Hot box investigations and theoretical assessments of miscellaneous vacuum insulation panel configurations in building envelopes

Grynning, S., Jelle, B. P., Uvsløkk, S., Gustavsen, A., Baetens, R., Caps, R., & Meløysund, V.

Citation for the published version (APA 6th)
Grynning, S., Jelle, B. P., Uvsløkk, S., Gustavsen, A., Baetens, R., Caps, R., & Meløysund, V. (2011). Hot box investigations and theoretical assessments of miscellaneous vacuum insulation panel configurations in building envelopes. Journal of Building Physics, 34(4), 297-324. doi:10.1177/1744259110382229

Hot Box Investigations and Theoretical Assessments of Miscellaneous Vacuum Insulation Panel Configurations in Building Envelopes

Steinar Grynning [a]*, Bjørn Petter Jelle [a, b], Sivert Uvsløkk [a],
Arild Gustavsen [c], Ruben Baetens [d], Roland Caps [e] and Vivian Meløysund [f]

[a]Department of Materials and Structures, SINTEF Building and Infrastructure, NO-7465 Trondheim, Norway.
[b] Department of Civil and Transport Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway.
[c] Department of Architectural Design, History and Technology, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway.
[d] Department of Civil Engineering, K.U.Leuven, B-3001 Heverlee, Belgium
[e] va-Q-tec AG, Karl-Ferdinand-Braun-Str. 7, D-97080 Würzburg, Germany
[f] Department of Materials and Structures, Oslo, SINTEF Building and Infrastructure, NO-0373 Oslo, Norway.
* Corresponding author: steinar.grynning@sintef.no, Phone +47 73 593375, Fax +47 73 593380

Keywords: Vacuum insulation panel, VIP, Laboratory, Hot box, Building insulation, U-value, Thermal bridge, Numerical simulation

ABSTRACT

Vacuum insulation panels (VIPs) are regarded as one of the most promising existing high performance thermal insulation solutions on the market today as their thermal performance typically range 5 to 10 times better than traditional insulation materials. However, the VIPs have several disadvantages such as risk of puncturing by penetration of nails and that they cannot be cut or fitted at the construction site. Furthermore, thermal bridging due to the panel envelope and load-bearing elements may have a large effect on the overall thermal performance. Finally, degradation of thermal performance due to moisture and air diffusion through the panel envelope is also a crucial issue for VIPs. In this work, laboratory investigations have been carried out by hot box measurements. These experimental results have been compared with numerical simulations of several wall structure arrangements of vacuum insulation panels. Various VIP edge and overlap effects have been studied. Measured U-values from hot box VIP large scale experiments correspond well with numerical calculated U-values when actual values of the various parameters are used as input values in the numerical simulations.

1. Introduction

There are many advantages and challenges associated with the application of VIPs in the construction. The advantages lie in the possibility of reducing the thickness of the building envelope while maintaining or reducing the thermal transmittance (U-value). A challenge is the concern about robustness and flexibility of these products. To meet these challenges work has to be carried out to ensure robust constructions with respect to both mechanical and chemical stresses. Using low permeable barriers (thicker metallic layers) will increase the thermal bridging effect while use of any exterior protection on VIPs will increase the thickness of the building structure.

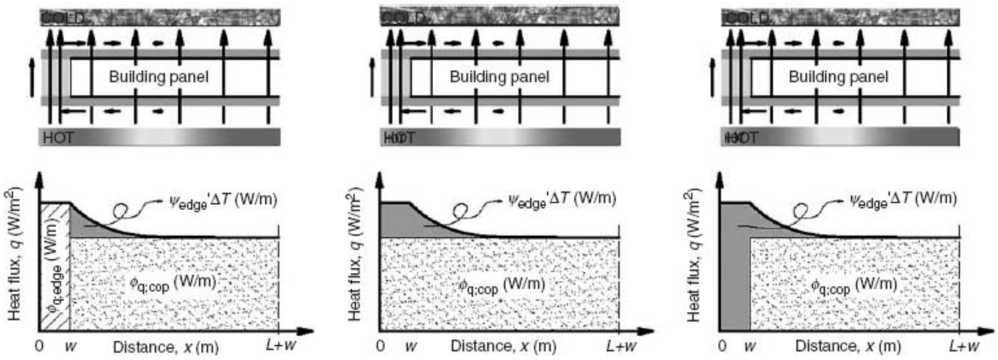
Extensive work has already been carried out on thermal properties and service life of VIPs (Baetens et al. 2010, Brunner et al. 2005). However, VIPs are composites where the panel core and the barrier have widely different thermal properties (Tenpierik et al. 2007). Most of this work is performed using numerical calculations (Schwab et al. 2005, Willems et al. 2005) and analytical assessments (Tenpierik and Cauberg 2007), or laboratory measurements on small scale (Wakili et al. 2004) and some as field studies (Platzer 2007).

In this work, hot box measurements of various full scale VIP wall structure are presented and compared with numerical and analytical calculations. With these means we evaluate the importance of several ways of arranging different VIPs in large scale structures, e.g. single and double layer configurations versus panel thicknesses, edge effects including air gaps between the VIPs, staggering of VIPs and taped VIP joints. A new type of panels with tapered edges that overlap the neighbouring panel is creating an effect similar to that of a staggered joint. On-going and future work includes tests on VIPs in more practical and useable configurations.

2. Investigations

2.1 Calculation of the thermal bridge value

All thermal bridge calculations are carried out according to NS-EN ISO 10211. In accordance with calculating methods for thermal bridges in Gustavsen et al. (2008) the auxiliary planes are placed in the centre of the structure under consideration. Thus, giving only the additional heat flux through the thermal bridges, ψ, compared to the thermal bridge-free construction comparable to definition b in Figure 1. The calculated value of ψ using this method will differ from values calculated using definition a or c.



Definition a Definition b Definition c

Figure 1 Definitions of the thermal bridge value ψ (Tenpierik et al. 2008).

2.2 Analytical calculation of thermal bridges caused by VIP high barrier envelopes

A simplified model, given in eq. 1 (Tenpierik and Cauberg, 2007), is used for analytical calculations in this report.

$$\psi_{vip,edge} = \left(\frac{1}{\sqrt{\alpha_1 d_f \lambda_f}} + \frac{\varphi d_p}{d_f \lambda_f} + \frac{1}{\sqrt{\alpha_2 d_f \lambda_f}} \right)^{-1} \quad (1)$$

where

ψ = linear thermal transmittance (W/(mK))
α = surface coefficient of heat transfer of surface "i" (W/(m²K))
λ_f = thermal conductivity of foil (W/(mK))
φ = factor dependent on the type of foil splice (-)
d_f = foil thickness (m)
d_p = panel thickness (m)

From eq. 1 one sees that the size of the thermal coupling coefficients of the surfaces of the VIP has an influence on the thermal bridge value. Using this model, higher thermal coupling coefficients gives a reduction in the thermal bridge values.

2.3 Numerical simulations of thermal bridges caused by high barrier envelopes

Numerical simulations have been performed using the two dimensional finite element program THERM (Mitchell et al., 2006). Linear thermal bridge values ψ caused by the high barrier envelope are calculated according to eq. 2, using definition b in Figure 1.

$$\psi = L_{2D} - \sum_{j=1}^{N_j} U_i l_i \quad (2)$$

where

Ψ = linear thermal transmittance (W/(mK))
L_{2D} = thermal coupling coefficient obtained from a 2-D calculation of the component separating the two environments being considered, including thermal bridges (W/(mK))
U_i = thermal transmittance of area i ($W/(m^2K)$)
l_i = length over which the value U_i applies (m)

2.4 U-value calculations

The U-value of a structure with thermal bridges included are calculated according to NS-EN ISO 6946:2007, as shown in eq. 3:

$$U = U_0 + \frac{\sum_i \psi_i l_i}{A} \quad (3)$$

where

U = Thermal transmittance of the structure including thermal bridges ($W/(m^2K)$)
U_0 = Thermal transmittance of the structure without thermal bridges ($W/(m^2K)$)
A = Area of the structure (m^2)

Based on eq. 3, the total U-value of the hot box test wall, U_{wall}, is calculated according to eq. 4:

$$U_{wall} = U_{cop} + \frac{\psi_p l_p}{A_{wall}} \quad (4)$$

where

U_{wall} = Thermal transmittance of the test wall ($W/(m^2K)$)
U_{cop} = The centre of panel thermal transmittance ($W/(m^2K)$)

2.5 Heat flow meter apparatus measurements

In order to examine the accuracy of the given nominal value for the core conductivity of the VIPs, λ_{cop}, measurements on both a 20 mm and 40 mm thick VIP were conducted in a heat flow meter apparatus.

2.6 Hot box measurements

Measurement series

Measurements in the hot box have been carried out on the following VIP configurations.

1. Single layer of 40 mm VIPs
2. Single layer of 40 mm VIPs with taped panel joints
3. Single layer of 20 mm VIPs
4. Double layer of 20 mm VIPs
5. Double layer of 20 mm VIPs with staggered joints[1]
6. Single layer of 18 mm VIPs with tapered edges (va-Q-plus)
7. Double layer of 18 mm VIPs with tapered edges (va-Q-plus)

All panels that have been tested are delivered from Dr. Roland Caps of the German company va-Q-tec. In series 1 to 4 VIPs of the type va-Q-vip B (2009) have been used. In series 6 and 7 va-Q-plus B (2009) a type of panels with tapered edges have been used. The panel configuration for test series 1 to 4 is shown in Figure 2. For the test wall, consisting of six panels, as shown in

[1] The panels in the second layer are placed so that the thermal bridging effect caused by the panel foil is minimized. To achieve this, panels with different sizes must be used.

Figure 2, the length of the butt joints between the panels and thus the length of this linear thermal bridge is l_p = 5.8 m.

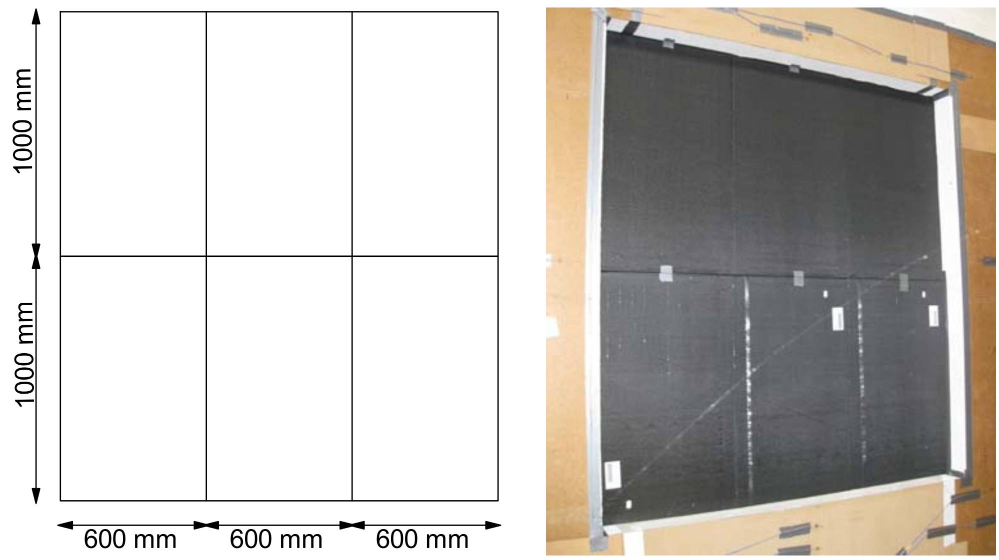


Figure 2. VIP configuration for hot box measurements, series 1 to 4.

Measurement conducted on 20 mm VIPs in a single layer configuration serve as a reference against the international research that has been performed on such panels (Binz et al. 2005, Brunner et al. 2005, Erb et al. 2005, Baetens et al. 2010). The Norwegian climate and building regulations (TEK 07) demands for lower U-values than what is achievable using only a single layer of 20 mm VIPs. This lead to the need for more extensive testing on thicker VIP-configurations e.g. 40 mm thick VIP layers.

Panel configurations with regular joints and staggered joints will give indications on whether or not the use of a double layer of 20 mm panels with staggered joints will give a reduction of thermal bridges compared to a single layer of 40 mm VIPs. The panel configuration for test series 5, with staggered joints is shown in Figure 3.

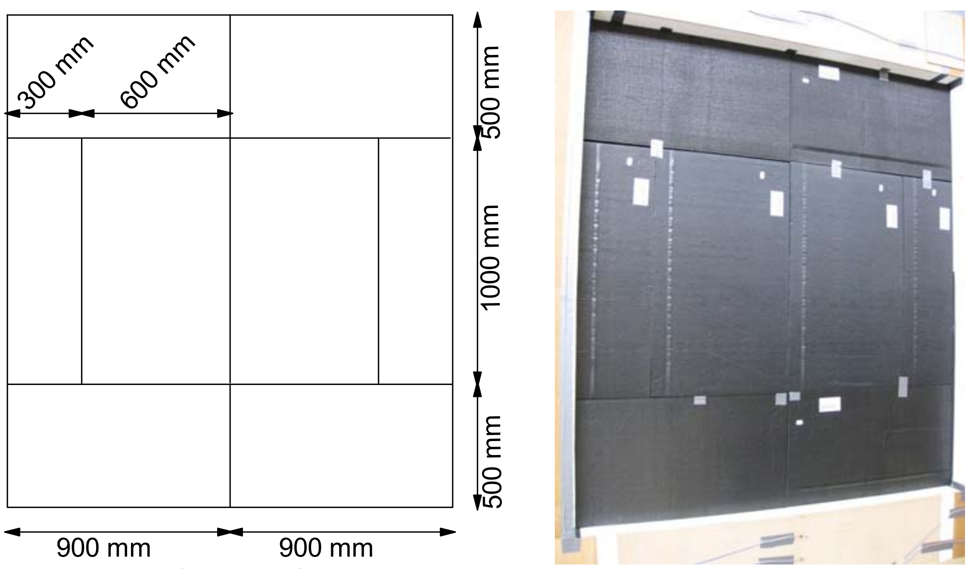


Figure 3. VIP test wall configurations for test series 5 with staggered panel joints.

For all VIP configurations in the hot box, the VIPs will be encased with 6 mm MDF plates on the faces exposed to the environment. A cross-section of the test wall is shown in Figure 4.

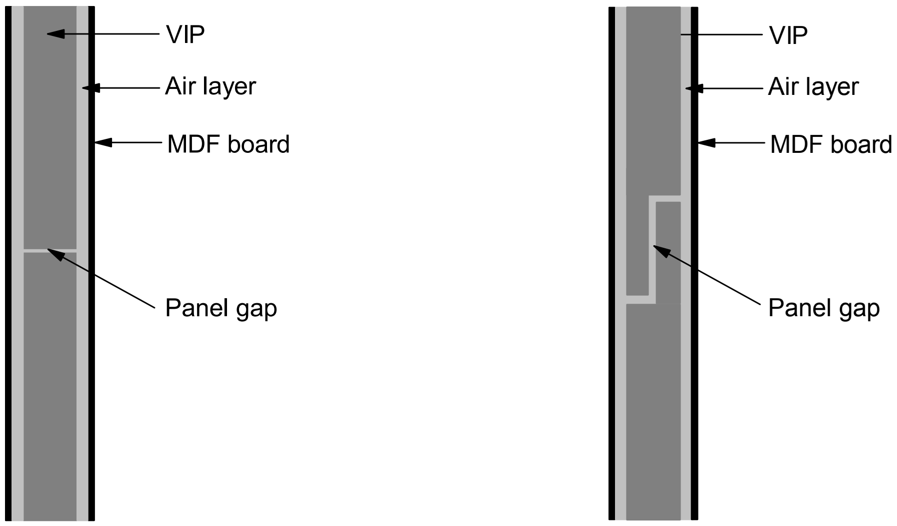


Figure 4. On the left: principal cross section of VIP test wall. On the right: principal cross section of panel joints for the test wall using VIPs with tapered edges (creating a lap joint). Both figures show, stylistic, the unintentional air layers that came into being during testing. The air layers were in reality smaller than that given in the figure. Figure is not to scale.

The test wall is inserted in a 190 mm thick surround panel made of Expanded polystyrene (EPS) covered with Medium Density Fibre boards (MDF) with known thermal conductivities. To prevent any air leakages between hot and cold side, the perimeter of the test wall was taped against the EPS of the template using an airtight tape. This also ensured that the MDF are held in place against the VIPs during the measurement.

Series 6 to 7 will be measured on a new type of VIP with tapered edges, thus creating a lap joint These panels are expected to give better possibilities for custom fitting of panels and to be less costly in production. The panel configuration for these series is shown in Figure 5. A cross section of the test wall showing the tapered edges of the panels are also shown in Figure 5.

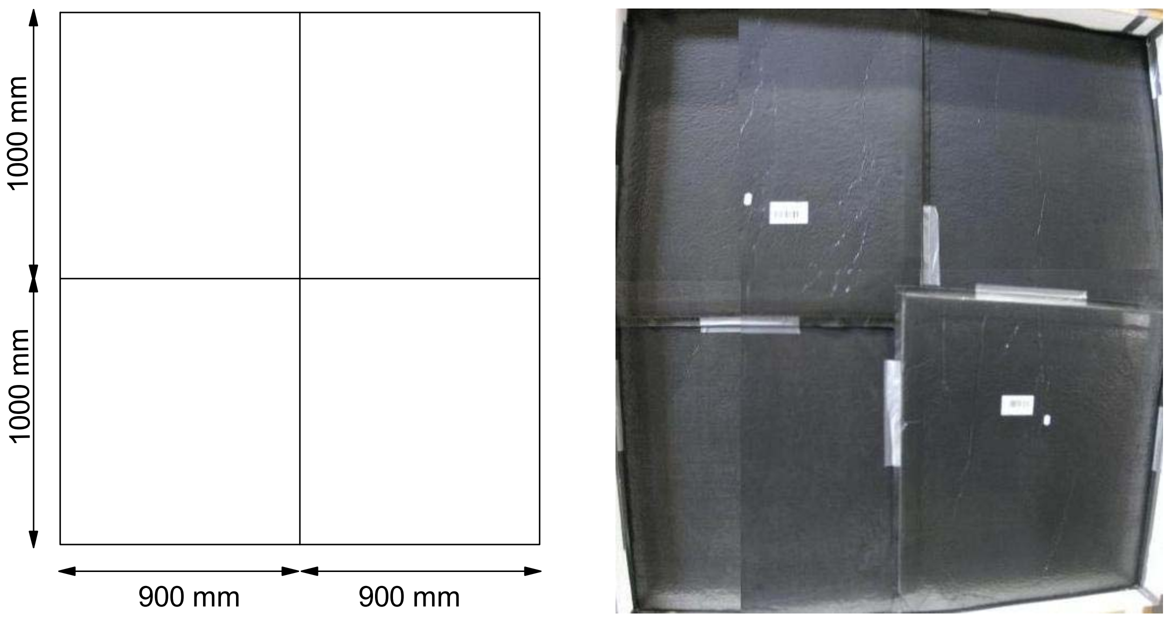


Figure 5. VIP test wall configuration for test series 6 and 7 with the new type of VIPs with tapered edges.

Thermocouples and heat flow meters

19 thermocouples on each side of the test wall were used to measure surface temperatures. Temperatures were measured and averaged to give a mean surface temperature. In addition detailed

temperature measurements were done for a horizontal and vertical panel joint. A schematic illustration of the thermocouple placements (red circles) are shown on Figure 6. Thermocouples were placed symmetrically on the hot and the cold side of the test wall. In addition to the temperature measurements, two heat flow meters were used to measure the heat flow near the centre of two panels. The placements of these are shown as (blue) crosses in Figure 6. Heat flow meters were only applied on the hot side of the test wall. Figure 6 also shows a photo of the placement of the thermocouples on the cold side of the test wall.

Measurements from the heat flow meters were compared with the calculated U-value U_{cop} based on the heat flow meter apparatus measurements of the thermal conductivity λ_{cop} for the VIPs

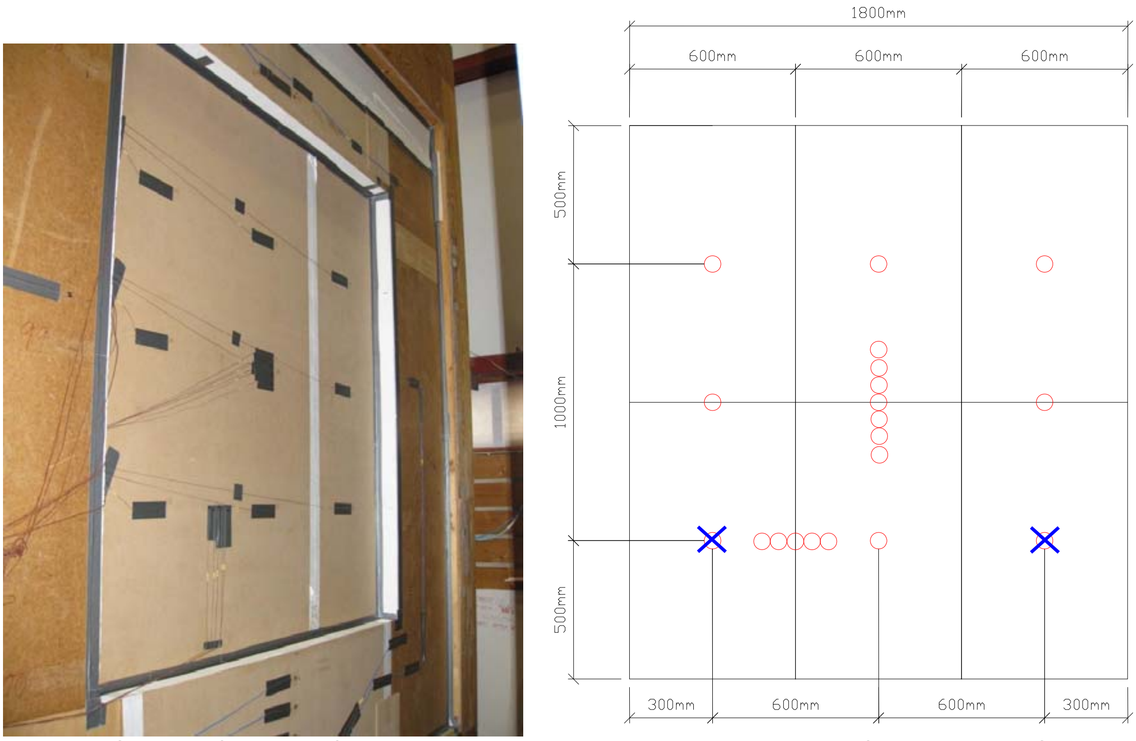


Figure 6. On the left: photo of thermocouples as mounted on the cold side of the test wall. On the right: placement of thermocouples and heat flow meters on warm side of the test wall. Thermocouples are shown as (red) circles, whereas the heat flow meters are shown as (blue) crosses.

VIP dimensions

The dimensions of the VIPs were measured thoroughly before testing. This included measurements of width, height and thickness. Some irregularities in the width and height were found. This will influence the measurements by giving room for larger and more varying panel gaps. The mean measured thicknesses of the VIPs were measured to be 5 % less than the nominal value for both the 20 and 40 mm panels. This is believed to be a result of the compression of the panels when vacuum is applied. Measurements carried out on a single punctured 20 mm panel confirm this assumption, as the thickness was measured to 18 mm before punctuation and 20 mm after. Dimensional measurements have not been carried out on the new generation VIPs with tapered edges, due to geometrical variations of the panels.

Panel gaps

The dimensional irregularities of the VIPs lead to gaps in the panel joints of the test wall, as shown in Figure 7. In order to study the effect of the width of the air gaps between panels on the total edge loss, the mean width of the panel gaps were measured before the hot box measurements were carried out. These gaps were measured to an average width of 2 mm. Numerical calculations for comparisons were therefore done for 2 mm wide gaps. Thermal bridge values for the edge loss with other panel gap widths can be found in other works (Brunner et al. 2005). However, it must be noted that the values are varying from 0 to 7 mm. An example of this is shown in Figure 9. The panel gaps were in general larger for the 40 mm than for the 20 mm thick VIPs.

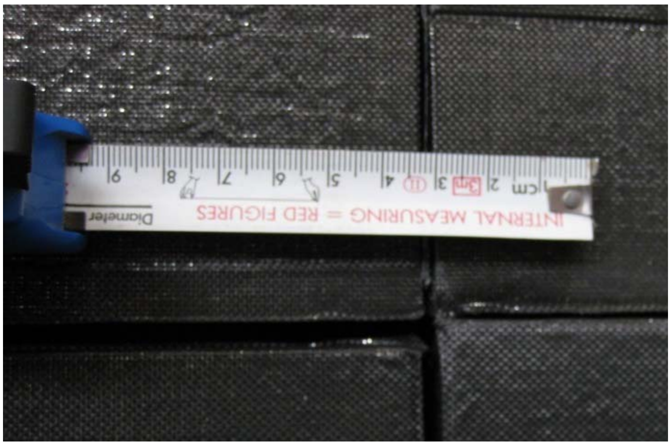


Figure 7. Irregularities in the VIP dimensions result in gaps of varying width between panels.

Air layers between VIP and MDF

Due to curving of the MDF plates, an air layer between the VIPs and the MDF occurred towards the centre of the test wall. In order to reduce the thickness of the air gap, plastic fasteners with a cross-section of 1 mm x 2 mm, were used in two positions to hold the MDF plates tight to the VIPs. It was ensured that no air leakage occurred through the holes in the MDF for the fasteners. The effect of the additional heat flow through the fasteners on the total U-value of the test wall was assumed to be negligible.

If no convection occurs between the hot and cold side of the test wall, these air layers will give a reduction of the U-value for the test-field compared to an *ideal* situation without any such air layers. The effect of the air layers have been corrected for in the measurements according to eq.5. Values for R_{cavity} are taken from Table 2 in NS-EN ISO 6946, and are based on the average measured air layer thickness for each series, as shown in Table 1.

$$U'_{wall} = \left(\frac{1}{U_{wall}} - R_{cavity} \right)^{-1} \quad (5)$$

Table 1. Measured thicknesses of air layers between VIP and MDF boards. Air layer resistance values are based on values given in NS-EN ISO 6946:2007, Table 2.

Test series	Description	Air layer resistance, R_{cavity} (m^2K/W)
#68301	20 mm VIP, single layer	0.07
#68701	20 mm VIP, single layer	0.03
#68703	20 + 20 mm VIP, double layer	No air layer
#68704	20 mm VIP, double layer. New panel. Only strips	0.04
#68201	40 mm VIP	0.04
#68211	40 mm VIP taped seams	0.04
#68702	20 + 20 mm VIP, double layer, staggered joints (measured on 2nd layer)	0.15
#68801	20 mm VIP, single layer. New panel.	No air layer
#68802	20 + 20 mm VIP, double layer. New panel.	No air layer

The corrected value U'_{wall} is given in tables adjacent to the directly measured values of U_{wall} in their respective chapters. This correction was applied to resemble the numerical simulations in which no air layer was modelled. It is assumed that that the air layers on hot and cold side were equally distributed on both sides of the VIPs.

Thermal bridge values

Thermal bridge values in the hot box measurements are calculated using eq.6.

$$\psi_p = A_{wall}\frac{U'_{wall} - U_{cop}}{l_p} \quad (6)$$

Calculating the thermal bridge value using eq.6 includes any heat loss in excess to the calculated U_{cop} to the thermal bridging effect of the panel joint. In reality, a large number of uncertainties might contribute to both U_{cop} and U'_{wall}.

Uncertainties

The uncertainty of the measured values from the hot box and heat flow meter apparatus measurements presented in the result tables throughout this entire article are estimated standard deviations of the mean values (99.73 % confidence interval), while no systematic errors are included.

2.7 Material data and calculation parameters

Table 2 shows the values of various parameters used for analytical and numerical calculations.

Table 2. Parameters for numerical simulations and analytical calculations.

Material	Thermal conductivity W/(mK)	Reference
Frame cavities	According to NFRC 100-2001	ASTM
Medium Density Fibre board (ρ = 400 kg/m³)	0.1	NS-EN ISO 10456
Mineral wool	0.037	NS-EN ISO 10456
Plaster board (gypsum)	0.25	NS-EN ISO 10456
Roof cladding	0.1	NS-EN ISO 10456
VIP, core material	0.004-0.006	(Erb et al. 2005)
VIP, foil	0.54	(Tenpierik and Cauberg 2007)
VIP, glass fibre	0.31	(Va-Q-tec 2009)
Wood	0.13	NS-EN ISO 10456

2.8 Equipment used in measurements

Hot box

Measurements in hot box have been done according to the governing standard, NS-EN ISO 8990:1997. The hot box at SINTEF's laboratory in Trondheim is a guarded hot box and has a measuring area of 2.5 m x 2.5 m.

Calibration of the thermal conductivity of the template, the edge loss effect and surface resistance coefficients has been done using the procedure described in NS-EN ISO 8990:1997 and ISO/DIS 12567-1, using 50 and 100 mm EPS panels covered with MDF. The MDF was applied in order to obtain the same physical properties of the surface in the calibration measurements as in the measurements of the VIPs.

Heat flow meter apparatus

In order to verify the thermal conductivity of the EPS used for calibration measurements the conductivity was measured in a heat flow meter apparatus at SINTEF's laboratory in Trondheim. Centre of panel conductivities for the VIPs were also measured in the heat flow meter apparatus. All measurements were done according to the governing standard NS-EN 12667.

3. Results and discussion

3.1 Heat flow meter apparatus measurements

The results from the heat flow meter apparatus measurement on VIPs were used for comparison with the U-value, U_{cop}, measured using two heat flow meters in the hot box test series. Using these two values for comparison we could state the thermal resistance R_{cavity} of the air cavities between the MDF and the VIPs in the test wall with a larger degree of certainty. The measured conductivity values from the heat flow meter apparatus are given in Table 3. Theoretical values for the centre of panel conductivity U_{cop} were calculated based on these measurements. Uncertainties in the measurements are estimated standard deviations of the mean values (99.73 % confidence interval), while no systematic errors are included.

Table 3. Measured centre of panel thermal conductivity values, λ_{cop} for 20 mm and 40 mm VIPs.

VIP thickness Nominal values	Measured thermal conductivity value λ_{cop} (W/(mK))	VIP measured thickness t_p (mm)	U-value, centre of panel U_{cop} (W/(m²K))
20 mm	0.0042 ± 0.0001	18.9 ± 0.2	0.207 ± 0.005
20 + 20 mm, double layer	0.0042 ± 0.0001	37.8 ± 0.4	0.107 ± 0.003
40 mm	0.0044 ± 0.0001	38.0 ± 0.1	0.112 ± 0.002

In addition, the heat flow meter apparatus was used to measure the thermal conductivity of the VIP core material at atmospheric pressure. This was measured, on a single sample, to $\lambda_{cop,atm}$ = 0.0200 W/(mK) ± 0.0001 W/(mK).

3.2 Numerical simulations and analytical calculations

Thermal bridges caused by high barrier envelope of VIPs

German producers of VIPs have to fulfil official requirements regarding fire protection. The core itself is non-flammable but the polymer parts of the foil will emit fumes when heated. Some producers therefore deliver the VIPs with a fire retardant covering. How this issue will be treated in Norway is still to be determined.

Hot box measurements have been conducted on VIPs with this fire retardant covering made of a 305 μm thick fibreglass textile. Panels used in the measurements are delivered by the German company va-Q-tec (va-Q-tec 2009a and va-Q-tec 2009b). The application of the fibreglass covering will increase the thermal bridges in the edge zone of the panels and.

The effect of the fire protection on the thermal bridges will be studied in the following chapters, using laboratory investigations as well as both numerical and analytical assessments. It is noted that the analytical model not is applicable for calculations for double layers of VIPs with staggered joints.

Results from simulations and calculations are shown alongside the measured values in the following chapters. There are some deviations between the numerical and the analytical calculation methods for quantification of the linear thermal bridge values for a butt joint of the VIPs. This might be due to the result of the additional transversal heat flow in the MDF-covering of the panels. In the numerical model this transversal heat flow is taken into account, but in the analytical model the funnelling-effect of this additional heat flow is not taken into account.

Influence of panel size on U-values

To get a better understanding of the effect of the thermal bridges on a larger scale, U-values are calculated for entire panels using eq.3. Values for VIPs with- and without fibre glass covering are shown in Figure 8.

According to eq. 3, it is seen that the panel size influences the total U-value of the panel. U-values as function of panel size for various 40 mm thick VIP configurations are shown in Figure 8. U-values for 20 mm panels are omitted in the figure to clarify the difference between staggered and non-staggered panel joints.

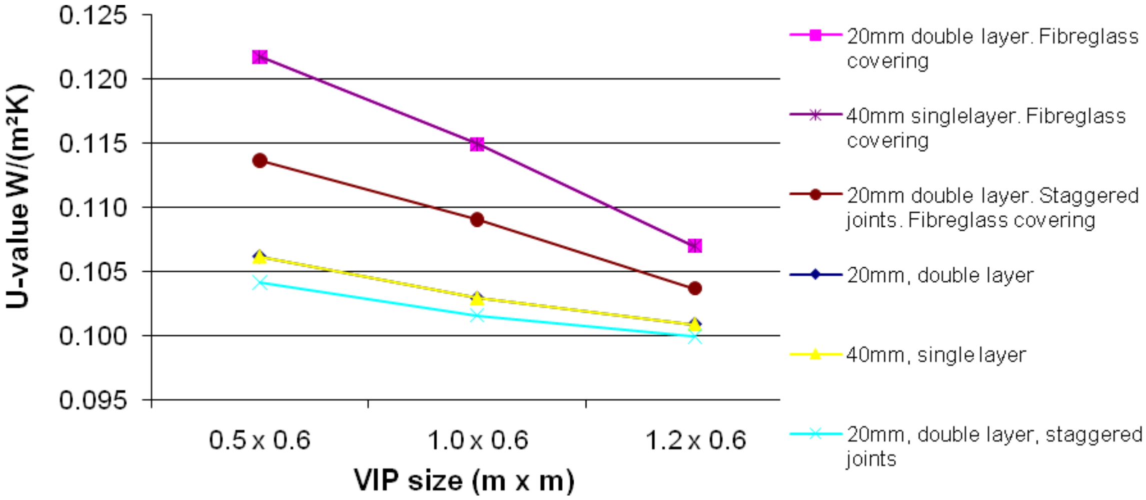


Figure 8. U-values as function of panel size for VIPs with total thickness 40 mm.

The effect of the increase in panel size on the resulting U-value is clearly seen from Figure 8. The reduction of the U-value with the increase of panel size is largest for the panels with fibre glass covering due to the higher thermal bridge values caused by the fibre glass.

Simulations and calculations for hot box test configurations

The total area of the test wall is A_{wall} = 3.6 m² and the lengths are l_p = 5.8 m. The core conductivity is set to λ_{cop} = 4 mW/(mK) Using numerically calculated thermal bridge values ψ_p and centre of panel U-values U_{cop} given in Table 4, this gives U-values for the test wall U_{wall} as shown in Table 5.

Table 4. Numerically calculated values for U_{cop} and ψ_{edge} for different panel gap widths.

Panel configuration	Nominal values, 2 mm panel gap		Measured λ_{cop} and t_p, 2 mm panel gap	
	U_{cop} (W/(m²K))	ψ_p (W/(mK))	U_{cop} (W/(m²K))	ψ_p (W/(mK))
20mm, single layer	0.189	0.0073	0.207	0.0078
20mm, double layer	0.097	0.0053	0.107	0.0054
20mm, double layer, staggered joints	0.097	0.0029	0.107	0.0030
40mm, single layer	0.097	0.0053	0.112	0.0054

Table 5. U-values for hot box test wall using numerically calculated values for U_{cop} and ψ_p.

Panel configuration	U-value (W/(m²K))		
	No gap	2 mm gap	Measured λ_{cop} and t_p, 2 mm panel gap
20mm, single layer	0.198	0.201	0.219
20mm, double layer	0.102	0.106	0.116
20mm, double layer, staggered joints	0.101	0.102	0.112
40mm, single layer	0.102	0.106	0.121

The conductivity of the core material, λ_{cop}, in the VIP will increase over time due to an increase in the internal gas and water vapour pressure. Calculations indicate that an increase in the λ_{cop} will reduce the thermal bridges, ψ_p . This will contribute to level out the differences between a single 40 mm layer compared to a double 20 mm layer with staggered joints.

3.3 Hot box measurements

20 mm VIPs in a single layer configuration

These two series were measured on a configuration using a single layer of 20 mm VIPs. Due to puncturing of one panel during the first test series of 20 mm VIPs, another series was tested to make sure we had a result that was not influenced by the puncture. Physical properties of the test wall are given in Table 6. The air layer thickness describes the total average width of the air gap between the VIPs and the covering MDF plates on both sides of the VIPs caused by the curving of the MDF. The value U'_{wall} is a corrected value where the additional insulation effect of the air layer is taken into account as described in the investigation section. Values are shown in Table 7.

Table 6. Measured parameters for hot box test wall. 20 mm VIPs.

VIP, 20 mm single layer.	Measured physical properties of VIPs and test wall		
VIP dimensions	Thickness	t	= 18.9 ± 0.2 mm
	Foil thickness	t_f	= 0.44 ± 0.01 mm
Gap between panels (measured average)	Vertical joints	d_v	= 2 mm
	Horizontal joints	d_h	= 2 mm
Test wall dimensions	Average sample thickness	d_s	= 39 or 35 mm
	Average air-layer thickness	d_{air}	= 8 or 4 mm

Table 7. Calculated and measured U-values for hot box test wall. 20 mm VIPs.

Method	U-value centre of panel U_{cop} (W/(m²K))	U-value centre of panel (Heat flow meters) U'_{cop} (W/(m²K))	U-value test wall U_{wall} (W/(m²K))	U-value test wall, corrected for air layers U'_{wall} (W/(m²K))	Edge loss ψ_p (W/(mK))
Numerically calculated					
Nominal λ_{cop} and t_p, no panel gap	0.189		0.198		0.0055
Nominal λ_{cop} and t_p, 2 mm panel gap	0.189		0.201		0.0073
Measured λ_{cop} and t_p, 2 mm panel gap	0.207		0.219		0.0078
Analytically calculated					
Nominal λ_{cop} and t_p, no panel gap	0.189		0.197		0.0050
Measured in hot box					
Series #68301	0.207 ±0.005	0.214	0.227 ± 0.001	0.234 ± 0.001	0.0170 ± 0.0009
Measured in hotbox w/ one new panel (Series #68701)	0.207 ± 0.005	0.214	0.226 ± 0.001	0.229 ± 0.001	0.0137 ± 0.0009

Discussion

The measured corrected U-value of the test wall, U'_{wall} (0.239 W/(m²K)), is approximately 19 % higher than the numerically calculated value (0.201 W/(m²K)) using nominal values and 2 mm panel gaps. There might be several reasons for this. Firstly, the measured thicknesses of the panels are approximately 5 % lower than the stated nominal thickness. Secondly, the measured λ_{cop} is between 5 and 10 % higher than the nominal value. The variation in these two parameters gives an increase of U'_{wall} by approximately 10 % if one uses the measured values as input variables in the numerical simulation. The remaining difference is most likely caused by the earlier mentioned convection.

For the two measurement series, # 68301 and 68701 (Table 7) the measured values do not correspond with the calculated values of U_{wall} within the interval of the uncertainties from the estimated standard deviations of the measured mean values. This indicates that other sources of error are present. None of the two measurement series were performed using tape to prevent air leakages (convection) between the hot and the cold side of the VIPs.

The presence of any such air leakages might be a contributing factor to explain that series # 68301 achieves a higher value of U'_{wall} than # 68701. Convection will in practice reduce the effective insulation of the air layers, thus reducing the value of R_{cavity} for test series # 68301 by a larger degree than for # 68701, due to the differences in the air layer thicknesses. The fact that the measured values of U_{wall} are nor significantly different for the two measurement series within the given error margins supports this assumption.

Calculating the thermal bridge values according to eq.6 might give rise to a systematic error, caused by convection, which is much higher than the difference in measured mean values. This might explain that the measured thermal bridge values ψ_p are substantially higher than the calculated values (Table 7).

20 mm VIPs in a 40 mm double layer configuration

These three series were measured on configurations using double layers of 20 mm VIPs, i.e. a total thickness of 40 mm VIPs. In the first measurement series one panel punctured during the test, which probably happened when the second layer of VIPs was installed in the template. The physical properties of the panels and test wall regarding the measurement series are given in Table 8. The measured values are shown together with numerically calculated values in Table 9.

Table 8. Measured parameters for hot box test wall. 20 mm VIPs in a 40 mm double layer configuration

VIP, 20 mm double layer.	Measured physical properties of VIPs and test wall		
VIP dimensions (per layer)	Thickness	t	= 18.9 ± 0.2 mm
	Foil thickness	t_f	= 0.44 ± 0.01 mm
Gap between panels (measured average)	Vertical joints	d_v	= 2 mm
	Horizontal joints	d_h	= 2 mm
Test wall dimensions	Average sample thickness	d_s	= 57 mm
	Average air-layer thickness	d_{air}	= 7 mm

Table 9. Calculated and measured U-values and edge losses for double layers of 20 mm VIPs

Method	U-value centre of panel U_{cop} (W/(m²K))	U-value centre of panel (Heat flow meters) U'_{cop} (W/(m²K))	U-value test wall U_{wall} (W/(m²K))	U-value test wall, corrected for air layers U'_{wall} (W/(m²K))	Edge loss ψ_p (W/(mK))
Numerically calculated					
Nominal λ_{cop} and t_p, no panel gap	0.097		0.102		0.0031
Nominal λ_{cop} and t_p, 2 mm panel gap	0.097		0.106		0.0053
Measured λ_{cop} and t_p, 2 mm panel gap	0.107		0.116	0.171	0.0054
Analytically calculated					
Nominal λ_{cop} and t_p, no panel gap	0.097		0.102		0.003
Measured in hot box					
Series #68311			0.124	0.125	Punctured panel
Series #68703	0.107 ± 0.003	0.105	0.116 ± 0.001	-	0.0055 ± 0.0005
Series #68704	0.107 ± 0.003	0.107	0.114 ± 0.001	0.115 ± 0.001	0.0049 ± 0.0005

Discussion

Test series # 68703 was measured using additional pressure on the test wall to minimize the air layers between the VIPs and the MDF plates. Comparison of this value with the corrected U-value U' from measurement series # 68704 shows that the U-values are not significantly different within the calculated error margins with a 99.73 % confidence interval. This indicates that the correction for air layers to the value U' are conducted in a correct way, also for the other measurements.

The measured U-values for U_{wall} correspond quite well with the numerically calculated values for the ideal situation without any air gaps between the panels, in contradiction to the measurements for the single 20 mm VIP layer. This might be due to the panel geometry. A certain (although minimal) displacement of the panel joints in the second layer occurs compared to the first layer. This might reduce the convection between the hot and the cold side of the VIPs.

During the testing of the 20 mm double layer configuration in test series # 68311 the measured value U_{wall} suddenly increased at one point of time. After opening the test wall it was discovered that one of the panels had punctured, which most likely happened while the VIPs were mounted in the hot box. The fact that this happened, emphasizes the importance of the discussion regarding the robustness of VIPs in buildings. It should be noted that the panels were handled with great care during the mounting in the test wall and it is not likely that the same amount of care will be shown at a construction site. Robust construction solutions are therefore a very important.

The puncturing of one panel clearly increases the equivalent U_{wall} for the test wall, increasing it with approximately 9 % compared to the measurements done on the configurations using intact VIPs. In theory the puncturing of one panel will increase the core conductivity to 20 mW/(mK). The part of the test wall containing the punctured panel reaches a theoretical centre-of-panel U-value U_{cop} = 0.157 W/(m²K). This applies for one sixth of the test wall area. Area weighting the U-values for the areas with and without a punctured panel, adding the theoretically calculated edge loss value, ψ_p = 0.003 W/(mK), the equivalent theoretical U-value for the entire test wall becomes U'_{wall} = 0.126 W/(m²K). The theoretical increase of U'_{wall}, from 0.116 W/(m²K) to 0.126 W/(m²K), is approximately 9 %, and thereby close to the measured value.

40 mm VIPs in a single layer configuration with and without taped panel joints

In order to study the effect of any undesired air-circulation (convection) between the hot and the cold side, measurements were performed on a sample where the VIP joints had been taped using duct-tape and one sample without taped joints. The measurements were done to quantify the effect of the air-circulation on the total U-value of the test wall. Due to large variations in the panel dimensions the measured gap widths ranged from 0 to 7 mm for the 40 mm VIPs. This is a somewhat higher spread than for the 20 mm panels.

Table 10. Measured parameters of hot box test wall using 40 mm VIPs

VIP, 40 mm single layer.	**Measured physical properties of VIPs and test wall**		
VIP dimensions	Thickness	t	= 38.0 ± 0.2 mm
	Foil thickness	t_f	= 0.44 ± 0.01 mm
Gap between panels (measured average)	Vertical joints	d_v	= 2 mm
	Horizontal joints	d_h	= 2 mm
Sample dimensions	Average sample thickness	d_s	= 56 mm
	Average air-layer thickness	d_{air}	= 6 mm

Based on the measurements and numerical simulations of the test wall U-values and edge loss values for the test wall have been found as shown in Table 11.

Table 11. Calculated and measured U-values for hot box test wall with 40 mm VIPs.

Method	U-value centre of panel U_{cop} (W/(m²K))	U-value centre of panel (Heat flow meters) U'_{cop} (W/(m²K))	U-value test wall U_{wall} (W/(m²K))	U-value test wall, corrected for air layers U'_{wall} (W/(m²K))	Edge loss ψ_p (W/(mK))
Numerically calculated					
Nominal λ_{cop} and t_p, no panel gap	0.097		0.102		0.0031
Nominal λ_{cop} and t_p, 2 mm panel gap	0.097		0.106		0.0053
Measured λ_{cop} and t_p, 2 mm panel gap	0.112		0.121		0.0054
Analytically calculated					
Nominal λ_{cop} and t_p, no panel gap	0.097		0.102		0.0030
Measured in hot box					
Series #68201	0.112 ± 0.002	0.108	0.121 ± 0.001	0.122 ± 0.001	0.0063 ± 0.0004
Series #68211w/ tape	0.112 ± 0.002	0.108	0.115 ± 0.001	0.116 ± 0.001	0.0025 ± 0.0004

Discussion

The measured values shown in Table 11 give slightly lower values than the calculated ones. This indicates that the heat loss through the panel joints is slightly lower than calculated. The measured value of U_{cop} is slightly higher than the value calculated numerically. The corrected U-value, U'_{wall} = 0.122 W/(m²K) of the non-taped wall coincides with the calculated value of U_{wall} = 0.121 W/(m²K).

The use of tape, to reduce air leakages in panel joints and convection in the test wall, reduces U_{wall} with approximately 5 % and thus has a considerable effect. Depending on the configuration of the VIPs in a real structure, this may be the difference between fulfilling the building regulations or not. If the VIPs are placed adjacent to air cavities on both the cold and hot side of the panel convection will occur and reduce the thermal performance of the VIPs. It is noted that the relative impact of convection between hot and cold side of the VIPs will increase with increasing temperature difference between the two sides.

An additional effect is that the tape will give high resistance to moisture diffusion through the joints and no additional diffusion barrier is needed. To prevent risk of fungi growth the relative humidity in the wall should be kept lower than 80 % RH. The thermal resistance of any additional insulation on the hot side of the VIPs should therefore not exceed 30 % of the total thermal resistance of the structure. No additional vapour barrier should be applied on the hot side of any additional thermal insulation due to the risk of trapping moisture. Although taped joints may contribute to the air tightness applying a separate wind barrier at the cold face is recommended to secure the air tightness of the structure.

20 mm VIPs in a 40 mm double layer configuration with staggered layers

These measurement series were conducted on a test wall configuration using two layers of 20 mm VIPs with a staggered second layer, i.e. a total VIP thickness of 40 mm. Using different panel sizes, the second layer were placed in such a manner that the panel joints had a maximum dislocation towards the first layer. The configuration is shown in Figure 3

These measurements study the effect of staggered joints on the heat loss in the panel joints. In theory, the thermal bridge value will be reduced by 30 to 50 % depending on the width of the panel gaps. The effect on U_{wall} on the other hand is smaller, approximately 5 to 13 % depending on the panel gap width. However, the savings in heat loss must be considered with respect to several practical aspects.

This configuration clearly increases the workload of installing the panels compared to using a single 40 mm panel. The planning and configuration of the panel layout will also be a bit more complex. It is noted that a double layer, staggered joint configuration is only suitable for VIPs laid in a continuous layer. The use of VIPs where a continuous layer can not be achieved, e.g. in a timber frame wall, is subject to far greater heat loss through thermal bridges caused by penetrating studs and similar.

The introduction of the staggered second layer of VIPs should in theory decrease the U-value of the test wall by 0.1 – 0.2 W/(mK) compared to a normal double 20 mm VIP layer depending on the panel gap width. The measured values are shown alongside the numerically calculated values in Table 12. Analytical calculations using a simplified model as given in eq. 1 is not applicable for this case.

Table 12. Calculated and measured U-values and edge losses for double layers of 20 mm VIPs with staggered panel joints.

Method	U-value centre of panel U_{cop} (W/(m²K))	U-value centre of panel (Heat flow meters) U'_{cop} (W/(m²K))	U-value test wall U_{wall} (W/(m²K))	U-value test wall, corrected for air layers U'_{wall} (W/(m²K))	Edge loss ψ_p (W/(mK))
Numerically calculated					
Nominal λ_{cop} and t_p, no panel gap	0.097		0.101		0.0023
Nominal λ_{cop} and t_p, 2 mm panel gap	0.097		0.102		0.0029
Measured λ_{cop} and t_p, 2 mm panel gap	0.107		0.112	0.167	0.0030
Measured in hot box					
Series #68702	0.107 ± 0.002	0.130	0.106 ±0.001	0.109 ± 0.001	0.0015 ± 0.0005
Staggered layer (#68321)	0.4 / 0.16		0.126	0.131	Punctured panel
Staggered layer, compressed centre of field (#68331)	0.32 / 0.135	0.335 / 0.15	0.125	-	Punctured panel

Discussion

The measured values in Table 12 show a clear reduction of U_{wall}. Compared to the measurements on a double layer of 20 mm VIPs without staggered joints, the thermal bridges seem to be more or less eliminated with a value of U_{wall} approximately the same as the U_{cop} values in Table 13. The reduction of the total U-value is close to nine percent thus giving a considerable decrease of the U-value. However, it must be evaluated with respect to the practical challenges in the installation period as well as the planning stages which demand some extra work to sort out the necessary dimensions of the panels.

During these measurements one of the panels punctured. This led to an increase in the U-value of approximately 19 % (from 0.106 W/(m²K) to 0.126 W/(m²K)). Also here, the puncturing of one panel increase the core conductivity to 20 mW/(mK). The part of the test wall containing the punctured panel reaches a theoretical centre-of-panel U-value U_{cop} = 0.157 W/(m²K). This applies for one sixth of the test wall area. Area weighted, the U-values for the areas with and without a punctured panel, adding the theoretically calculated edge loss value, ψ_p = 0.003 W/(mK), the equivalent theoretical U-value for the entire test wall becomes U'_{wall} = 0.122 W/(m²K). The theoretical increase of U'_{wall}, from 0.107 W/(m²K) to 0.122 W/(m²K), is approximately 14 %, and thereby slightly lower than the measured increase of 19 %.

18 mm new generation VIPs in a single layer configuration

This measurement series was conducted on a test wall configuration using one of 18 mm VIPs with tapered edges. Due to the fact that the panel joints overlapped, no tape was applied over the edges in order to reduce convection between the hot and the cold side of the test wall.

Table 13. Measured parameters of hot box test wall using 18 mm VIPs with tapered edges in a single layer configuration

VIP, 18 mm single layer	Nominal physical properties of VIPs and test wall		
VIP dimensions	Width	w	= 900 mm
	Height	h	= 1000 mm
	Thickness	t	= 18 mm[2]
	Foil thickness	t_f	= 0.44 mm
Gap between panels (measured average)	Vertical joints	d_v	= N.A.
	Horizontal joints	d_h	= N.A.
Sample dimensions	Average sample thickness	d_s	= N.A.
	Average air-layer thickness	d_{air}	= 0 mm

The MDF plates, covering the VIPs were held tightly against the VIPs using pressure applied over the centre of the test wall and tape alongside the edges of the test wall.

In an ideal situation, i.e. when the panels are placed in a pattern creating a perfect overlap these panels will perform in a similar way as a staggered layer configuration using traditional, square cut panels. The test configuration and panel layout are shown in Figure 5. This will reduce the effect of the thermal bridges compared to a configuration with butt joints. However, due to the dimensional irregularities of these panels ideal configurations of the panels were hard to achieve. This created a bulky and slightly thicker centre part of the test wall where the four panels met.

Table 14. Calculated and measured U-values and edge losses for single layer of new generation 18 mm VIPs with tapered edges.

Method	U-value centre of panel U_{cop} (W/(m²K))	U-value centre of panel (Heat flow meters) U'_{cop} (W/(m²K))	U-value test wall U_{wall} (W/(m²K))	U-value test wall, corrected for air layers U'_{wall} (W/(m²K))	Edge loss ψ_p (W/(mK))
Numerically calculated					
Nominal λ_{cop} and t_p, no panel gap	0.21		0.216		0.0017
Nominal λ_{cop} and t_p, 2 mm panel gap	0.21		0.218		0.0023
Measured in hotbox					
Series #68801	0.21	0.162	0.225		0.0142

Discussion

Due to the large irregularities in panel dimensions, uncertainty values for the measurements done on this configuration are omitted in Table 14. This is based on an assessment that the uncertainty connected to this quantity is likely of a higher degree than the one for the measured mean values.

The thermal performance of these panels is slightly better than the regular panels. If we correct for the fact that the regular panels are 10 % thicker the U-values of the new generation panels are in fact better pr mm panel thickness, i.e. they have a lower average thermal conductivity value for the test wall arrangement.

[2] Due to dimensional irregularities for these VIPs only nominal values have been used as input for the numerical and analytical calculations.

Some problems arose during the mounting of the panels in the hot box. Due to the tapered edges, the panels could not be stacked on top of each other in the same way as for the regular clean cut panels. However, this problem will likely be much smaller in a real situation were the panels can be glued to the wall or placed in a controlled manner as floor or roof insulation, which is a more likely area of use for this type of panels.

18 mm new generation VIPs in a 36 mm double layer configuration

This measurement series was conducted on a test wall configuration using two layers of 18 mm VIPs with tapered edges, creating a 36 mm double layer configuration. Due to the fact that the panel joints overlapped, no tape was applied over the edges to reduce convection between the hot and the cold side of the test wall.

Table 15. Measured parameters of hot box test wall using 18 mm VIPs with tapered edges in a double layer configuration, i.e. 36 mm in total.

VIP, 18 mm double layer	Nominal physical properties of VIPs and test wall		
VIP dimensions	Width	w	= 900 mm
	Height	h	= 1000 mm
	Thickness	t	= 18 mm[3]
	Foil thickness	t_f	= 0.44 mm
Gap between panels (measured average)	Vertical joints	d_v	= N.A.
	Horizontal joints	d_h	= N.A.
Sample dimensions	Average sample thickness	d_s	= N.A
	Average air-layer thickness	d_{air}	= 0 mm

The MDF plates, covering the VIPs were held tightly against the VIPs using pressure applied over the centre of the test wall and tape alongside the edges of the test wall.

Table 16. Calculated and measured U-values and edge losses for double layer of new generation 18 mm VIPs with tapered edges, i.e. 36 mm in total.

Method	U-value centre of panel U_{cop} (W/(m²K))	U-value centre of panel (Heat flow meters) U'_{cop} (W/(m²K))	U-value test wall U_{wall} (W/(m²K))	U-value test wall, corrected for air layers U'_{wall} (W/(m²K))	Edge loss ψ_p (W/(mK))
Numerically calculated					
Nominal λ_{cop} and t_p, no panel gap	0.108		0.112		0.0010
Nominal λ_{cop} and t_p, 2 mm panel gap	0.108		0.114		0.0017
Measured in hotbox					
Series #68802	0.108	0.1	0.141		0.0313

Discussion

Due to the large irregularities in panel dimensions, uncertainty values for the measurements done on this configuration are omitted in Table 16. This is based on an assessment that the uncertainty connected to this quantity is likely of a higher degree than the one for the measured mean values.

The thermal performances of these panels are slightly better than the regular panels. If we correct for the fact that the regular panels are 10 % thicker the U-values of the new generation panels are in fact better pr mm panel thickness, i.e. they have a lower average thermal conductivity value for the test wall arrangement.

[3] Due to dimensional irregularities for these VIPs only nominal values have been used as input for the numerical and analytical calculations.

Some problems arose during the mounting phase of the panels in the hot box. Due to the tapered edges, the panels could not be stacked on top of each other in the same way as for the regular clean cut panels. However, this problem will likely be much smaller in a real situation were the panels can be glued to the wall or placed in a controlled manner as floor or roof insulation, which is a more likely application for this type of panels.

4. Comparison of edge loss thermal bridge values

The thermal bridge values from the results chapter are summarized in Figure 9. The measured values for the thermal bridges of the panel edge losses correspond quite well with the numerical simulations, as shown in Figure 9. The only series where a large deviation occurred is the single 20 mm VIP configuration. This large deviation is probably caused by a larger grade of convection due to the air gap between MDF and VIP compared to the other VIP configurations.

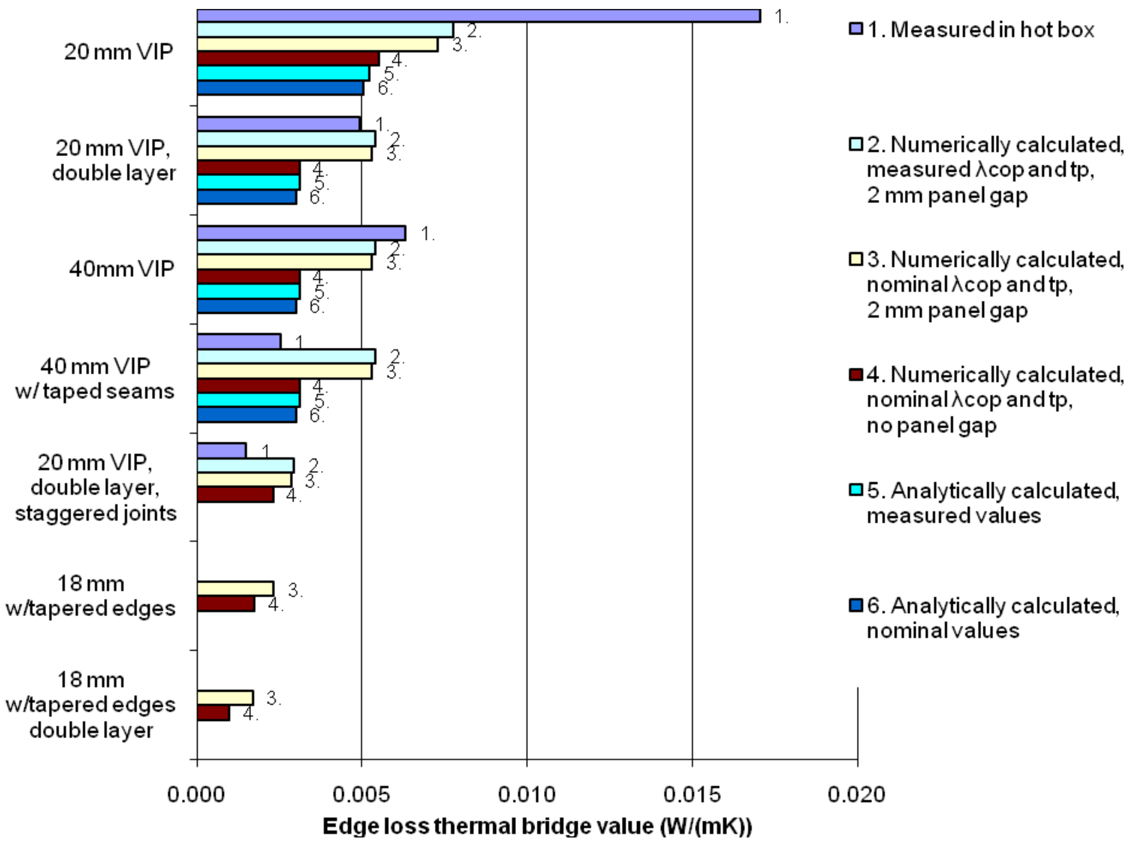


Figure 9. Comparison of measured and numerically calculated edge loss values of various VIP wall structure arrangements. Due to limitations in the analytical model (See eq. 1), no analytical thermal bridge values are calculated for the VIP configurations with staggered joints or tapered edge panels.

From Figure 9 on can see that for each of the VIP configurations without staggered joints or tapered edges the difference between the analytically calculated values (Series 5 and 6) are in the same range as the corresponding numerically calculated values in Series 4. When the numerically calculated values are corrected for the measured mean panel gap width and panel properties, these values approaches the measured values for the 20 mm and 40 mm configurations. For the 20 mm double layer and 40 mm with taped seams configurations these numerically calculated values exceed the measured values. Due to a large uncertainty regarding the measured values of the thermal bridges, these values are omitted in Figure 9.

5. Comparison of U-values for various VIP configurations

The U-values from the results chapter are summarized in Figure 10. The hot box measurements indicate that the effective U-values of VIPs in wall structure arrangements like the ones discussed in this work is somewhat higher than experienced through numerical simulations. The main reasons for this seem to be that the measured thicknesses t_p of the VIPs are lower than the nominal thicknesses and that the measured core conductivity is slightly higher than the nominal value of λ_{cop}. Measurements carried out on a limited number of panels indicate that the thicknesses of the panels are approximately 5 % less than the nominal values.

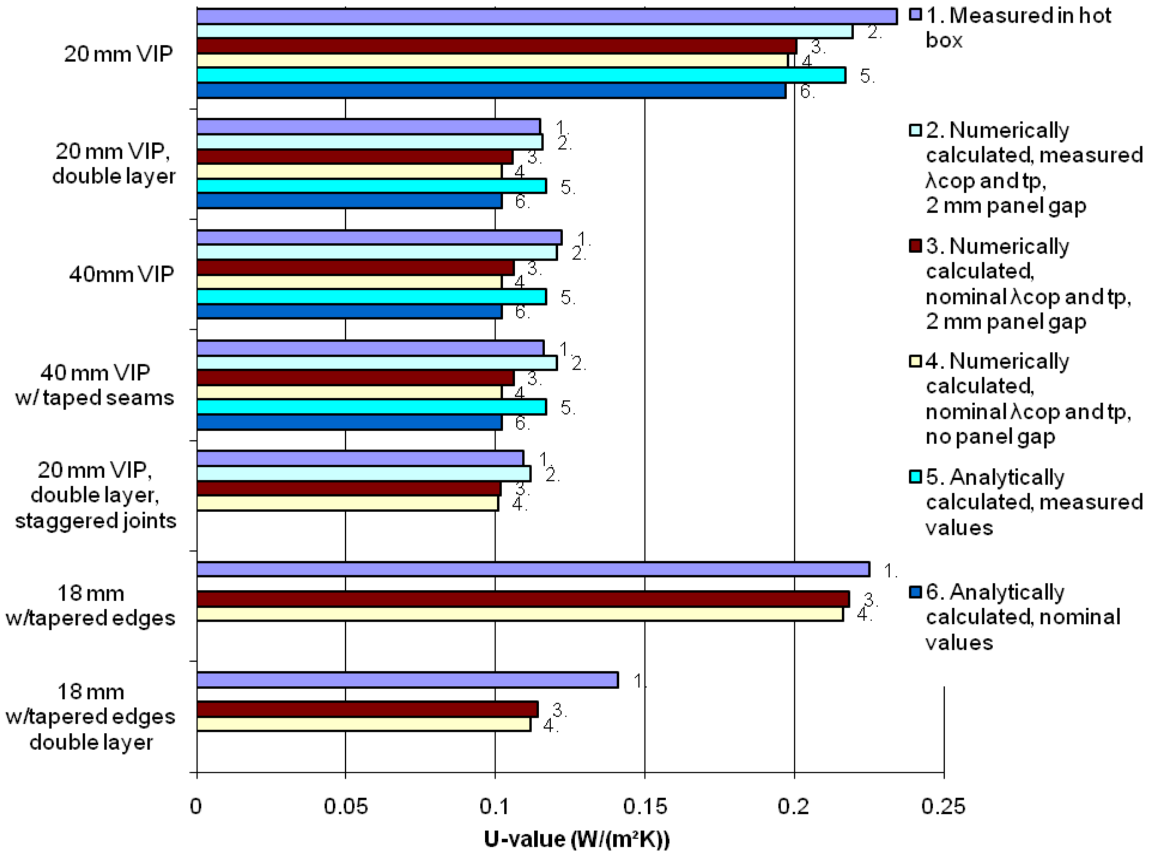


Figure 10. Comparison of measured and numerically calculated U-values of various VIP wall structure arrangements.

The measured U-value for the different VIP configurations are higher than any of the theoretical values for three of the different configurations, 20 mm single layer, 40 mm without tape and finally the 18 mm panels with tapered edges in a single layer configuration. The measured values are lower for the remaining four configurations. The analytical and numerically calculated values are approximately the same for the five first test series.

However, the measurement uncertainties suggest that there is no significant difference between measured and theoretical values, when the numbers are rounded to two decimals. U-values shall be rounded to two significant digits when stated for use in energy calculations for building (NS-EN ISO 6946:2007).

6. Conclusions

Based on numerical simulations, analytical calculations and full scale tests on various VIP wall structure arrangements it seems that the numerical simulation tools and methods for calculating thermal bridge values and U-values for VIPs in large scale structures are applicable. However, the input parameters must be treated with a certain degree of carefulness. It is found that the measured U-values from hot box investigations correspond quite well with the numerical calculated U-values as long as realistic and measured values of the various parameters are chosen as input values in the numerical simulations.

Acknowledgements

This work has been supported by the Research Council of Norway, AF Gruppen, Glava, Hunton Fiber as, Icopal, Isola, Jackon, maxit, Moelven ByggModul, Rambøll, Skanska, Statsbygg and Takprodusentenes forskningsgruppe through the SINTEF/NTNU research project ”*Robust Envelope Construction Details for Buildings of the 21st Century*” (ROBUST). The company va-Q-tec, by Roland Caps, is acknowledged for supplying the vacuum insulation panel test walls.

Nomenclature

Symbol	**Description**	**Unit**
A	Area	m²
d	Thickness	m
h	Height	m
l	Length	m
L^{2D}	Thermal coupling coefficient (from numerical simulation)	W/(m²K)
R	Thermal resistance	(m²K)/W
U	Thermal transmittance (U-value)	W/(m²K)
w	Width	m
α	Surface coefficient of heat transfer	W/(m²K)
Δ	Difference	-
θ	Temperature	K
λ	Thermal conductivity	W/(mK)
φ	Factor dependent of VIP foil seam type	-
ψ	Linear thermal transmittance (thermal bridge)	W/(mK)

Index	**Description**
0	Zero-reference
atm	Atmospheric pressure
cavity	Cavity
cop	Centre of panel
edge	The edge of the template test wall
eq	Equivalent
f	Foil
fasteners	Fasteners
gap	Gap between VIPs
i	number in series
p	Panel
roof	Roof
se	Exterior (cold) surface
si	Inside (warm) surface
VIP	Vacuum insulation Panel
VIP, edge	The edge of the VIP
wall	Wall tested in hot box e.g. test wall
wood	Wood

References

R. Baetens, B. P. Jelle, J. V. Thue, M. J. Tenpierik, S. Grynning, S. Uvsløkk and A. Gustavsen, "Vacuum Insulation Panels for Building Applications: A Review and Beyond", *Energy and Buildings*, **42**, 147-172, 2010.

A. Binz, A. Moosmann, G. Steinke, U. Schonhardt, F. Fregnan, H. Simmler, S. Brunner, K. Ghazi, R. Bundi, U. Heinemann, H. Schwab, H. Cauberg, M. Tenpierik, G. Johannesson, T. Thorsell, M. Erb and B. Nussbaumer, **"**Vacuum Insulation in the Building Sector - Systems and Applications", final report for the IEA/ECBCS Annex 39 HiPTI-project (High Performance Thermal Insulation for buildings and building systems), 2005

S. Brunner, H. Cauberg, M. Erb, U. Heinemann, E. Kücükpinar-Niarchos, K. Kumaran, Ph. Mukhopadhyaya, K. Noller, D. Quénard, H. Sallée, H. Schwab, H. Simmler, C. Stramm, & M.J. Tenpierik, (2005); *Vacuum Insulation Panels. Study on VIP-components and Panels for Service Life Prediction in Building Applications (Subtask A)*, final report for the IEA/ECBCS Annex 39 HiPTI-project (High Performance Thermal Insulation for buildings and building systems), 2005.

H.P Ebert, J. Fricke, H. Schwab, C. Stark, Wachtel J., "Thermal Bridges in Vacuum-insulated Building Facades", *Journal of Thermal Envelope & Building Science*, **28** No.4, 2005.

M. Erb, U. Heinemann, H. Schwab, H. Simmler, S. Brunner, K. Ghazi, R. Bundi, K. Kumaran, P. Mukhopadhyaya, D. Quénard, H. Sallée, K. Noller, E. Kücükpinar-Niarchos, C. Stramm, M. Tenpierik, H. Cauberg, A. Binz, G. Steinke and A. Moosmann, "Vacuum Insulation Panel Properties and Building Applications Summary", final report for the IEA/ECBCS Annex 39 HiPTI-project (High Performance Thermal Insulation for buildings and building systems), October 2005.

J. Fricke, H. Schwab, U. Heinemann, "Vacuum Insulation Panels – Exciting Thermal Properties and Most Challenging Applications", *International Journal of Thermophysics*, **27**, No. 4, July 2006.

A. Gustavsen, J.V. Thue, P. Blom, A. Dalehaug, T. Aurlien, S. Grynning, S. Uvsløkk, "Kuldebroer – Beregning, kuldebroverdier og innvirkning på energibruk", Prosjektrapport 25, SINTEF Byggforsk, ISBN 978-82-536-1037–5 (pdf), 2008.

ISO/DIS 12567-1, "Thermal preformance of windows and door – Determination of thermal transmittance by the hot box metod", Draft International Standard; Revision of first edition ISO 12567-1,2000.

R. Mitchell, C. Kohler, D. Araseth, "THERM 5.2 / WINDOW 5.2 NFRC Simulation Manual", Lawrence Berkeley National Laboratory, July 2006.

NS-EN ISO 10211, "Thermal bridges in building construction – Heat flows and surface temperatures – Detailed calculations". International standard, First edition 2007-12-15.

NS-EN ISO 6946:2007, "Building components and building elements Thermal resistance and thermal transmittance Calculation method", December 2007

NS-EN ISO 10456:2007, "Building materials and products Hygrothermal properties- Tabulated design values and procedures for determining declared and design thermal values", December 2007

NS-EN ISO 8990, "Thermal insulation Determination of steady-state thermal transmission properties Calibrated and guarded hot box", First edition April 1997.

NS-EN ISO 12667, “Thermal performance of building materials and products Determination of thermal resistance by means of guarded hot plate and heat flow meter methods Products of high and medium thermal resistance”, First edition May 2001.

W. Platzer, 2007, Optimisation and Testing of a VIP Exterior Thermal Insulation Composite System (ETICS)”, Proceedings of the 8th International Vacuum Insulation Symposium, Würzburg, September 18-19, 2007.

H. Scwab, C. Stark, J. Watchel, H. P. Ebert and J. Fricke, ”Thermal bridges in vacuum-insulated building facades”, Journal of Thermal Envelope and Building Science, 28, 345-355, 2005.

H. Simmler and S. Brunner, ”Vacuum insulation panels for building application Basic properties, aging mechanisms and service life”, *Energy and Buildings* **37,** 1122–1131, 2005.

TEK 07; Tekniske forskrifter til plan og bygningsloven 4.utgave 2007.

M. J. Tenpierik and H. Cauberg, “Analytical Models for calculating thermal bridge effects caused by Thin High Barrier Envelopes around Vacuum Insulation Panels”, *Journal of Building Physics*, **30,** 185-215, 2007.

M. J. Tenpierik, J.J.M. Cauberg and T. I. Thorsell, ”Integrating vacuum insulation panels in building constructions: An integral perspective”, Construction Innovation, 7, 38-53, 2007.

M. J. Tenpierik, W. H. Van der Spoel, and H. Cauberg, ”Analytical models for calculating thermal bridge effects in high performance building enclosure”, *Journal of Building Physics*, **31**, 361-388, 2008.

va-Q-plus B, http://www.va-q-tec.com/va-q-plus_b_en.html, retrieved 17.12.2009.

va-Q-tec; Product information, Vacuum Insulation Panel (va-Q-vip B), Würzburg Germany, va-Q-tec GmbH, 2009(a).

va-Q-tec and ZAE Bayern, Unpublished results (2007) according to method described at http://www.zae-bayern.de/files/thermoscan.pdf, information received from va-Q-tec (Roland Caps) in communication with SINTEF, 2009(b).

va-Q-vip B, http://www.va-q-tec.com/va-q-vip_b_en.html, retrieved 17.12.2009.

K.G. Wakili, R. Bundi and B. Binder; “Effective thermal conductivity of vacuum insulation panels”, Building Research & Information, 32:4, 293-299, 2004.

W. M. Willems, K. Schild and G. Hellinger; “Numerical Investigation on Thermal Bridge Effects inVacuum Insulating Elements”; Proceedings of the *7th International Vacuum Insulation Symposium*, pp. 5-14, 2005, EMPA, Dübendorf, September 28-29, 2005.