function for the core material. Unqualified sealing result in approximately 30% total gas permeation in seams. Heating is always a sealing process to join each laminates. In the sealing process, the film surfaces are heated with pressure which creates a bond between two polymer layers due to diffusion. The temperature and time for sealing are very important factors because both of them will influence the sealing quality. The seal begins to form at the allocated temperature and then its strength increases to a maximum suitable value. Generally, low Density Polyethylene (LDPE) and High Density Polyethylene (HDPE) have been employed in VIP to act as the sealing layer. But in terms of available experiment, there is no significant difference between the seal strength of these materials which concluded that the choice of the sealing layer material should be based on the air and water vapor permeability. Other materials such as polybutylene (PBT) and high retort-cast polypropylene (HR-CPP) can be employed for sealing layers if high temperature working environment required. (Alam et al, 2011).

4.4 Absorption material: getters, desiccants and opacifiers

Getters and desiccants are acting as absorption material for adsorbing water vapors (desiccants) and gases (getters) inside the VIP core. It will extend the VIP useful life. The vapors or gases may rise from either environment or via out gassing of core and envelope. Opacifiers are functioning to reduce the radiative conductivity of the core material, since it is opaque to infrared radiation. Silicon carbide (SiC) is the favorable

material that used as opacifier in fumed silica VIP core. Other opacifiers such as carbon black, titanium dioxide (TiO₂) and iron oxide (Fe₃O₄) are also common materials. (Alam et al, 2011).

4.5 Drawbacks

Although VIP has significant great thermal insulation and less thickness advantage and it is widely employed and developed worldwide. But the drawback is apparent, since it is constructed in block, there must be some thermal bridge that exists in the seams between each VIP block. On the other aspect, deterioration is another tricky problem which will cause irreversible damage.

4.5.1 Thermal bridge

It is clear that VIPs cannot be treated as a single material but that they must be treated as a whole system. A lot of researchers carry out experiment on reducing and estimating the thermal bridging during its service life time. Thermal bridge should be considered for high insulation property material. From the construction of VIP and its function, it can be noticed some levels of thermal bridges: thermal bridge due to VIP envelope; the thermal bridge due to air gaps between two adjacent envelopes. These two types of thermal bridges will be detailed in next sections. (Ruben et al, 2010)

Thermal bridge due to VIP envelope

The two types of thermal bridge effects have a certain influence on the overall thermal performance of a VIP insulation layer: Due to this thermal bridge, the effective conductance Λ_{eff} of the vacuum insulation panel is higher than the “centre-of-panel ” thermal conductance. (Ruben et al, 2010)

$$\Lambda_{\text{eff}} = \Lambda_{\text{cop}} + \psi_{\text{edg}} \frac{P}{A}$$

P is perimeter of edges and A is the panel area. The linear transmittance ψ_{edg} in the equation depends on the panel thickness d, the “centre-of-panel” thermal conductivity

λ_{cop} , the barrier film thickness t_f and the equivalent foil thermal conductivity λ_f . This will result in different values for ψ_{VIP} depending on the laminate layers and the thermal properties. (Ruben et al, 2010)

Literature measurements shows some values of the linear transmittance ψ_{edg} from 0.001 to 0.400 W/mK, the effective conductivity λ_{eff} in the range of 0.0051–0.0086 W/mK for VIPs with a panel size of 1.00 m by 0.50 m by 0.02 m. The centre-of-panel conductivity λ_{cop} of 0.004 W/mK, depending on the properties of the envelope material. These data range show us the importance of the prediction of the influence of the panel edges. It comes to a calculation value of the overall thermal conductivity of the insulation layer or the assembly. (Ruben et al, 2010)

Thermal bridge due to air gaps between two adjacent envelopes

Because the VIP edge get the irregular shapes, the condition is possible that an air gap occurs between two adjacent VIP during construction. The influence of air gap was investigated. It was assumed that no air leakage from one side of the panel to the other side through the gaps. So it became clear that the influence of the air gap with laminated aluminum foils has a little influence on the linear thermal transmittance for the laminated aluminum foils: An increase in the range of 7~15% of $\psi_{\text{VIP,edg}}$ is tested for an air gaps up to 5 mm. However, an average value of $\psi_{\text{VIP,edg}} = 0.320$ and 0.170 W/mK is tested for panel-thicknesses of respectively 10 and 20 mm. Consequently, the VIP with laminated aluminum foils is recommended not be used in buildings with the panel size smaller than 1 m^2 due to the high relative importance of the linear transmittance of the edges. Compared to the aluminum foil laminates, the $\psi_{\text{VIP,edg}}$ changes more with the air gap variation if aluminum-coated multilayer foils are used for: An increase in the range of 600~900% of $\psi_{\text{VIP,edg}}$ is tested for air gaps of 5 mm compared to 0 mm air gaps. However, the value of the $\psi_{\text{VIP,edg}}$ keeps in the range of $0.012 \sim 0.022$ W/mK which is smaller when compared to laminated aluminum foils.

Accordingly, the gap for aluminum coated multilayer VIP barrier foils should be as small as possible to make suitable use of the high thermal resistance of VIP. (R. Ruben et al, 2010)

4.6 Deterioration

Deterioration occurs on some old buildings which have VIP insulation material installed for several years, so the shortcoming of VIP is gradually noticed. Since it is a new fashion building envelope material, it is easy that researchers only see the better property and ignore the lifespan.

The view of the deteriorated facade can be found in figure 4. There are many visible blisters can be seen in different place of the building facade. In the researcher's photo, there were 17 out of 88 VIPs in the whole facade showed a similar phenomenon. This clear incident indicates that the inner pressure of the VIPs must have risen gradually so that the overpressure caused the dishing of the building envelope. The driving force for this overpressure is due to the increasing of temperature which induced the daily solar radiation that resulting in the expansion. Hereby, the gas laws and temperature dependent desorption of water vapor are both of the reasons. This problem is about the kind of leakage responsible for this behavior. If the VIP barrier is damaged carelessly during the handling or installing, this phenomenon could be obviously clear. If the metalized barrier layers of the envelope were damaged, air and moisture would have permeated into the VIP over a longer period. Leakage might occur in thin metalized layers through which called pinholes of around 0.1~20 microns. The amount and size of the pinholes is the quality measure of these layers. That is the reason why VIP envelope is always covered by three layers of aluminum. Nevertheless, permeation can still go through the poorly sealed seams, but this is the responsibility of the supplier. (S. Brunner et al, 2012)



Figure 4 Expansion of VIP inside the building envelope (S. Brunner et al, 2012)

Another observed damage on the facade was the cracks in the building envelope engendered by the blisters (Shown in figure 5). These will allow moisture to bypass the very slow process of diffusion to reach the layers beneath the rendering directly in an efficient way of capillary react. Infrared pictures of the deteriorated facade were taken before sunrise in the morning. This method aims to get a maximum temperature gradient without thermal disturbance caused by solar irradiation. Figure 6 shows the investigated facade with the VIP insulation between the windows. Each VIP block is detectable due to the thermal bridge effect due to an EPS encapsulation building envelope. The area in a darker color means a lower surface temperature which indicates a lower thermal conductivity representing intact panels. Others in a lighter color indicating a higher surface temperature and therefore it have a higher thermal conductivity. It also means that VIP got a higher internal pressure as well as aerated panels. (S. Brunner et al, 2012)



Figure 5 The cracks due to inside VIP expansion (S. Brunner et al, 2012)

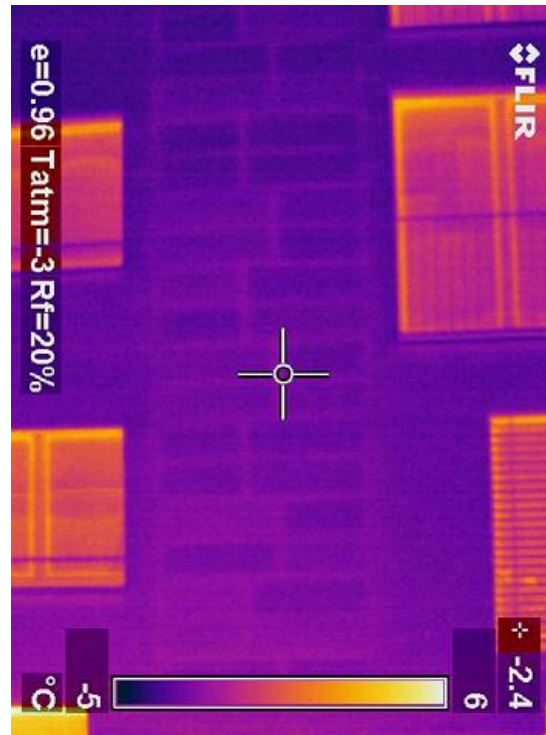


Figure 6 Infrared photo on a part of building façade (S. Brunner et al, 2012)

4.7 Heat transfer

After VIP material maintained a certain lower pressure value, the conductive heat transfer could be suppressed. The rest heat transfer models are solid conduction, radiation and gaseous conduction.

In general, thermal conductivity relationship can be expressed as (Alam et al, 2011):

$$\lambda_C = \lambda_S + \lambda_R + \lambda_G + \lambda_{CV} + \lambda_{COUP}$$

The λ_S is the solid thermal conductivity (W/mK); λ_R is the radiative thermal conductivity; λ_G is the gaseous thermal conductivity; λ_{CV} is the thermal convection within pores; λ_{COUP} is the thermal conductivity due to the coupling effect.

The thermal conductivity λ_{CV} of VIP core can be reduced by suppressing the thermal conductivity terms shown in the equation to minimum and is expected to be within the range of 0.004W/mK. In the equation λ_{COUP} represents coupling effect which becomes obvious at higher pressures for powders and fiber materials due to interaction effect between them in the VIP core. (Alam et al, 2011)

4.7.1 Solid conduction

Solid conduction occurs in the skeleton structure of core material, so the heat is transferred by physical contact of the constituent particles of the core material. The magnitude depends on the material structure, density and external pressure on the core. The following equation has the relationship with the material density.

$$\lambda_S = \rho^\alpha$$

The ρ is the density (kg/m³) and the index α has a value of unity for foam and in the range of 1.5~2 for nanomaterials. It is obviously that a material with a low density gets a lower solid conductivity. (Alam et al, 2011)

4.7.2 Radiation

Radiative heat transfer requires no medium and in the form of electromagnetic waves. It is a significant mode of heat transfer in vacuum conditions. It can be calculated by:

$$\lambda_R = (16n^2\sigma T_r^3)/(3E(T_r))$$

The n is the mean index of refraction; σ is the Stefan–Boltzmann constant (5.67*10⁻⁸W/m²K⁴); T_r is the average temperature (K) of the insulation material; E is the extinction coefficient of the insulation material (m⁻¹). (Alam et al, 2011)

By adding some opacifier to the core material, the radiative heat transfer can be reduced. It is found that at room temperature, the thermal conductivity of pure silica is higher by 0.002~0.003W/mK than that of silicon carbide opacified precipitated silica. (Hull T.R& Stec A.A, 2011)

4.7.3 Gaseous thermal conduction

Heat transfers in the form of convection and conduction processes in gases. The intensity depends on the ratio of mean free path of gas molecules and the material pore size. The following equation can be employed to estimate the gas conductivity; λ_G is the function of Knudsen Number. (Alam et al, 2011)

$$\lambda_G = \lambda_0 / (1 + 2\beta Kn)$$

The λ_0 is the thermal conductivity of air at atmospheric pressure; β depends on accommodation coefficient and the adiabatic coefficient of the gas which is also a coefficient; Kn is the Knudsen Number, and it is equal to the ratio of molecular mean free path length (l) to the pore size diameter (U). (Alam et al, 2011)

$$Kn = l/U = (k_B T) / (\sqrt{2} \phi d^2 p \Phi)$$

The k_B is the Boltzmann's constant (1.38×10^{-23} J/K); T is the thermodynamic temperature (K); d is the diameter of gas molecule (m); p is the pressure (Pa) of gas.

The next equation is used to calculate the value of gaseous thermal conductivity for different pore sizes.

$$\lambda_G = \lambda_0 / (1 + 0.0032/P\Phi)$$

The P is the pressure, Φ is the pore width of the porous insulation material.

In figure 7, it can be seen that even at atmospheric pressure, the materials with pore size in the nanometeric range still have negligible gaseous thermal conductivity. It is obviously that with the pore size increasing, relatively lower pressure is required to keep acceptable gaseous thermal conductivity. (Alam et al, 2011)

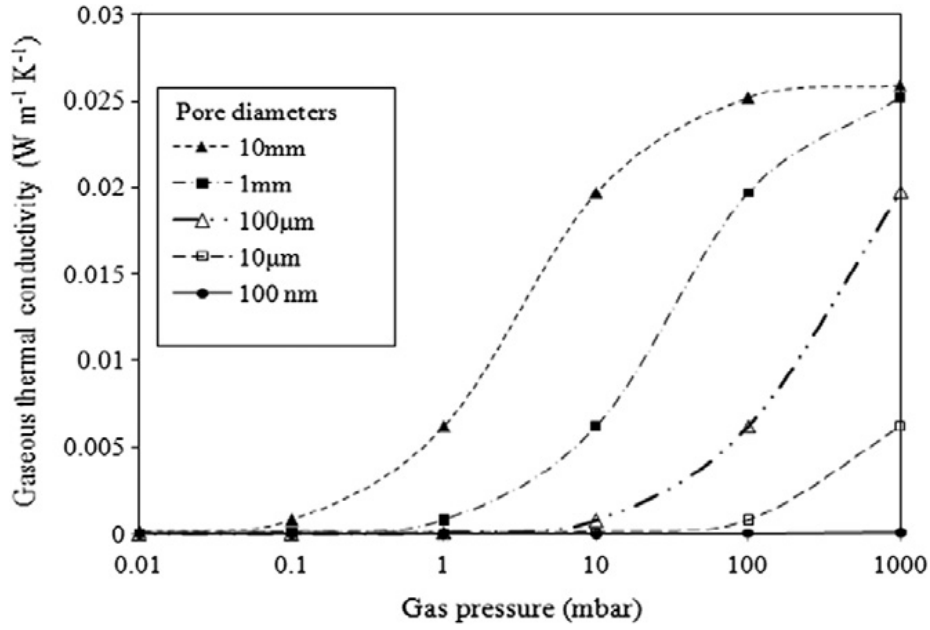


Figure 7 Relationship of gaseous thermal conductivity as a function of gas pressure
(Alam et al, 2011)

4.8 Economic situation

Here comes one example which studied by some UK researchers. Figure 8 compares the payback period predicted for VIP and EPS employed building under different scenarios of interventions, and the details are shown in table 1. For convenience calculations of typical U-values for current UK buildings, walls $0.51\text{W/m}^2\text{K}$ roofs $0.25\text{W/m}^2\text{K}$, floors $0.18\text{W/m}^2\text{K}$ and windows $1.4\text{W/m}^2\text{K}$ were average assumed. The payback period (PBP) indicates the time required to recover the cost of insulation. It is defined as the ratio of material cost to the annual savings in heating cost. Then the annual heating cost (C_A) could be calculated. The parameters used for payback period calculation are shown in table 1. (Alam et al, 2011)

$$\text{PBP} = C_{\text{ins}} / (C_{A,\text{eis}} - C_{A,\text{imp}})$$

$$C_A = (86400 \cdot \text{HDD} \cdot C_f \cdot U \cdot \text{PWF}) / (H_v \cdot \eta)$$

$$\text{PWF} = N / (1 + i)$$

In equation, PBP is the Payback period(year); C_{ins} is the insulation cost (£); $C_{A,\text{eis}}$ is the annual heating cost with current U-value (£ per annum); $C_{A,\text{imp}}$ is the annual heating cost with improved U-value (£ per annum); C_f is the cost of fuel (£/m³);

H_v is the heating value of fuel (J/m^3); η is the heating system efficiency. PWF is the present worth factor which contains interest rate (i) is equal to inflation rate; N is the insulation life time (years). (Alam et al, 2011)

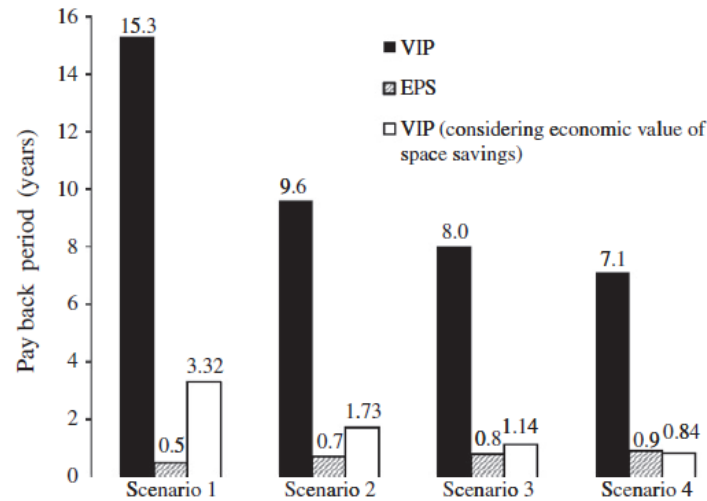


Figure 8 Payback period of VIP and EPS in different scenarios

Table 1 Insulation scenarios and parameter for calculate payback period

Parameters		Value
Scenario 1	Average building U -value	$0.40 (\text{W m}^{-2} \text{K}^{-1})$
	(VIP) Thickness	10 mm
	Cost	$\text{£}70 \text{ m}^{-2}$
Scenario 2	(EPS) Thickness	48.3 mm
	Cost	$\text{£}2.40 \text{ m}^{-2}$
	Average building U -value	$0.31 (\text{W m}^{-2} \text{K}^{-1})$
Scenario 3	(VIP) Thickness	25 mm
	Cost	$\text{£}80 \text{ m}^{-2}$
	(EPS) Thickness	113 mm
Scenario 4	Cost	$\text{£}6.19 \text{ m}^{-2}$
	Average building U -value	$0.27 (\text{W m}^{-2} \text{K}^{-1})$
	(VIP) Thickness	40 mm
Scenario 4	Cost	$\text{£}80 \text{ m}^{-2}$
	(EPS) Thickness	180 mm
	Cost	$\text{£}8.38 \text{ m}^{-2}$
Other parameters	Average U -value	$0.24 (\text{W m}^{-2} \text{K}^{-1})$
	(VIP) Thickness	60 mm
	Cost	$\text{£}80 \text{ m}^{-2}$
Other parameters	(EPS) Thickness	256 mm
	Cost	$\text{£}10.78 \text{ m}^{-2}$
	Fuel	Natural gas
Other parameters	Emission conversion factor	0.20
	HDD	$1931 ^\circ\text{C day}$
	C_f	$\text{£}0.40 \text{ m}^{-3}$
Other parameters	H_v	$39.5 \times 10^6 (\text{J m}^{-3})$
	η	0.9
	N	25
Other parameters	i	10%

In scenario 1, VIP and EPS with a thickness of 10 mm and 48.3 mm respectively were considered for building insulation, the average U -value was calculated as $0.40 \text{ W/m}^2\text{K}$. In scenario 2, VIP and EPS with a thickness of 25 mm and 113 mm respectively were considered, resulting in an average U -value of $0.31 \text{ W/m}^2\text{K}$. Predicted payback periods

of VIP for scenarios 1 and 2 are really long compared to those calculated for EPS. In scenario 3, the payback period of VIP and EPS insulation were predicted just sufficient to achieve an average U-value of $0.27\text{W/m}^2\text{K}$. It was found that VIP gets approximately 10 times longer than that for EPS in payback period. In scenario 4, the compared payback period of insulation required to achieve an average building U-value of $0.24\text{W/m}^2\text{K}$. EPS had a payback period 8 years that shorter than VIP but EPS required an unsuitable thickness of 256 mm. The main reason for the longer payback period of VIP in all scenarios is the high cost. In the case of current commercial buildings, especially those cannot be insulated on the outer surfaces; the VIP is a favorable alternative to traditional insulation materials as the surface of the building will not be optimized as much. In Scenario 4, VIP was found to achieve a considerably shorter payback period if the economic value of the potential space savings due to thinner VIP was employed in all cases, it was even achieved a shorter period than EPS in scenario 4. The economic value of saved space, an average rent of London commercial buildings was considered as $\pounds 40\text{ ft}^{-2}$. (Alam et al, 2011)

4.9 Beyond

Although VIP got lots of advantage, but the drawback is still apparently. So if we can fabricate the VIP without these disadvantages, then it will be a break through in building design. Back to the topic, the shortcoming needs a review.

One of the special characters of VIP is their envelope, it performs some functioning in service life, but it will gradually be damaged/degrade as time goes by. The metal corrosion will result in increasing of thermal conductivity and also cause bad effect on the vacuum condition. Also water and vapor intake cause the same problem. So if the VIP material fabricated without envelope and without the possible of water and vapor intake, then the improvement will be a significant leap.

On the other hand, envelope can not be cut on site. That would be a tricky thing, because the “to be covered” area requires exactly calculation to design the VIP size which can avoid an improper VIP cover. Without the envelope, the VIP insulation

material is possible to be cut like EPS. On-site cutting is allowed so that the covering work is more flexible. (Ruben et al, 2010)

The question is coming, it need to build a high performance thermal insulation material which no longer need envelope with only core but still with vacuum technology applied. Three conditions can be discussed. The first condition can be found in the pore construction. The core material of current VIPs is 100% open porous, and a possible modification can be adopted with porous materials of 100% closed pores, maintaining a vacuum situation on the pores level. The second condition is based on the need of a vacuum which is expressed as function of the pore sizes. Pores sizes and pore size distribution can lead to an influence on the quality of vacuum. Even just develop a material that no longer needs vacuum but still based on the principles of vacuum technology. The third condition is together with two above combinations. (Ruben et al, 2010)

4.9.1 Nano insulation material (NIM)

The nano insulation material (NIM) may be defined as a homogeneous material and also achieves high insulation performance qualities mainly due to its open or closed nanoporous structure. The principle of vacuum insulation panels is based on the Knudsen effect which described that gaseous thermal conductivity λ_g can be influenced by both the mean free path l_{mean} of the gas and maximum pore size δ of the medium. When gas pressure reducing, the gaseous thermal conductivity is still unaffected until the mean free path of the gas molecules reaches values in the same order of size as the largest pores in the material. When the material pore diameter changes to a condition that is less than the average free length of gas molecules path, the air molecules will only collide with the pore surfaces, however, energy transformation is also unaffected by elastic impact. In this case, vacuum is no longer required because of the used material got a maximum pore size which much smaller than l_{mean} of free air. It is called either 'mesoporous materials' with a pore size of 50 nm or less, or 'microporous materials' with a pore size of 2 nm or less. All of them

could reduce the gaseous thermal conductivity without a vacuum condition employed. A nano insulation material (NIM) is now achieved. In another words, the thermal conductivity degradation due to gas penetration can be neglected because air is allowed in the pores, which result in an air-tight envelope omitted. (Ruben et al, 2010). The comparison is shown in figure 9.

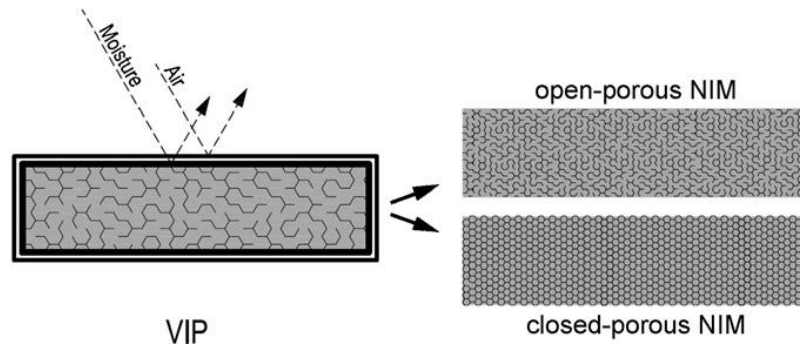


Figure 9 Conception comparisons between VIP and as set forth NIM (Ruben et al, 2010)

General well-known mesoporous materials are aluminium oxide or oxides of some metals like ^{41}Nb , ^{73}Ta , ^{22}Ti , ^{40}Zr and ^{50}Sn with high thermal conductivities. In 1990s, oil company ‘Mobil’ developed a mesoporous silican which result in materials called MCM-41 with pore sizes between 1.5 and 10 nm (Beck, 1992) and SBA-15 with pore sizes between 4.6 and 30 nm (Zhao, 1998) Nowadays, the development of mesoporous materials is on the way. During the synthesis, the pore size of the materials can be adjusted by controlling the reaction time and temperature, using swelling organic molecules, adjusting the surfactant, post-synthesis or changing the calcinations conditions to achieve. (Giraldo, 2007).

5. Discussion and conclusion

The thermal insulation functions can be performed better than all kinds of traditional materials. On the other hand, due to problem that traditional polymer material must be constructed relative thicker to achieve better thermal performance, VIPs material still get a better situation than that. VIPs can be constructed thinner which saves the space.

Obviously, VIPs material achieves better performance on both insulation and space saving. Employing VIPs as the building envelope cover will not only increase the thermal comfort, but also reduce the CO₂ emission due to the reduction of thermal input. As an insulation material, the application in the place such as south of China will mitigate the discomfort feeling in winter and insulate the external heat in summer. What is more, space saving benefits the applied building which is another forms of saving.

But the cost is still high due to its nature, and the developing of core and barrier materials should be carried on. An essential point is its drawback, the determination may occur for long time usage. Like S. Brunner said, researchers may ignore the lifespan when they improve VIPs' thermal performance. The VIP envelope sealing damage is the deadly factor. It is the direct cause of the thermal performance decreasing, and forms a large thermal bridge. The expansion is also can not be omit, because with too much single VIP expansion, the building envelope will be destroyed by the cracks. And after a rainy day, the damage to the building envelope, especially mortar covered, will be a disaster.

So the development requires considerations that include both the thermal performance and duration. From Giraldo's researches, the VIP material without envelope is the optimal choice. The cut-on-site property saves the material as well. However, the cost will not decrease, that is the trickiest part. The widely adopting in developing country like China still required cautious considerations.

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