Thermal performance of VIP panels: Assessment of the edge effect by experimental and numerical analysis.

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ABSTRACT:
Throughout the last 10 years Vacuum Insulation Panels (VIPs) have gradually been accepted as thermal insulation panels for walls, roofs and floors. However, to this day these products have known a marginal market penetration, with the exception of a few buildings in Switzerland and Germany. This is in shear contrast with the general trend to insulate buildings increasingly more. In principle, a VIP panel of 30 mm thickness can replace a common insulating material of 200 to 300 mm if the thermal bridges are sufficiently dealt with. The slender VIP panels of 30 mm thickness would allow to maintain the conventional wall construction praxis while insulating 6 to 10 times more efficiently. This implies that if VIP panels were generally used, a significant shift towards low-energy and passive buildings would be possible while maintaining standard construction practice. The aim of this research project is to diminish some of the obstacles that currently hamper the use of VIP panels. Thermal characterization of whole panels (including edge effects), will be based on experiments both in laboratory conditions as well as on site. Firstly, the effect of thermal bridges due to the foil will be assessed with a horizontal guarded hot plate apparatus and full scale hot-box. The next step is a validation of a numerical model that simulates the effects of the thermal bridges, based on the different experiments. This model can contribute to a more accurate assessment of the VIPs and the influence of various parameters.

In the last phase of the project these results will be compared to an on-site measuring campaign. This paper focuses on the experimental test with the guarded hot plate and the validation of the numerical simulation model. A review of the current state of the art on thermal bridge calculation and experiments is reported, and a new simulation methodology is proposed.

1 INTRODUCTION

Vacuum Insulation Panels (VIP) typically consist of a vacuum-packed silica core material encapsulated within a thin vapor tight foil. The foil cover requires a thin layer of metal that acts as a barrier and thus maintains the vacuum over a long period of time. Typically, two or three thin aluminum layers or coatings are used to reduce the permeability of the overall foil. However, the aluminum layer causes a thermal bridge at the edges of the VIP.

As well, the air gap between adjacent panels can also cause thermal bridging effects. Exact sizes for VIPs are difficult to manufacture because the silica core shrinks differently upon evacuation of air to create the vacuum. Hence, air gaps may occur between VIPs due to production control tolerances. Needless to say these different boundary conditions create both linear and point thermal bridges. For specific building applications other thermal bridging effects may arise as well. Due to the combination of a thin product having a high thermal resistance, any irregularities in the plane of insulation will amplify the thermal effects. If e.g., wall ties are inserted between VIPs in a cavity brick wall, typical point-like thermal bridges occur.

The first section of this paper comprises an analysis of measurements on thermal bridging reported in literature, an overview of simulation methodologies and results, and a critical analysis of current simulation practice. The second part of this paper is focused on the experimental setup of guarded hot plate experiments, whereas the third section elaborates on a proposed simulation method. Results, conclusions and discussion are reported in sections 4 and 5.

1.1 *EPBD*

An annex of the Belgian Energy Performance Building Directive (EPBD, 2009) prescribes a method to calculate the thermal conductivity value λ_{equ} for VIP panels, using default values to take into account different effects. The thermal conductivity of the core

(λ_{core}) material of the VIP must first be measured under vacuum and in dry state. Subsequently, to incorporate the effect of aging of the product (loss of vacuum over time and effect of moisture on the conductance) the document offers a correction value $\Delta\lambda$ that must be added to λ_{core} and depends on the dimensions of the panel. Thirdly, the effect of thermal bridging is taken into account, based on the thickness of the panel and the specific composition of the foil.

The thermal conductivity can be expressed by:

$$\lambda_{equ} = \lambda_{core,aged} + \psi \cdot dP/A \qquad (1)$$

Where:

- λ_{equ} = value of equivalent thermal conductivity of product, [W/m.K],
- $\lambda_{core,aged}$ = value of thermal conductivity of core of product after aging [W/m.K],
- d = thickness of VIP [m], in direction of heat flow,
- P = circumference of VIP [m],
- A = area of VIP [m²], perpendicular to direction of heat flow,
- Ψ = linear heat transmission coefficient [W/m.K], that expresses extra heat loss due to foil.

The thermal performance of the VIPs declines over time as a result of two phenomena: the accumulation of an amount of water in the core of the product and the increase in internal gas pressure. The thermal conductivity after aging is determined by:

$$\lambda_{core,aged} = \lambda_{10,core,dry,90/90} + \Delta\lambda \qquad (2)$$

The EPBD offers two methods to determine the aging factor $\Delta\lambda$. The first method requires a sample to be submitted to a rapid aging test to assess the overall long-term performance. In absence of any artificial aging methodology available for this type of product this method is currently not applicable. The second way of determining the long-term performance is by separating the individual effects of accumulation of water and the increase of internal pressure. This method assumes these two effects are not correlated. The influence of the thermal conductivity of the core of the material can be expressed as follows:

$$\Delta\lambda = \frac{\partial\lambda}{\partial p}\Delta p(T,HR) + \frac{\partial\lambda}{\partial X}\Delta X(T,HR) \qquad (3)$$

Where :

- $\Delta\lambda$ = variation of thermal conductivity [W/m.K]
- Δp (T,HR) = increase of internal pressure [mbar] during lifespan of VIP, depends on temperature (T) and relative humidity (HR) of environment.
- ΔX (T,HR) = increase of accumulation of water [% in mass] during lifespan of VIP, depends on T and HR.

Table 1 Effect of increase of internal pressure, accumulation of water and thermal bridging on the thermal conductivity for a specific panel size.

Panel size	$\geq$ 50 cm x 50 cm x 2 cm
$\frac{\partial\lambda}{\partial p}\Delta p$	0.0018 W/mK
$\frac{\partial\lambda}{\partial X}\Delta X$	0.0020 W/mK
Ψ (metalized film)	0.010 W/mK

Table 1 clearly shows the effect of thermal bridging on the overall performance of VIP panels; the magnitude of the effects due to thermal bridging supersedes those from aging. A literature review reveals that the numerical simulation of thermal bridges remains a challenge, as, to the knowledge of the author, no satisfactory validation study has yet been completed.

1.2 *Numerical calculation*

Different numerical thermal simulation software has been used to investigate the thermal bridging effects in VIPs: (Tenpierik, Cauberg, & van der Spoel, apr 2008) (Tenpierik and Cauberg, 2009) (Nussbaumer et al., 2005, 2006) (Wakili et al., 2005) used Trisco, (Grynning, et al., 2009) (Haavi et al., 2009) used Therm, and (Schwab, et al., 2004) used Heat. As with any simulation the results should be interpreted with prudence, because they strongly depend on the accuracy of the material data and boundary conditions as well as the simulation methodology and experience of the user. Therefore, numerical simulations must be optimized by validation with experimental data.

The multilayer foil is reduced to a single layer, or to one layer per material, for the implementation of VIPs within all simulation models, possibly because of grid dimensions of the software (Tenpierik et al., 2008). This is a highly simplified representation of reality. A comparison of thermal properties of different foil types and their effect on thermal bridging can be found in (Simmler et al., 2005). However, no validation of these simulations is available. Tenpierik and Cauberg (2008) offer a analytical calculation method based on numerical simulations but the effect of the simplified modeling of the multilayer foil was not investigated. Furthermore, it is yet unclear how the different authors simulated the folding of the foils at the seams. Except for the work of Wakili et al. (2004), none of the publications referenced above show model schemes for foils, nor is there a discussion on simulation methodology. For example, is a fold modeled as a thicker foil or is there any other layer in between (i.e., air, substrate layers). Wakili et al. (2004) show a topological model of the seal at the

interface between two panels: aluminum layers are joined into one layer, and substrate layers are also joined. Inside the fold there is a 1 mm air gap and in between panels there is a 0.4 mm air gap. However, the air gaps "are adjusted so as to obtain a good correspondence of the calculated and measured values".

The input of material data is typically based on measurements (COP value) and tabulated values found in standards. Nussbaumer (2005) however, optimized the thermal conductivities in the simulations to fit the results: "…found by stepwise adjustment and comparison with measurements".

Most authors refer to ISO 10211 (2008) for the grid density, but only Wakili et al. (2004) report grid sizes. Similarly, heat transfer coefficients are not mentioned (Haavi et al., 2009; Grynning et al., 2009) or they "correspond to the measured values" but are not reported (Nussbaumer et al., 2005, 2006), or simplified values from ISO 10077-2 (2003) (Nussbaumer at al., 2005), (Tenpierik & Cauberg, 2008) or DIN 4108 (Schwab et al., 2005) are used. Wakili et al. (2004) use a heat transfer coefficient of 1000W/m².K to compare simulations to guarded hot-plate measurements.

1.3 Analytical calculation

Using the analytical model proposed by Tenpierik and Cauberg (2007) the linear heat transmission coefficient can be calculated in a single step:

$$\text{(4)}$$

$$\psi_{vip,edge}$$
$$= \frac{1}{1 + \frac{\lambda_c}{\alpha_1 d_p} + \frac{\lambda_c}{\alpha_2 d_p}}$$

$$\cdot \left[\frac{\alpha_1 (N_2^2 - B)}{\frac{\varphi d_p \lambda_f}{\lambda_f'} (N_1^2 N_2^2 - B^2) - \lambda_1 \sqrt{N_1^2 N_2^2 - B^2} \left(\frac{2B}{\sqrt{D}} + 1 \right) - \lambda_2 \sqrt{N_1^2 N_2^2 - B^2} \left(1 - \frac{2B}{\sqrt{D}} \right)} \right]$$

In this equation α_n [W/m²·K] is the heat transmission coefficient at boundary surface n ($n=1$ or 2), d_p [m] is the thickness of the vacuum insulation panel, φ [-] is the ratio of t_f / t'_f, t_f [m] is the thickness of the foil or film, t'_f [m] is the thickness of the foil or film at the panel edge, λ_f [W/m·K] is the foil/film thermal conductivity and λ'_f [W/m·K] is the thermal conductivity of the foil/film at the panel edge. The parameters N_1, N_2 and B are calculated as:

$$N_i = \sqrt{\frac{\alpha_i}{t_f \lambda_f} + \frac{\lambda_c}{t_f \lambda_f d_p}} \tag{5}$$

$$B = \frac{\lambda_c}{t_f \lambda_f d_p} \tag{6}$$

λ_1 and λ_2 in equation 4 are the eigenvalues of the linear system of differential equations derived to represent the thermal phenomenon. They are determined by:

$$\lambda_1 = -\sqrt{\frac{(N_1^2 + N_2^2) - \sqrt{(N_1^2 - N_2^2)^2 + 4B^2}}{2}}$$

$$\lambda_2 = -\sqrt{\frac{(N_1^2 + N_2^2) + \sqrt{(N_1^2 - N_2^2)^2 + 4B^2}}{2}} \tag{7}$$

D is the discriminator of the second square root of the eigenvalues λ_1 and λ_2:

$$D = (N_1^2 - N_2^2)^2 + 4B^2 \tag{8}$$

Radiation is not taken into account, nor tolerances between panels. Tenpierik (2008) states this formula allows an easy and accurate calculation of thermal bridges. Research by (Grynning et al., 2009) concludes that simple rectangular simulations provide validation of the analytical calculation in the case of two joined perfectly VIPs without any air gaps. However, this model was only validated by a simplified, rectangular numerical model in Trisco for a limited number of dimensions. It has not been benchmarked with experimental data.

1.4 Hot-box experiments on VIPs

To obtain a better understanding of the effect of thermal bridging on a larger scale, U-values were calculated for entire panels and compared to full-scale hot-box measurements. Calculations of the overall U-value, U_{eq}, including thermal bridges can be done according to formula 9 (conversion of formula 1):

$$U_{eq} = U_{cop} + \psi \cdot \frac{L}{A} \tag{9}$$

Where:
- U_{eq} = overall U-value for test wall including thermal bridges [W/m².K]
- U_{cop} = U-value for centre of panel part of test wall [W/m².K]
- ψ = linear thermal transmittance [W/m.K]
- L = length over which ψ applies [m]
- A = area over which U_{eq} applies [m²]

Results from the hot box experiments were used to validate numerical simulations using different software programs.

Nussbaumer et al. (2005) reported a validation of numerical simulations with the program Trisco, based on a guarded hot box measurement on a wooden door system with integrated vacuum insulation panels. The overall difference between simulations and measurements is 8%, but the effect of the VIP edges was not studied separately.

Nussbaumer et al. (2006) also compared experimental data obtained from hot-box measurements with numerical simulations for VIPs applied to a concrete wall. The VIPs were 40 mm thick, and had an 10 mm layer of EPS on both sides. The edges

were also surrounded with about 6 – 13 mm EPS (the overlap seal was not folded). These measures of course distinctively diminished the bridging effect. Furthermore, although the overall correlation between the measured and calculated U-value was good, no conclusions could be drawn with regards to the thermal bridges (only total heat fluxes and U-values were reported). Note that, as mentioned above, the material properties for simulations were changed to match the results.

Experimental research using a hot-box has been done on different configurations of VIPs with different panel sizes and thickness by (Grynning, et al., 2009). Results indicate that the use of a double layer of 20 mm panels with staggered joints gives a reduction of thermal bridges compared to a single layer of 40 mm VIPs. It should be noted that most measurements were done without taping the gaps between the VIPs, possibly causing convection between the panels. The average width of the gaps between the panels (production and installation tolerances) was about 2mm, but varied from 0 mm to 7 mm. The effect of taping the gaps was tested for 40 mm panels: without tape the ψ-value went up 152%. Assuming that all simulations were using simplified methods to model convection, only the one measurement on VIPs with taped gaps should be considered here. For that case, the measured ψ-value was 0.0025W/m.K ($\pm$0.0004). Simulations were done with and without the 2mm gap: 0.0031W/m.K and 0.0053W/m.K respectively. Simulating the latter with the measured λ_{cop} resulted in 0.0054W/m.K, an error between 46% and 61%, and on average 53%. Although simulations were done on models including the gaps, no information is reported on the way both radiation as convection are modelled in those gaps. The authors concluded that the reliability of numerical simulation tools for calculating thermal bridging values and U-values for VIPs in full-scale structures was satisfactory and applicable in practice, but stated that "the input parameters must be treated with a certain degree of carefulness." (Grynning, et al., 2009)

Wooden wall constructions with 3 different types of studs (massive studs, I-studs and U-studs) were tested in a hot box by (Haavi, et al., 2010). The construction consists of 6 mm MDF, 65 mm mineral wool, 40 mm VIP, 65 mm mineral wool, 6 mm MDF. None of the constructions had joined VIPs, and all of them encapsulated the VIP edges in insulation. U-values have been calculated in the numerical thermal simulation program THERM. With the exception of the setup having massive studs (11%), the U-values derived from the numerical simulations are lower than the measured U-values (about 9 to 11%). The higher U-value for the massive studs was explained by a too high thermal conductivity of the massive wooden studs. In this research the contribution of the thermal bridge to the overall U-value is not further investigated, and no error analysis of the hot-box measurements is reported.

1.5 *Guarded hot plate apparatus*

Experimental investigations with a guarded hot plate have been conducted at EMPA. (Simmler et al., 2005) The effect of the composition of the foil on the ψ-value is analyzed. Measurements using a guarded hot plate and two dimensional numerical analysis of the heat flux confirmed that the influence of the edge effect on the thermal conductivity cannot be neglected (Wakili et al., 2004). The measurements were done with a gradient of 10°C. The VIPs were sandwiched between two rubber sheets to avoid lateral heat losses from the guard to the measuring area. The accuracy of the measured thermal conductivities were within 3%. Three types were used, with different multilayer structure of the barrier envelope. The numerical software used was Trisco, and the layers of identical material were put together in one layer. Because of the very thin layers, special attention was paid to the grid size to help ensure accuracy and numerical convergence of the simulation. Only overall R-values are reported: the calculated values are 3% to 9% higher than the measured results. Note that the geometry of the simulation model was altered to match the experimental results. Furthermore, a comparison for other dimensions is only shown in a graph, clearly indicating greater deviations and trends compared to experiments.

1.6 *Conclusions*

A literature review shows the different attempts that have been made to validate models with experimental results. No validation of analytical models was found; only comparisons with numerical models. Most publications compare overall U-values or R-values, without an in depth analysis of the linear thermal transmittance of the joints between panels. In one validation study the material properties in the simulation model were changed to match the results (Nussbaumer et al., 2005, 2006) and in another the simulation geometry was similarly changed (Wakili et al., 2004). Grynning et al. (2009) found a difference of 53% between measured and simulated ψ-values for the most reliable test setup.

2 EXPERIMENTAL SET-UP

Previous research using hot box experiments, numerical simulations and analytical calculations demonstrate the great influence the foils have on the overall performance of VIPs due to the thermal

bridging effect. As a literature review revealed that the only validated numerical simulation of thermal bridges in VIPs provided errors of, on average, 53%, it was of interest to develop a reliable testing methodology to advance in this matter. To reduce the number of parameters influencing results, it was decided that measurements would first be conducted on a guarded hot plate apparatus. Future research will use a hotbox setup for validation.

2.1 *Guarded hot plate apparatus*

The guarded hot plate used was a FOX 600 (Lasercomp), calibrated according to ISO 8301. The apparatus is comprised of a hot and a cold plate that can be set to specified temperatures. Each time a sample is inserted and the stack is closed, the average thickness of the sample is determined within an accuracy of 0.025 mm. Heat flux transducers are bonded to the surfaces of both plates. They are made of thousands small thermocouples, thus providing highly sensitive transducers and integration of signals. In order to optimize the accuracy of the measurement, this apparatus has a specific measuring area and a guard to secure stable boundary conditions. Transversal heat fluxes towards the edge of the sample are eliminated by inducing a small temperature correction by the guard. The dimensions of the measuring area are 254x254 mm. (Lasercomp, 2001)

The U-value was calculated as:

$$U = \lambda / d \tag{10}$$

Where λ [W/m.K] is the thermal conductivity and d [m] the thickness of the insulation. Both the convective heat transfer coefficient and the radiation heat transfer coefficient are very high, as the plates are pressed on the insulation panel with a normalized force.

The heat flow Φ [W] is:

$$\Phi = U \cdot A \cdot \Delta T \tag{11}$$

Where ΔT [K] is the difference in temperature between inner and outer conditions and A [m²] is the measured area of one panel.

The linear thermal transmittance ψ [W/m.K] can be obtained from:

$$\psi = \left(\frac{\Phi_{tot} - \Phi_{cop}}{l \cdot \Delta T} \right) \tag{12}$$

with Φ_{cop} [W] the centre-of-panel heat flow, ΔT [K] the applied temperature difference and l [m] the measured length of the thermal bridge.

To determine the equivalent U-value generally equation 9 is used, and hence some confusion can arise about the definition of the size of the thermal bridge. Experimentally the thermal bridge between two panels is measured, and equation 12 represents this thermal bridge. On the other hand, when determining the edge effect of a VIP, a factor of ½ is

added to the right side of the equation. The overall performance of a single panel is calculated according to equation 9, so only half of all the thermal bridges around the perimeter are taken into account.

Wakili et al. (2004) reports on the specific boundary conditions when testing VIPs in a guarded hot plate. ISO 8301 (1991) does not provide clear guidelines for heterogeneous materials, and EN 12667 (2001) requires that for layered samples the thermal conductivity of one layer is never higher than twice the conductivity of any other layer. ASTM C-177 (1997) requires a low conductance material in line with the metered section and primary guard in the case where the sample has a high lateral to axial conductance ratio. To improve the accuracy of the measurements a few reference test series were first completed on simple samples. In that way the effect of the foil and guard were analyzed separately and the settings for the simulations were then determined. The guard provides an extra heat flow therefore the heat transfer in the zone of the guard will be slightly different from that in the measuring area given that lateral heat fluxes may occur.

2.2 *Samples*

The reference samples measured to assess side effects are XPS-panels having dimensions (610x610x20 mm) to fit the guarded hot plate. The samples of VIPs were provided by Microtherm (type: "SlimVac"). The foil used to maintain a vacuum in the VIPs is a multilayer film, the composition of which is provided in Table 2.

Table 2 Characteristics multilayer film

	lambda [W/m.K]	Thickness [µm]
PE	0.15	55
Al	237	0.03
Pet	0.29	12
Al	237	0.03
Pet	0.29	12
Al	237	0.03
Pet	0.29	12

To assess the effect of transversal heat fluxes from the guard, measurements were first completed with the multilayer applied over the entire surface of the XPS panels and therafter, with the foil only over the measuring area. These can be compared to the measurements on the panel without a foil on it.

The SlimVac (Microtherm, 2009) VIPs have a core material that consisted of an opacified blend of filament reinforced silica, optimized for thermal performance in a vacuum of 1-5 mbar. The standard finish has slightly rounded edges and projecting seal flanges on all four edges. The panels used in the experiments had been ordered with seal flanges neatly taped back and retained. Afterwards the vacuum pressure levels were checked again to ensure the panels were not damaged by taping the seal flanges.

2.3 *Procedure*

Measurements in the guarded hot-plate were done according to ISO 8301. Measurements on XPS took approximately one hour to reach temperature equilibrium. The duration of the test increased with the thickness of the sample and the thermal resistance. The heat flux was measured when a thermal equilibrium was reached according to that specified in ISO 8320.

Since the thermal conductivity of an XPS panel is measured without the influence of a film, the thermal bridge due to the foil can be determined. After the XPS panel was measured, a panel with a foil on both sides located only at the measuring area was tested. Then a sample with whole foils on both sides was measured. As such, the effect of the foil on any lateral heat flux can be determined. During the second test set, the effect of the foil on thermal bridges was analysed by testing two side by side XPS panels with a foil around them. There were no seals at the edge, so it was expected that measurements would correlate to those derived from simulations. Again, there was a test with the film only at the measuring area, and a film on the whole panel. The simulation methodology to deal with these side effects could then be used and applied to the simulations on VIPs.

For actual measurements, the centre-of-panel thermal conductivity of VIPs of thickness 20 mm and 30 mm, were first determined. In principle, these values should be equal, but minor differences may occur due to slightly density variations. Similar variations might even occur due to panel size and may influence the results. Subsequently, the linear thermal transmittance was measured by placing two panels next to each other in the guarded hot plate. The overall area-averaged thermal conductivity of this composition and the thermal transmittance could then be calculated as determined previously using equation 9. The average width of the gap between the panels was determined during each test. This procedure was repeated with different gap sizes and for panels of 20 mm and 30 mm.

3 SIMULATION METHODOLOGY

Thermal simulations were done using the thermal numerical software Bisco 10.0w (Physibel, 2009). Based on a steady state heat balance the software calculates temperatures and heat fluxes, comparable to other similarly available software programs. However, as compared to other programs, the software uniquely allows simulation of non-rectangular sections by using an automatically generated triangular grid. As well, a conversion program renders it possible to convert CAD-drawings into models with user defined grid-sizes. Based on the overall simulated heat flux and the centre of panel thermal conductance, the linear thermal transmittance of the thermal bridge can then be calculated.

For the input of material data the conversion into the triangulated grid and the grid size must be taken into account. For example: the multilayer film that is used has a total thickness of 91.9 μm, but was inserted in Bisco with a total thickness of 0.9 mm and a grid size of 0.1 mm. The different layers were simulated separately with their own thermal conductivity adjusted to the grid size. As the program uses only one grid size for the entire drawing, applying actual dimensions of the foil would render it impossible to calculate due to the high number of nodes. A series of simulations were done using Trisco (Physibel, 2009) to analyze the effect of simplification in the layer composition and grid size. The results revealed that the difference between simulations with a foil consisting of 7 layers (each layer comprises at least 9 grid cells) and a simplified model with three thicker layers having scaled thermal conductivities was below the accuracy achievable from simulation.

4 RESULTS

4.1 *Calibration study (XPS)*

Side effects and aptitude of the test methodology was assessed on a range of configurations of XPS panels: without foil, with a foil that is used for VIPs in the measuring area, and with the complete foil. The effect of the foil on thermal bridging between two panels was assessed by measuring the heat flux through two XPS panels with dimensions of 610mm by 305mm and covered with the multilayer foil.

In search of a method to 'calibrate' the thermal analysis software, the results of these experiments were used to adjust simulation parameters and error analysis. Once the simulations parameters are determined in Bisco, these settings were used to simulate the heat flux in the VIPs and validation with experimental data. The dimensions of the panels in Table 4 and 5 indicates whether a centre-of-panel value was measured (610x610 mm) or adjacent panels with a thermal bridge (610x305 mm).

Based on the measured U-value for the XPS, the heat flux through the XPS with foils should be 2.0373W (manual calculation based on thermal conductivity and width of materials). When there is only a foil in the centre, it should reflect the actual value, as no transversal heat flux from the guard can disturb the measurement. The foil can disturb the measurement in two ways: (i) the foil creates an heterogeneous temperature distribution at the surface of the measurement area affecting the average temperature difference; (ii) the transversal heat flow can disturb the heat flux measurement through the panel.

	610x610mm	610x610mm (foil in centre)	610x610mm (foil all over)	610x305mm (foil in centre)	610x305mm (foil all over)
λ [W/m.K]	0.0312	0.0312	0.0313	0.0327	0.0326
Thickness [m]	0.0197	0.0199	0.0199	0.0203	0.0203
Exp. Ψ [W/m.K]	-	-	-	0.0099	0.0070
Num. Ψ [W/m.K]	-	-	-	-	0.0068

The results indicate that the difference between the predicted value and the experimental result is 0.13%. The guard increases the heat flux through whole panels whereas it has an opposite effect on the adjacent panels. The most plausible explanation is that in the first case the heat flux measurement is primarily affected (+ 0.0084W), whereas is the second case the effect of the area averaged temperature difference dominates the results (- 0.0231W). Simulations of the transversal heat fluxes and surface temperature distribution proved to be insensitive for changes in the thermal conductivity of the core material (from XPS to VIP core). Hence, the simulations will be corrected for the combined effect (-0.0147W). However, if this were to be considered as error on the results, the absolute effect on the Ψ-value would be only 0.00289W/m.K. The effect of the guard was simulated in Bisco: 0.00457W (experimental 0.0084W). Taking into account the three-dimensional losses at the perimeter of the square measuring area, this approximation is reasonable. If the heat transfer coefficient of the simulations are set to 100.000, the simulated Ψ-value is 0.0068 instead of 0.0070 W/m.K. This confirms the assumptions on the effect of the transversal heat fluxes and the proposed correction factor. The model is similar to '4 mm gap' in section 4.2.

4.2 VIP

A range of simulations of VIPs were done with a varying degree of accuracy in terms of converting reality to modelling assumptions. The most accurate model has a folded foil, a 4 mm gap and a film existing of three layers: Al, PE and Pet.

Furthermore, the results were compared with the analytical calculations according to Tenpierik et al. (2008). Table 4 shows the experimental results, and the analytical calculation, whereas in Table 5, experimental values are compared to those obtained from the simulations. In the Table, *Multilayer* refers to: the foil was simulated in three layers; *folded edges*: similar to 'multilayer' but the seal was simulated with the actual folds in it; *4 mm gap*: similar to

'folded edges', but a gap of 4 mm was assumed at the interface. The analytical calculations correlate quite well with the experimental data, overestimating the thermal bridge both for panels of 20 mm (7.9%) as for the 30 mm panels (22.7%).

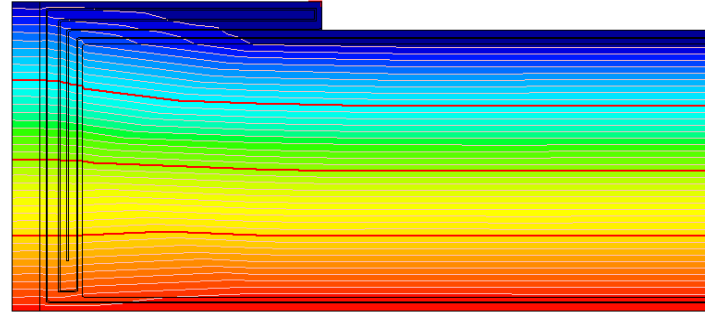Figure 1 Temperature Range (increment: 0,5°C)

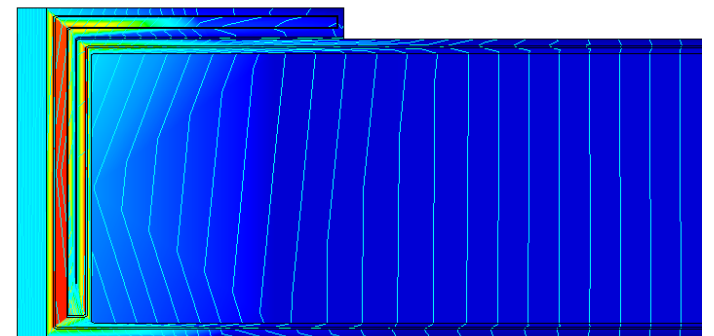Figure 2 Heat flow (lines, increment: 0.01W/m) and heat flux (colors, increment: 0.1W/m²)

Table 4 Experimental results and analytical calculation

	610x610 x20mm	610x305 x20mm	610x610 x30mm	610x305 x30mm
λ [W/m.K]	0.004584	0.005999	0.004565	0.005726
Thickness [m]	0.0203	0.0206	0.0303	0.0303
Exp. Q [W]	0.2915	0.3754	0.1941	0.2435
Exp. Ψ [W/m.K]	-	0.0165	-	0.0097
Analyt. Ψ [W/m.K]	-	**0.0178**	-	**0.0119**

Table 5 Experimental results and numerical simulations

	Experimental	Multilayer	Folded edges	4mm gap
610x305x20mm				
Num. Q [W/m]	0.3754	0.3338	0.3678	0.4069
Num. Ψ [W/m.K]	**0.0165**	0.0054	0.0121	**0.0198**
610x305x30mm				
Num. Q [W/m]	0.2435	0.2195	0.2443	0.2631
Num. Ψ [W/m.K]	**0.0097**	0.0021	0.0070	**0.0107**

The numerical results of the most advanced model show reasonable correlation for the 20 mm panel (20.0% overestimation) and good correlation for the 30 mm panel (10.3% overestimation). The models

which do not incorporate air gaps are not reliable. Hence on the basis of these results it is of particular importance to note the effect of the air gap. The uncertainty in estimating the air gap between the panels could possibly explain the difference between the experimental, analytical and numerical results.

5 CONCLUSIONS AND DISCUSSION

A literature review on thermal bridges in Vacuum Insulating Panels was presented which offered an outline of experimental research (guarded hot plate and hot box), analytical calculations and numerical simulations published on this subject. Essentially, validation studies comprised of analytical and numerical simulations are scarce and not well documented. The aptitude of the guarded hot plate apparatus for testing thermal bridges was analyzed based on experiment with XPS panels. The results of these experiments helped point out that there is a significant effect of the guard on the results, and a correction factor was proposed for this particular setup.

A comparison of experimental results on VIPs of 20 mm and 30 mm thick showed good correlation with analytical results (overestimation of 8% and 23 %), and good correlation with the numerical simulations (overestimation of 20% and 10% respectively). The tabulated value of the Belgian EPBD annex underestimates the heat losses for the 20 mm panel, but overestimates it for the 30 mm panel. Higher accuracies might be difficult to achieve in standard guarded hot plate measurements, as variability and accuracy in the experimental setup (tolerances, gap distances, influence of the guard) induce significant uncertainties in the results. Additional tests will be done according to ASTM C1484-01. Future research will use guarded hot box experiments and on-site flux measurements to validate numerical simulations for VIPs subjected to more realistic boundary conditions.

6 ACKNOWLEDGEMENTS

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