From VIP to Building Panel

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1 Introduction

Vacuum Insulation Panels (VIP) have the potential to play an important role in achieving energy efficient buildings by increasing the thermal insulation performance of the building envelope. Until now, research work has been concentrated on the VIPs themselves. But the question is how to implement a VIP panel in a building construction in such a way that the thermal advantages are fully used.

For this it is necessary to look to the interaction between the thermal insulation layer and the building component in which it is integrated of and to the interaction of the insulating building component with other building components such as the bearing construction.

The required performance of a facade panel is multifunctional. Besides the thermal insulation, durability and live time are defining qualities. Only then the performance of other aspects is of interest. This means that the application of a panel is based on a combination of qualities of physical, constructional and even esthetical qualities. This has a feedback on the way a panel is to be composed.

2 Thermal insulation

Assessing the thermal conductivity of different insulation materials, the advantage of vacuum insulation is enormous. But also the improvements of the so-called traditional insulation materials are of importance, see table 1 for an overview.

Insulation material	λ_{core} in mW/mK
Glass fibres	35
EPS, PUR	30 – 25
Fumed silica	20
Modified resol foam	20
VIP	4

Table 1: Overview of λ of different insulation materials

The given value of 4 mW/(m·K) for VIP is the centre-of-panel thermal conductivity under ideal circumstances. Taking into account the aging effect due to pressure increase and moisture accumulation, EMPA declares a λcore of SiO_2 based VIP of 8 mW/(m·K) with polymer-based barrier and 6 mW/(m·K) with aluminium foil barrier.

Thermal bridging due to the barrier envelope increases the thermal conductivity.

The design value λ_{eq} follows (1) from

$$\lambda_{dg} = \lambda_{core} + \psi_{edge} \cdot d \cdot \frac{P}{A} \tag{1}$$

with

ψ_{edge} = linear thermal edge transmittance in mW/(m·K)
P = perimeter of VIP panel in m
A = surface of VIP panel in m^2
d = thickness of the VIP panel in m
λ_{dg} = design value of VIP panels in mW/(m·K)

Ghazi Wakili [1] calculated for the term $\psi_{edge} \cdot d$ P/A a value between 0,56 and 0,74 mW/(m·K) depending on the thickness of the metallized barrier envelop (90 nm – 300 nm) and 3,78 mW/(m·K) for an aluminium barrier of 8 µm.

This results in a design value of

- metallized barrier: 8,5 mW/(m·K)
- aluminium barrier: 10 mW/(m·K)

Looking to the special attention of working up VIP in a building panel, it may by clear that the proposed design value reduces the advantage of using VIP. This means that research is necessary dealing with the improvement of barriers with a metallized barrier and a silica core the live time is longer than 50 years.

Thermal analyses of the first panel prototypes show the enormous effect of the materialisation of the inner and outer facing of a panel and the way the facing sheets are connected for mechanical reason, table 2.

Connecting Spacer	**Panel dimension**	
	1 x 1 m^2	1,4 x 1,4 m^2
Conventional alu	1,44	1,09
Improved Swiss spacer	0,47	0,39
Barrier film: polymer + laminated aluminium Facing: glass / aluminium Center of panel: U = 0,26 W/(m^2·K)		

Table 2: Influence of spacers on mean U-value of a building panel

The often-used center of panel value is not representative for the thermal quality of the panel. A clear and correct information is the first condition for a reliable communication with building designers.

In general, the calculation of the thermal resistance and thermal transmittance is given in ISO standard 6946 [2]. For a building component consisting of homogeneous and inhomogeneous layers an estimating approach is give in the way

$$R_T = \frac{R^I{}_T + R^{II}{}_T}{2} \tag{2}$$

with

R_T = thermal resistance of a plane building component in m^2K/W
$R^I{}_T$ = calculated maximum value of the thermal resistance in m^2K/W
$R^{II}{}_T$ = calculated minimum value of the thermal resistance in m^2K/W

The given calculation methods for R^{I}_{T} and R^{II}_{T} are however not appropriate if the insulation layer is broken through a metal layer. This is for example the case if the spacer is metallic. Then a more accurate numerical calculation method as given in ISO 10211 is appropriate [3]. However the Dutch Practice Code 2068 [4] introduces a weighting coefficient in combination with (2).

How to deal with an insulating panel in a construction component (frame) is given in ISO 10077-1. In connection with the calculation method for a window fixed in a frame, the calculation of the thermal performance of a building part consisting of a panel placed in a frame, follows from:

$$U_{bp} = \frac{A_p U_p + A_f U_f + l_p \psi_p}{A_p + A_f} \tag{3}$$

with

U_{bp} = thermal transmittance of building element in $W/(m^2 \cdot K)$
A_p = visual area of the panel in m^2
U_p = center of panel thermal transmittance in $W/(m^2 \cdot K)$
A_f = frame area in m^2
U_f = thermal transmittance of frame in $W/(m^2 \cdot K)$
Ψ_p = linear thermal transmittance due the combined thermal effects of panel and frame in W/mK

Application of (3) means that the thermal effect of the spacer resulting from the interaction with the frame and facings is summarised in Ψp. Figure 1 and (4) gives the calculation procedures [3].

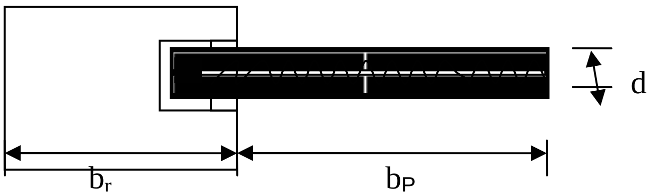

Figure 1: Building part section with frame and panel

$$\Psi_P = L_\Psi^{2D} - U_f b_r - U_g b_p \tag{4}$$

where

Ψ_P = linear thermal transmittance, in $W/(m \cdot K)$
L_Ψ^{2D} = thermal conductance of the section shown in figure 3, in $W/(m^2 \cdot K)$
U_f = thermal transmittance of the frame section, in $W/(m^2 \cdot K)$
U_P = thermal transmittance of the central area of the panel, in $W/(m^2 \cdot K)$
b_r = the projected width of the frame section, in m
b_P = the visible width of the panel, in m

The thermal transmittance of the frame section, Uf is defined by (5). In the calculation model of figure 3 this means that the panel is replaced by an monolite insulation layer with thermal conductivity λ = 0,035 $W/(m^2 \cdot K)$ and without facings.

$$U_f = \frac{L_r^{2D} - U_p \cdot b_p}{b_f} \tag{5}$$

where

L_r^{2D} = the thermal conductance of the section shown in figure 1 but with the monolite insulation layer in $W/(m^2 \cdot K)$

3 Thermal bridging due to panel edge construction

Two (façade) panel constructions can be distinguished: the sandwich construction and the edge spacer construction see figure 2.

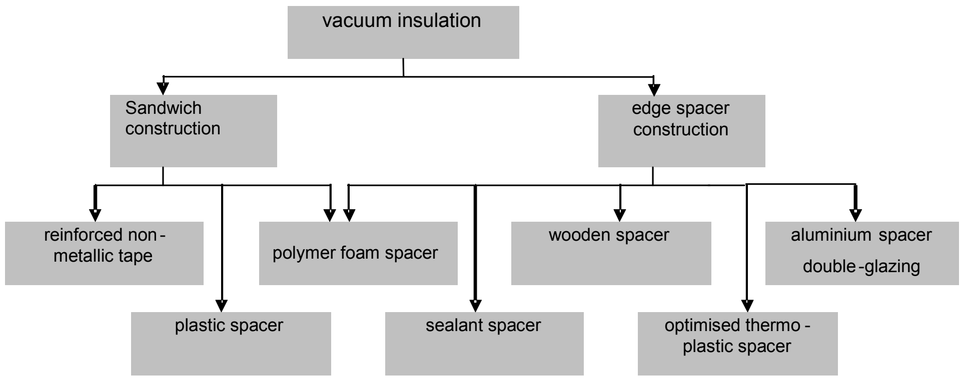

Figure 2: Overview of panel construction and edge spacers

The difference between the two types lies in the load transmitting system. With a edge spacer construction the facings of the building panel are mechanically jointed by means of a load transmitting edge spacer, while with the sandwich construction the facings are adhered to a core material to form a structurally active sandwich. This sandwich construction, contrary to the edge spacer construction, does not introduce a thermal bridge with the panel. The ψ edge –values for different edge spacers, which are shown in figure 3, are calculated with the 3D steady-state simulation software TRISCO. Table 3 and 4 gives some calculation results.

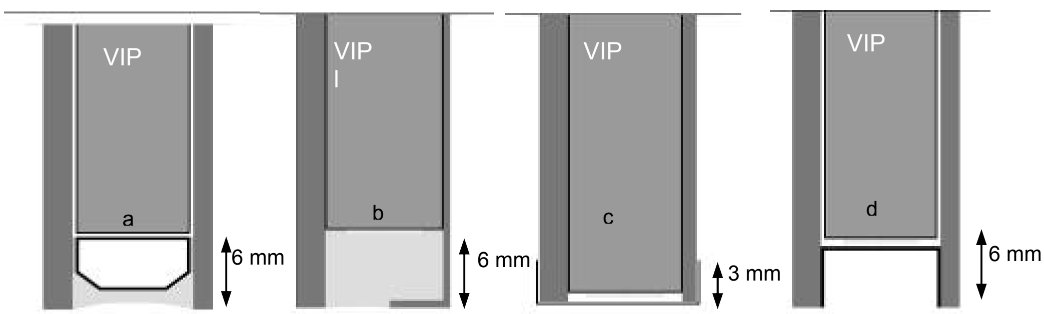

Figure 3: Different edge spacer constructive
a) aluminium spacer double-glazing **b) sealant spacer**
c) reinforced non-metallic tape **d) polymer U-section**

The following specifications of the edge spacer materials are used:

- Fumed silica based VIP (λ = 0.004 W/(mK))
- Edge spacer a: standard double-glazing aluminium edge spacer (λ = 225 W/(mK))
  polysulfide sealant λ = 0.40 W/(m·K)) and silicon sealant (λ = 0.35 W/(mK))
- Edge spacer b: butyl sealant (λ = 0.24 W/(m·K))
- Edge spacer c: non-metallic tape ($\lambda \approx$ 0.33 W/(m·K)); thickness ≈ 0.15 mm
- Edge spacer d: polymer U-section (λ = 0.40 W/(m·K)); thickness = 0.5 or 1.0 mm
  adhesive (λ= 1.0 W/(m·K))

Barrier: metallized HDPE film

outside facing: insulation: inside facing:	glass 6 mm vacuum insulation panel 20 mm trespa 3 mm	 aluminium 1.5 mm	 steel 0.75 mm
spacer a		0.320	0.230
spacer b	0.016	0.095	0.084
spacer c	0.011	0.011	0.011

Table 3: Calculated linear thermal transmittance ψ-edge W/(mK) for different edge spacers constructions and facings.

Spacer c construction corresponds with a sandwich panel. The ψ - edge is considerably lower than the other more constructional spacers. Also the effect of the facings is explicit visible.

		Outside facing: Insulation: Inside facing:	Mdf* 4 mm mdf 4 mm	glass 4 mm vacuum insulation panel 20 mm glass 4 mm	aluminium 2 mm aluminium 2 mm
spacer d	1.0 mm		0.053	0.060	0.085
spacer d	0.5 mm		0.051	0.058	0.079
spacer d	Insulated air gap		0.024	0.025	0.030

**mdf: medium density fibreboard*

Table 4: Calculation results for the linear thermal transmittance ψ-edge [W/(mK)] for the edge spacer d construction with different facings and spacer thickness

As can be seen, aluminium spacers (spacer a) are not suitable for façade panels with incorporated vacuum insulated panels; a linear thermal transmittance, *ψ-edge*, of approximately 0.25 to 0.35 leads to an increase in effective *U*-value for a panel of 1 x 1 m^2 with 20 mm vacuum insulation panel from approximately 0.2 to 0.45 W/(m^2·K) or 0.55 W/(m^2·K), i.e. an increase of 125% or more. Better performances can be expected from the spacers b and d, while the best performance is calculated for the sandwich panel with a reinforced non-metallic tape with U_{eff} = 0.22 W/(m^2·K) for a 20 mm vacuum insulation panel construction. This reinforced tape, however, might not adequately transmit forces, especially if wind suction is the main load to be transmitted.

For sandwich panels, however, this edge spacer does not have to transmit loads and can thus be used for safety and protection against damage.

4 Thermal performance of a door panel

Several door manufacturers investigate the possibility of using VIPs instead of polyurethane foam as thermal insulation in outer doors. These doors are mostly build up from hdf facings or hdf-alu-hdf sandwich facings and a polyurethane core. The adhesion between the facings and the core foam makes sure that the door acts as a structural sandwich. A wooden frame, however, is added to the doors at the sides to create an aesthetically attractive side, to give support to the door mountings and to add additional stiffness to the door. Often, a steel stabilizer is added at one side of the door panel to prevent door warping. This stabilizer can have different forms: a tube, a U-shape or two parallel strips. These stabilizers, however, cause a non-negligible thermal bridge.

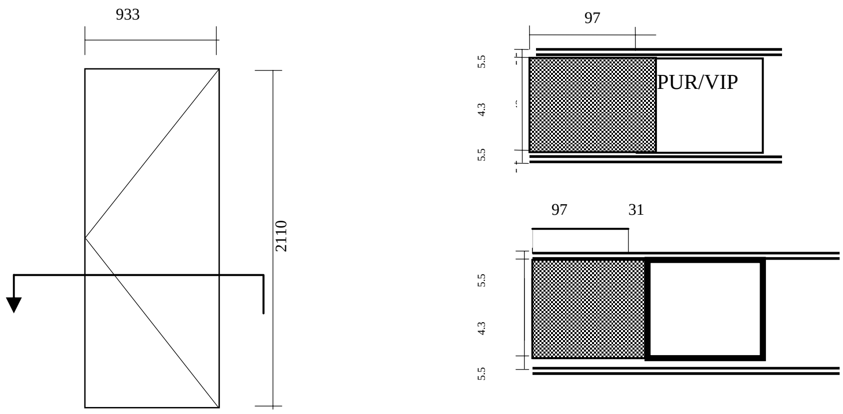

Figure 4: Overview of door panel constructions with polyurethane and stabilizers

The thermal resistance of four different door variants was calculated: with polyurethane or VIP as core with or without a steel stabilizer. Figure 5 shows the effective or overall U-value of a door panel with a thickness of 54 mm. The results quite distinctly show that replacing polyurethane foam by vacuum insulation leads to a reduction in U-value of 20% to 31%. The thermal bridging due to the stabilizer however is also quite visible a reduction of 25% to 35% if no stabilizer is used.

To overcome the panel-warping problem without steel stabilizers a 0.3 or 0.5 mm thick aluminium plate in the facings on both sides of the door has been introduced some years ago.

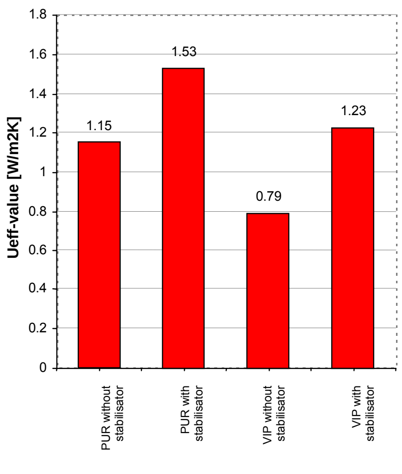

Figure 5: Effective U-value of an outer door panel doors with different core materials and stabilizers

5 Structural requirements

Structural requirements on the vacuum insulation panel itself only apply to VIP used in sandwich components. In other construction systems the VIP does not have to bear loads because the panel facings and the edge spacer construction fulfil these.

According to ASTM C 393: *Standard Test Method for Flexural Properties of Flat Sandwich Construction* three-point and four-point bending tests have been conducted on 20 mm thick fumed silica core based VIP and on sandwich panels made of the same 20 mm thick VIP sandwich panels with facings of 4 mm mdf or glass. The adhesive used to fix the facings on the vacuum insulation is a Polyurethane based glue.

Table 5 summarises the measured flexural mechanical properties for single vacuum insulation panels (vacuum intact and with lost vacuum). Comparing the results with the data on fumed silica panels themselves, vacuum insulation panels have a Young's modulus higher than the fumed silica core material itself. This, however, is not so astonishing, because the core is restricted in its movement by a low gas pressure, i.e. vacuum, and a barrier envelope. The value for the Young's modulus, however, is rather low compared to steel, aluminium, glass or the barrier envelope, which have moduli of 210000, 70000, 70000 and approximately 2000 MPa respectively. VIP is therefore preferably applied in situations in which no big flexural loads act upon the VIP panel.

	Flexion Modulus VIP *MPa*	**Ultimate Flexural Strength VIP** *MPa*	**Deformation at Yielding VIP** *%*	**Deformation at Fracture VIP** *%*
VIP, intact	63.8 ± 8.6*	639.8 ± 109.9*	1.34 ± 0.38*	-
VIP, no vacuum	38.6 ± 10.7*	611.6 ± 45.3*	0.80 ± 0.16*	-

** Silicia core uncertainty for a 95% confidence interval*

Table 5: Flexural properties of vacuum insulation panels

Table 5 also shows that VIP which have lost their vacuum are less stiff than undamaged panels, while the ultimate flexural strength of both panels is more-or-less equal. This indicates that the pressure difference caused by the vacuum on one side has a significant influence on the Young's modulus but not on the strength of the panel. For practical purposes, in the case of a perpendicular to surface loaded panel, a loss of vacuum will increase the deflection of the panel with a factor of about 2, but will not cause the panel to fail directly.

So, additional safety precautions are not required, unless indirect failure due to slipping out of its grooves is imminent. This, however, could actually only be the case if vacuum insulation panels are applied without a protecting and load bearing facing on both sides, which is only a theoretical situation.

	Measured flexural stiffness panel Nm^2	**Ultimate Flexural Strength Panel**** *MPa*	**Deformation at Fracture Panel** *%*
Mdf facing VIP, intact	15.4	4.3 ± 0.6*	12.2 ± 4.5*
Mdf facing VIP, no vacuum	6.7	3.9 ± 0.5*	12.3 ± 0.6*
Glass facing VIP, intact	30.6	4.1 ± 1.6*	1.2 ± 0.3*
Glass facing VIP, no vacuum		4.1 ± 0.5*	1.5 ± 0.3*

* *uncertainty for a 95% confidence interval*

** *flexural properties of sandwich panels with vacuum insulation panels as core material and different facings.*

Table 6: Results of tests of sandwich panels with a VIP core

The measure flexural stiffness of the sandwich panels are substantial less then the calculated theoretical flexural stiffness. Since the flexural stiffness of the VIP itself is only slightly smaller then the measured sandwich panel flexural stiffness it can be concluded that the behaviour of these tested panels is far from ideal sandwich behaviour. So, more research has to be conducted into the optimization of adhesive – VIP and adhesive – facing interfaces.

The measured data are representative for panel dimensions of 350x150 mm^2. At this time it is uncertain whether the data can be used for structural calculations on panels of different dimensions or not, because the influence of the high barrier envelope and the vacuum on the mechanical behaviour on a microscopic level has not yet been fully investigated.

6 Environmental conditions

The temperature and relative humidity conditions around the vacuum insulation panel incorporated into a façade panel or a door are important parameters concerning the process of thermal conductivity ageing.

Thermal calculations on a building panel with an incorporated vacuum insulation panel have been performed. Figure 4 shows the construction of the panel that was subjected to the calculations.

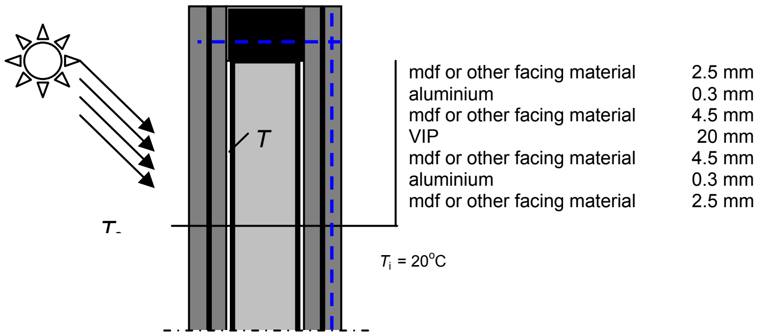

Figure 6: Cross-sectional drawing of a building panel used in the thermal simulations

The temperature of the VIP barrier film on the outside was calculated for a period of one year. Hourly average Dutch climatic data for 1991 (test reference year) are used. In Figure 7 the results are presented in the form of a frequency distribution of temperatures.

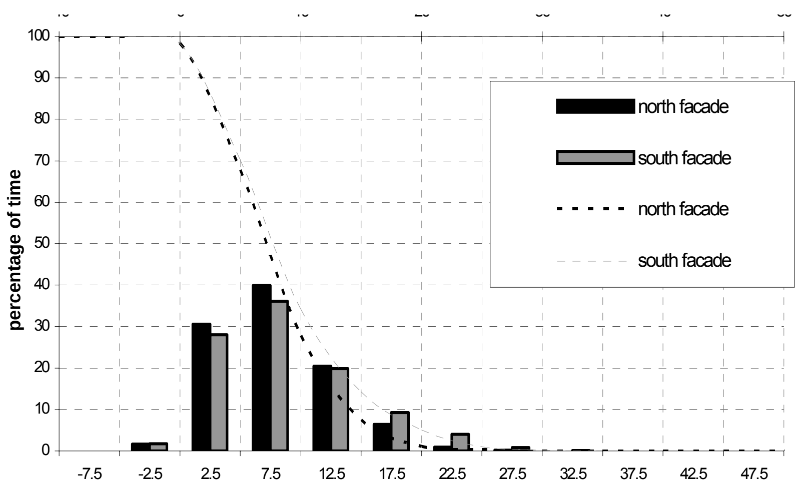

Figure 7: Temperature frequency distribution of VIP (U-value=0.2 W/(m^2·K)) high barrier film in a façade panel for a north and south façade according to Dutch climatic data.

The calculated maximum temperature of the barrier film is 44.6°C for a south façade and 41.3°C for a north façade.

For vacuum insulation panels with a fumed silica core the film is the temperature-limiting factor. This means that VIP with barrier envelopes comprising an LDPE sealant layer can operate up till a temperature of 85°C max. This is however beyond the standard temperature range for building applications. The only remaining concern about high temperatures for VIP in building panels is the combination of high temperature and high partial water vapour pressure on the serve life.

Simulations have been conducted of the moisture behaviour of a (door) panel, figure 8, in which a VIP is incorporated. For this the following is assumed: a panel is normally produced in a more or less conditioned environment. For the calculations a reference of 21°C and 50% relative humidity was taken. Under these environmental conditions a certain amount of water is present in the facing of the panel, the equilibrium moisture content *EMC (*in mass or volume percent) which approximately equals the equilibrium water content, Ψ_e [mass or volume %]. For doors a typical facing is made of medium/high density fiberboard (mdf/hdf). Other facings are possible as well, therefore different facing materials are simulated.

The panel is regarded as a closed system; the liquid water and water vapour in that part of the facing, which is inside the closed system, is more or less trapped. No moisture exchange between the inside of the door or panel and the exterior air takes place. Because of the presence of an aluminium barrier layer in the facing the simplification of a closed system for a short time scale will not be far from reality.

For the amount of water present in the closed system, m_w [kg] the following formula can be derived [5]:

$$m_w = A\left[\left[d_{mdf}(\varepsilon - \psi_e) + d_{air}\right]\frac{\phi p_{sat}(T)M_w}{RT} + d_{mdf}\psi_e\rho_w\right] \tag{6}$$

In which:

A	panel surface area [m^2]
d_{mdf}	thickness of mdf layer between VIP and aluminium [m]
d_{air}	thickness of air gap [m]
ε	porosity [-]
ψ_e	equilibrium water content in the liquid phase [V_{H2O}/V]
ϕ	relative humidity [-]
p_{sat}	saturation pressure [Pa] p_{sat} = f(T)
R	universal gas constant [J mol^{-1} K^{-1}] R = 8.31 J mol^{-1} K^{-1}
ρ_w	density of water ρ_w = 1000 kg m^{-3}
M_w	Molar mass of water [kg mol^{-1}] M_w = 0.018 kg mol^{-1}
T	absolute temperature [K]

In (6) the environmental conditions during production are valid.

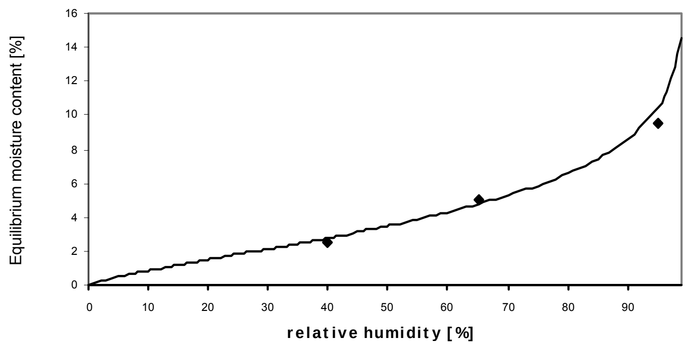

Figure 8: Equilibrium water content ψe as a function of relative humidity ϕ for MDF.

Between the equilibrium water content and RH there exists a correlation. For mdf the correlation between the equilibrium water content and relative humidity is depicted in figure 8. In this figure some empirical values are given by dots. For many building materials the sorption isotherm can be modelled with a modified Henderson's equation of the following form:

$$\psi_e = \frac{1}{100} \cdot \left[\frac{-\ln(1-\phi)}{A(\theta + B)} \right]^{1/C} \qquad (7)$$

In this equation θ is the temperature in ^{0}C and A, B and C are model constants, which depend on the material evaluated. For some of the evaluated materials these model constants can be found by fitting equation (7) to textbook data [5], which yields the following values:

mdf:	$A = 1.484\text{x}10^{-3}$ [$°C^{-1}$];	B = 89.72 [°C]; C = 1.237 [-]
hardboard:	$A = 0.766\text{x}10^{-3}$ [$°C^{-1}$];	B = 62.80 [°C]; C = 1.552 [-]
plywood:	$A = 1.311\text{x}10^{-3}$ [$°C^{-1}$];	B = 123.5 [°C]; C = 1.082 [-]
gypsum board:	$A = 4.886\text{x}10^{-3}$ [$°C^{-1}$];	B = 348.4 [°C]; C = 0.421 [-]

A change in temperature leads to a new equilibrium situation between Ψ_e and ϕ. So a change in T will result in a change in ϕ in the air gap between the VIP barrier and the facing. The results of the calculations are presented in figure 9 for a hardboard, plywood, mdf and gypsum board facing. From this figure one can conclude that the relative humidity in the facing material pores and at the interface VIP-facing increases with increasing temperature for hygroscopic facing materials. Theoretically figure 9 is only valid if no air space between VIP and facing is present.

For highly hygroscopic materials, however, a small air gap is insignificant concerning the calculated relative humidity.

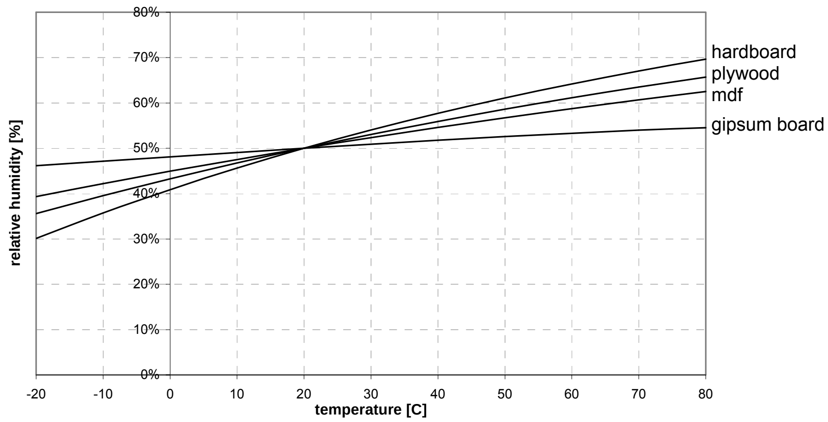

Figure 9: Relative humidity at the boundary between VIP and facing as function of temperature for four different facing materials and at production-conditions of 50% relative humidity and T = 20 °C. No air space between VIP and facing

For non-hygroscopic or for practically non-hygroscopic facing materials this air gap dominates the moisture behaviour; due to the increase in saturation pressure with increasing temperature there is a decrease in RH according to the perfect gas law.

From figure 9 one can learn that the relative humidity at the interface between VIP and facing increases with increasing temperature. This relative humidity increase raises the permeability of the high barrier envelope with respect to moisture permeation. This means that water vapour will enter the VIP more easily. The increase in relative humidity, however, is small (some 12% absolute for a mdf facing and a temperature increase from 20°C to 65°C). But, the increase of partial water vapour pressure at the same boundary, p_v, is much higher due to a more or less exponential increase of saturation pressure with temperature as a consequence. At 65°C for an mdf facing the driving force for permeation is a factor 13 higher. This reduces the service life of a panel, which is exposed to, for example solar radiation extremely.

The percentile temperature distribution of figure 7 can be used to calculate a yearly average vapour factor due to water vapour, f_v on the VIP:

$$f_v = \frac{1}{t_n - t_i} \sum_{i=1}^{n} \left[\frac{1}{A_{tot}} \sum_{j=1}^{3} A_j \cdot \frac{p_{v;ij}}{p_{v;0}} \right] \Delta t_i \tag{8}$$

If now this vapour load factor is calculated with formula (8) based on the graphs of figure 7 and 9, a value of 0.46 (north facade) and 0.51 (south facade) for the load factor is found. Regardless of the high instantaneous vapour load during insulation, the yearly average vapour load factor less than unity, or in other words less than the yearly average laboratory load factor. This is because most of the time the temperature at the interface between VIP and facing is less than the reference temperature 21°C. In this analysis, however, non-linear (temperature and moisture) effects in the high barrier films have not yet been taken into account. If such non-linearity's are taken into account the yearly average vapour load factor might become higher.

7 Conclusion

The addressed subjects of thermal bridges, environmental conditions and mechanical properties are important realizing durable VIP integrated building panels.

The thermal bridging problem can be controlled by applying sandwich constructions and by selecting the appropriate facings. More research is needed concerning the mechanied behaviour of sandwhich constructions with a VIP core. Concerning the service life the thermal hygric load of VIP based building panels appears not to be critical.

8 Literature

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