EPS ENCAPSULATED VIPS – A THERMAL PERFORMANCE STUDY

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Theme 4: VIP Performance – Optimisation, Testing, and Modelling

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Abstract:
For reasons of protection, reduced dimensional tolerances or ease of installation, a vacuum insulation panel is sometimes integrated into an EPS insulation board. Such boards however have as disadvantage that an additional thermal bridge is created along the panel's perimeter due to a strip of EPS. A parameter study into the effects of integrating a VIP into an EPS insulation board was executed for panels with a fixed size of 1x1 m^2 and thickness of 100 mm as specified by a manufacturer. Such an element with fixed outer dimensions was filled with two identical VIPs having variable thickness and size. In this study several tools for calculating the overall thermal performance of such a component were used: numerical simulation software, analytical models previously developed by authors and international standards. The effect of multiple parameters was investigated: the thermal conductivity of the VIP's core, the thickness of the barrier envelope, the VIP's thickness, the thickness of the EPS layers and the width of the EPS strips along the component's perimeter.

The study showed that for a component with fixed outer dimensions a maximum in thermal performance occurred at a certain thickness of the VIP inside. For the three-dimensional case studied, this thickness was near 30 mm. This phenomenon can be explained from a decomposition of heat flows through the separate elements of such a component: For increasing VIP thickness, the heat flow through the central area decreases due to the proportionality of the thermal resistance of this region to thickness; the heat flow through the EPS edge strip more-or-less remains constant; and the heat flow through the aluminium laminate in the thermal bridge region increases with increasing VIP thickness – the higher the product of laminate thickness and thermal conductivity, the more rapid the increase. The combined effect of these heat flows results in the occurrence or otherwise of a local maximum in thermal performance at a specific VIP thickness.

Two parameters can be held responsible for this occurrence: the product of laminate thickness and thermal conductivity on the one hand and the boundary heat exchange coefficients represented by a change in thickness of the EPS top and bottom layer on the other hand. As seen during the analysis, the phenomenon does not occur if the boundary heat transfer coefficients are constant, or similarly if the thickness of the EPS top and bottom layer is constant. If this variability in boundary heat transfer does exist, than the product of laminate thickness and thermal conductivity as a second criterion determines whether or not a local maximum in thermal performance exists.

1. INTRODUCTION

Because of their fragile nature, their high dimensional tolerances and their prefabricated character, vacuum insulation panels are sometimes encapsulated by a layer of EPS foam on all sides. Although the integration of VIPs in EPS insulation boards may solve several practical issues, the strip of EPS along the system's perimeter increases the thermal edge effect resulting from the barrier laminate. The question is whether or not such EPS edge strips render the high thermal performance of a vacuum insulation panel useless.

Several manufactures have already produced these EPS encapsulated VIPs for several years. A variant with PU foam for example was used by Variotec as core for high performance spandrel and door panels[i] (Stölzel, 2003). Moreover, in a demonstration project for a Passivhaus in Bersenbrück, EPS encapsulated VIPs were applied for insulating massive façade walls (Zwerger and Klein, 2005a; Zwerger and Klein, 2005b; Platzer et al., 2005). To reduce thermal bridges due to the EPS edge strips, an additional layer of 80 mm EPS was added to the wall, so that an effective *U*-value of 0.147 $W \cdot m^{-2} \cdot K^{-1}$ was achieved with a total thickness of the insulation layer of 140 mm of which 20 mm VIP. Zwerger and Klein argue that this additional layer of insulation can be omitted if EPS only covers the top and bottom surface of a VIP and not the perimeter as a result reducing thermal edge effects (Zwerger and Klein, 2005a).

Some researchers did also small-scale studies into the effects of applying such an additional insulation layer to a vacuum insulation panel. In their study for reducing the thermal bridge effect due to stainless steel barrier envelopes around VIPs by creating so-called serpentine edges, Thorsell and Källebrink also investigated the effect of such an additional insulation layer – not covering the panel's edges - on the linear thermal transmittance of VIPs (Thorsell and Källebrink, 2005; Thorsell, 2006a; 2006b). They found that the linear thermal transmittance of a VIP edge decreases for decreasing boundary heat transfer coefficient, i.e. for increasing insulation layer thickness. In other words, they found that the overall thermal performance of the encapsulated VIPs studied increases if the thermal resistance of the insulation layer increases. This analysis was performed for a 30 mm thick VIP (λ_c = 0.005 $W \cdot m^{-1} \cdot K^{-1}$) with a stainless steel barrier envelope (λ_f = 15 $W \cdot m^{-1} \cdot K^{-1}$) with a serpentine edge. The results however will be similar if the panel would not have such an edge.

Not only Thorsell and Källebrink studied the influence of adjoining insulation layers, also Ghazi Wakili et al. and Willems et al. studied the influence of encapsulating a VIP by EPS foam (Ghazi Wakili et al., 2005; Willems et al., 2005). Ghazi Wakili et al. researched a VIP with a thickness of 20 or 30 mm, with a metallised barrier and a thermal conductivity of 0.008 $W \cdot m^{-1} \cdot K^{-1}$ encapsulated by 10 mm material with variable thermal conductivity on all sides. Willems et al. studied EPS encapsulated VIPs incorporating VIPs with a thickness of 10 to 40 mm, with a metallised barrier and a thermal conductivity of 0.008 $W \cdot m^{-1} \cdot K^{-1}$ encapsulated by EPS of variable thickness. Both reached similar conclusions as Thorsell and Källebrink (Thorsell and Källebrink, 2005).

As an empirical study finally, Nussbaumer et al. studied the application of an EPS encapsulated VIP attached to a concrete wall among others using a climate chamber (Nussbaumer et al., 2006). They showed that such insulating components with 40 mm VIP could improve the thermal performance of a concrete wall with 95% and that in accordance with previously mentioned studies the protective EPS layers reduce the thermal edge effect of the high barrier laminate along the VIP's perimeter.

2. BACKGROUND OF CASE-STUDY

Commissioned by the industry, a parameter study has been executed into the thermal improvement of EPS insulation boards by integrating VIPs. It was executed for panels with a size of 1x1 m^2 and thickness of 100 mm[ii]. Such an element with fixed outer dimensions was filled with two identical VIPs having variable thickness and size. The dimensions and geometry of such a component are presented in Figure 1. Only a quarter of an EPS encapsulated VIP was simulated to reduce computation time and to still have sufficient accuracy despite the limitations of the computer software (32K nodes). Within this parameter study, the influence of three parameters on the effective thermal resistance was studied:

- The thickness of the VIPs, d_p: 0, 10, 20, 30, 40, 50(, 60, 75, 90, 95 and 99) mm;
- The thermal conductivity of the VIP core, λ_c: 0.004, 0.006 and 0.008 $W \cdot m^{-1} \cdot K^{-1}$;
- The width of the EPS edge, $a_{edge,1}$ and $a_{edge,2}$: 25 and 50 mm.

To study these variations systematically, numerical simulations using the ANSYS software package were run using the Finite Element Method. One result of such an analysis is the heat flow through the element from the warm side of the panel towards the cold side, Q [W]. This heat flow can be used to determine the average or effective thermal resistance of the plate, $R_{c;eff}$ [$m^2 \cdot K \cdot W^{-1}$] as[iii]

$$R_{c;eff} = \frac{S \cdot \Delta T}{Q} - \frac{1}{\alpha_i} - \frac{1}{\alpha_e} \qquad (1),$$

in which S is the surface area of the EPS encapsulated VIP (=0.5w·0.5l =0.25 m^2). Using this R-value as a measure of overall thermal performance, performance improvement by adding a VIP to an EPS insulation board can now be studied. An EPS insulation board with a thickness of 100 mm is used as reference having a thermal resistance, $R_{c;0}$, of 2.778 $m^2 \cdot K \cdot W^{-1}$. In the 3D parameter study the barrier envelope consisted of a 40 mm thick aluminium foil based barrier (with a thickness of 60 mm along the panel's edge)[iv].

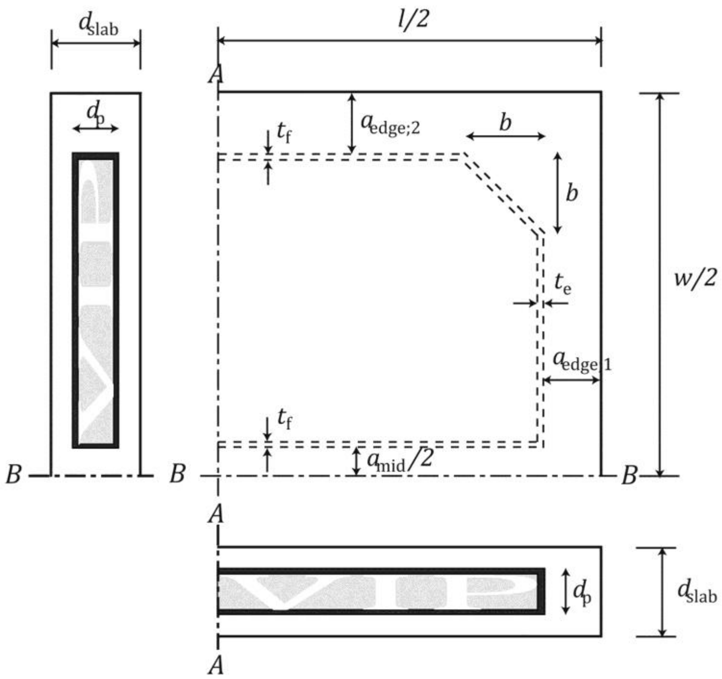

Figure 1: Schematic representation of a quarter of an EPS encapsulated VIP.

3. 3D PARAMETER STUDY – RESULTS AND DISCUSSION

The results of the numerical simulations according to the method and 3D model described in the previous section are presented in Table 1 in form of a thermal resistance ratio being the calculated effective thermal resistance divided by the thermal resistance of a 100 mm thick EPS insulation board. This resistance ratio reflects the improvement of the thermal performance of the EPS insulation board by adding a vacuum insulation panel. Moreover, Figure 2 presents a subset of the results graphically: the effective thermal resistance of an EPS encapsulated VIP with $a_{edge,1}$=25 mm and $a_{edge,2}$=50 mm.

From this table and this figure, four interesting observations can be made. First, the thermal performance of an EPS encapsulated VIP decreases with increasing thermal conductivity of the VIP core. This is not surprising since an increased λ_c conduces to an increased heat flux through the central area of the component. Second, the overall thermal performance of an EPS encapsulated VIP decreases with increasing width of the EPS strips along its edge which is to be expected too since the thermal conductivity of EPS is higher than of evacuated fumed silica. The wider the EPS edge strips thus, the worse the thermal bridge and as a result the worse the component's overall thermal performance. Third, a maximum in effective thermal performance exists for a certain VIP thickness. For all the EPS encapsulated VIPs studied 3-dimensionally, this maximum lies near a VIP thickness of 30 mm. Contrary to expectation, the thermal performance does not improve beyond a certain thickness of the vacuum insulation panel despite that the thermal performance of the central area, i.e. not considering thermal bridges, does increase proportional to the thickness of the VIP. The cause for the existence of such a maximum in thermal performance must therefore be related to thermal edge effects caused by the use of aluminium. In the next section this phenomenon is studied in more detail and explained using 2-dimensional numerical and analytical models. Fourth, the thermal performance of an EPS encapsulated VIP with very thick VIP (beyond 85 tot 95 mm depending on the thermal conductivity of the core material) drops even below the performance of a 100 mm thick EPS board. So, a very thick vacuum insulation panel inside an EPS mantle does not automatically imply an improved thermal performance relative to an equally thick EPS insulation board.

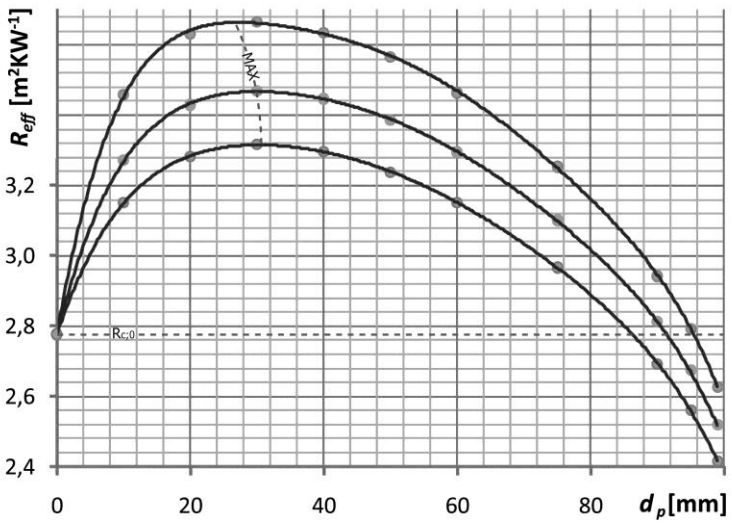

Figure 2: Effective thermal performance of an EPS encapsulated VIP with a 40 μm aluminium barrier envelope (AF:40). $a_{edge,1}$=25 mm; $a_{edge,2}$=50 mm; top line: λ_c=0.004 W·m^{-1}·K^{-1}; middle line: λ_c=0.006 W·m^{-1}·K^{-1}; bottom line: λ_c=0.008 W·m^{-1}·K^{-1}.

Table 1: Results of the parameter study of an EPS encapsulated VIP using ANSYS numerical simulation software: thermal resistance ratio, $R_{c;eff}$ / $R_{c;0}$ [-].

		$a_{edge;2}$ [mm]	25		50	
λ_c	d_p	$a_{edge;1}$ [mm]	25	50	25	50
0.004	10		1.27	1.24	1.24	1.22
	20		1.34	1.30	1.31	1.27
	30		1.35	1.31	1.32	1.28
	40		1.34	1.29	1.31	1.27
	50		1.32	1.27	1.28	1.24
0.006	10		1.19	1.17	1.18	1.16
	20		1.26	1.23	1.23	1.21
	30		1.27	1.24	1.25	1.22
	40		1.27	1.23	1.24	1.21
	50		1.25	1.21	1.22	1.18
0.008	10		1.14	1.13	1.13	1.12
	20		1.20	1.18	1.18	1.16
	30		1.21	1.19	1.19	1.17
	40		1.21	1.18	1.19	1.16
	50		1.19	1.16	1.17	1.14

4. MAXIMUM IN THERMAL PERFORMANCE - 2D ANALYSIS

The phenomenon that a maximum in thermal performance occurs for an EPS encapsulated VIP at a certain thickness of this VIP inside is studied in more detail in this section using a 2D model with only one thermal bridge. It is studied numerically using the software tool TRISCO and analytically both using models for calculating the linear thermal transmittance of an edge of a VIP or of a building component previously presented by authors (Tenpierik and Cauberg, 2007; Tenpierik et al., 2008) and the calculation procedure described in ISO 6946:2007.

The 2D model consists of a VIP (core and barrier envelope) integrated into an EPS board. The EPS layers on top and below the VIP are of equal thickness (=(0.1-d_p)/2). The total thickness of the EPS encapsulated VIP component, the width of the component's central area and the width of the EPS edge strip are kept constant at 100 mm, 500 mm and 25 mm respectively. The thickness of the VIP within the component, d_p, is varied from 1 to 99 mm while the thickness of the aluminium foil based barrier laminate, t_f, is varied from 0 to 6 to 10 to 20 to 40 μm. The thermal conductivity of the VIP core and the boundary transfer coefficients are kept constant at 0.004 $W \cdot m^{-1} \cdot K^{-1}$, 7.8 $W \cdot m^{-2} \cdot K^{-1}$and 25 $W \cdot m^{-2} \cdot K^{-1}$. As a result of this configuration only one linear thermal bridge consisting of both the aluminium barrier and the EPS edge strip is studied.

Figure 3 presents a graphic overview of the results of the effective thermal resistance computation as function of VIP thickness, d_p, and the thickness of the aluminium barrier, t_f. The figure summarises aforementioned ways of calculating the effective thermal resistance: markers represent numerical calculations, continuous lines analytical computations with the advanced model for calculating thermal edge effects in building components, dotted lines analytical calculations according to ISO standard.

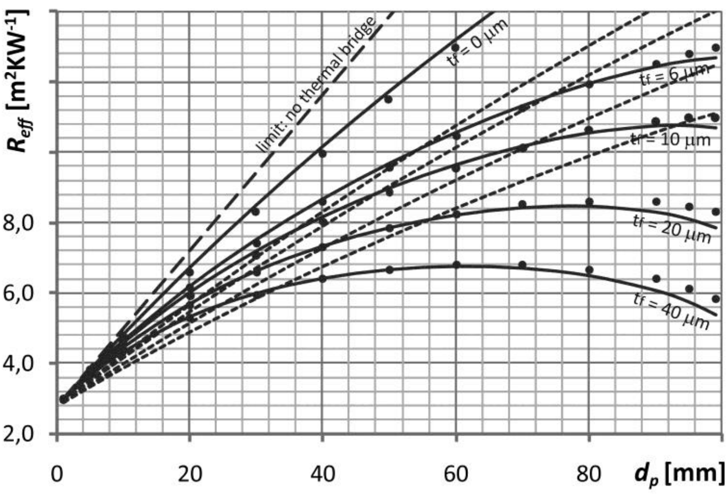

Figure 3: Effective thermal resistance of an EPS encapsulated VIP (2D model) as function of VIP thickness d_p (abscissa) and foil thickness t_f (different lines). markers: numerical results; continuous lines: analytical model; dotted lines: ISO 6946; dashed line: no thermal bridge; λ_c = 0.004 $W \cdot m^{-1} \cdot K^{-1}$; λ_f = 160 $W \cdot m^{-1} \cdot K^{-1}$; α_1=7.8$m^2 \cdot K \cdot W^{-1}$; α_2=25$m^2 \cdot K \cdot W^{-1}$.

In this figure, the limiting case (dashed line) represents a component without the thermal bridge caused by either the foil or the EPS edge strip, i.e. only the central area of the EPS encapsulated VIP component. Since no thermal bridge is present, the thermal resistance of this configuration is a linear function of VIP thickness and forms the maximum achievable thermal resistance of the EPS encapsulated VIP studied. The difference now between the line representing this limiting case and the line representing t_f = 0 µm – solely thermal edge effect due to 25 mm EPS edge strip - gives the influence of the EPS strip along the edge of the component. The difference between the line for t_f = 0 µm and the lines for t_f = 6, 10, 20 and 40 µm give the influence of the aluminium foil based barrier laminate.

As can be seen from the figure, due to the thermal bridge (either EPS strip or EPS strip and barrier foil) the thermal resistance of EPS encapsulated VIPs deviates from and is lower than the thermal resistance of the limit component without thermal bridge. Besides, from this figure it expectedly becomes clear that the thicker the barrier envelope, the larger the difference in thermal resistance between the limit case and the component with thermal bridge[v].

Another observation from the figure is that below a certain thickness of the barrier envelope, i.e. below certain strength of the thermal bridge, no local maximum value in thermal resistance at a certain VIP thickness exists. For the EPS encapsulated VIP studied 2-dimensionally, this laminate thickness lies near 10 µm. So, within the range of EPS encapsulated VIPs studied in this section, components with an aluminium barrier envelope layer thickness beyond 10 µm do have a local maximum in thermal performance at a certain VIP thickness while other components do not. This indicates that the barrier envelope at the component's edge is (partially) responsible this phenomenon.

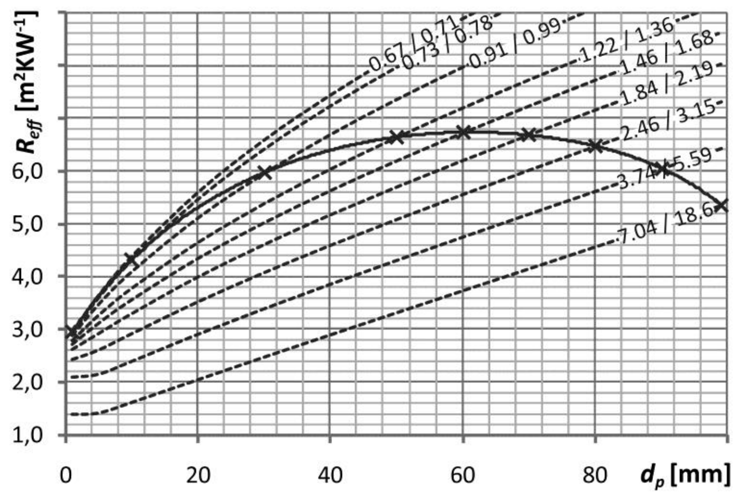

Figure 4: Effective thermal resistance of a VIP with an EPS edge strip of 25 mm (on one side) and no EPS top and bottom layers as function of VIP thickness (abscissa) and boundary heat transfer coefficients (different lines). Values along the broken lines denote boundary heat transfer coefficients on both sides of the panel [$W \cdot m^{-2} \cdot K^{-1}$]. The continuous line represents the corresponding EPS encapsulated VIP. $\lambda_c = 0.004$ $W \cdot m^{-1} \cdot K^{-1}$; $\lambda_f = 160$ $W \cdot m^{-1} \cdot K^{-1}$; $t_f = 40$ μm.

Moreover, Figure 4 indicates the responsibility of the thickness of the EPS layer on top and at the bottom of the panel, i.e. of the modified boundary heat transfer coefficient[vi]. This figure presents $R_{c;\text{eff}}$ as function of VIP thickness of a VIP with a 40 μm aluminium barrier, an EPS edge strip of 25 mm (on one side) but no EPS top and bottom layers, or in other words it presents the effective thermal resistance of an EPS encapsulated VIP without top and bottom EPS layers. Contrary to a regular EPS encapsulated VIP, the absence of EPS top and bottom layers gives this component constant modified boundary heat transfer coefficients, i.e. boundary heat transfer coefficients that include the resistance of the EPS layers. Lines for panels with several boundary heat transfer coefficients are plotted. As we can see from this figure, the effective thermal resistance of these components always increases with increasing VIP thickness; no local maximum in overall thermal performance exists, even for barrier laminates thicker than 10 μm.

Besides, the boundary heat transfer coefficients chosen to plot these lines represent the following VIP thicknesses in the corresponding EPS encapsulated VIP from the top most line to the bottom line: 1, 10, 30, 50, 60, 70, 80, 90, 99 mm. The crossing of these lines with vertical lines through these corresponding VIP thicknesses, produces the values of $R_{c;\text{eff}}$ of a corresponding EPS encapsulated VIP with a barrier laminate thickness of 40 μm. The line through these crossings is plotted in the figure, too. It equals the line for t_f = 40 μm in Figure 3. As can be seen from this line, a local maximum in thermal performance at a certain VIP thickness now arises indicating that variation in boundary heat transfer coefficients in any case is also partly responsible for the phenomenon.

A decomposition of the heat flows through the elements of the EPS encapsulated VIP component also shows the influence of the barrier laminate and its thickness on the effective thermal performance of the EPS encapsulated VIP component. The heat flows through the central area of the component and the EPS edge strip are more-or-less the same for a component with an aluminium foil based barrier laminate of 0 μm, 20 μm and 40 μm. However, the heat flow through the barrier laminate in the thermal bridge increases for increasing laminate thickness, as can be expected since the conductance of a thicker foil is higher. More interestingly, however, the heat flow through this barrier laminate at the component's edge increases for increasing VIP thickness and it increases stronger if the laminate is thicker. The extent of this increase can only be explained by the influence of the thinning of the EPS top and bottom layer, i.e. the increase of the modified boundary heat transfer coefficient. The combined effect of a decrease in heat flow through the central area of the component and an increase in heat flow through the aluminium foil based barrier laminate for increasing VIP thickness now results in the coming into existence of a local minimum in heat flow or a local maximum in thermal performance. It also explains why such a maximum in performance does not exist for all laminate thicknesses.

5. CONCLUSIONS

As we have seen, the thermal performance of an EPS insulation slab with constant thickness can be improved by including two identical vacuum insulation panels. As a result a so-called EPS encapsulated VIP emerges. If a strip of 25 or 50 mm EPS along the panel's perimeter and a strip of 50 mm EPS between both VIPs are considered, the system's thermal performance can be improved with approximately 35% at maximum with 30 mm thick VIPs. Concerning this improvement, it is important to bear in mind that the thermal conductivity of the core equals $4 \cdot 10^{-3}$ $W \cdot m^{-1} \cdot K^{-1}$ and more importantly that the barrier envelope consists of a 40 μm thick aluminium foil. If more common metallised barrier films or thinner aluminium based laminates are used as VIP envelope, a higher performance increase can be obtained.

Besides, it was shown for a 2-dimensional EPS encapsulated VIP component that a local maximum in thermal performance exists at a certain thickness of the VIP inside, not being the maximum thickness of this VIP. This phenomenon was numerically also seen in a more complex 3-dimensional component. It can be explained from a decomposition of heat flows through the separate elements of such a component: the heat flow through the centre-of-panel area, the heat flow through the EPS edge strip and the heat flow through the barrier laminate in the thermal bridge area. For increasing VIP thickness, d_p, the heat flow through the central area decreases since the thermal resistance of this region increases directly proportional to this thickness; the heat flow through the EPS edge strip remains constant; and the heat flow through the aluminium barrier laminate increases with increasing VIP thickness – the higher the product of laminate thickness and thermal conductivity, the more rapid the increase. The combined effect of these heat flows result in the occurrence or otherwise of a local maximum in thermal performance at a specific VIP thickness.

Two parameters can be held responsible for this occurrence: the product of laminate thickness and thermal conductivity on the one hand and the boundary heat exchange coefficients represented by a change in thickness of the EPS top and bottom layer on the other hand. As seen during the analysis, the phenomenon does not occur if the boundary heat transfer coefficients are constant, or similarly if the thickness of the EPS top and bottom layer is constant. If this variability in boundary heat transfer does exist, than the product of laminate thickness and thermal conductivity as a second criterion determines whether or not a local maximum in thermal performance exists. If this product is small then the decrease of the heat flow through the centre-of-panel area for increasing VIP thickness is always more rapid than the increase of the heat flow through the barrier laminate within the thermal bridge for increasing VIP thickness; no maximum in thermal performance then exists. If this product is high, then a maximum does exist.

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[i] These panels are however no longer mentioned in the booklet *Veni Vici VIP* by Variotec (2007). Instead the booklet mentions sandwich elements (Qasa-light and Qasa-sandwich) with either 0.3 mm thick aluminium or 4 mm thick high density (500 $kg \cdot m^{-3}$) massive PU face sheets. These panels should however be considered as 'regular' building panels.

[ii] The type and size of the panel was specified by the manufacturer. This specification included the outer dimensions of the EPS insulation board, the shape of the VIPs inside, the existence and size of EPS strips at the panel's edge as a place for connectors penetrating the insulation layer, and the choice for an aluminium foil laminate with an aluminium thickness of 40 μm to safeguard the service life at all cost.

[iii] It is important to note that all thermal resistances specified in this paper are resistances of the material only, thus without boundary resistances of the interface between material and air.

[iv] VIP to VIP distance: a_{mid}= 50 mm; thermal conductivity laminate: λ_f = 160 $W \cdot m^{-1} \cdot K^{-1}$; thermal conductivity Polystyrene: λ_{EPS} = 0.036 $W \cdot m^{-1} \cdot K^{-1}$; temperature 1: T_i = 293 K; temperature 2: T_e = 273 K; boundary heat transfer coefficients: α_i = 7.8 $W \cdot m^{-2} \cdot K^{-1}$; α_e = 25 $W \cdot m^{-2} \cdot K^{-1}$.

[v] Another interesting observation is that the difference between the effective thermal resistance calculated numerically and the effective thermal resistance determined with the advanced analytical model is very small. Only for large VIP thickness a small deviation occurs. However, the results from the thermal bridge models from ISO 6946:2007 differ significantly from both aforementioned models. This clearly indicates that the models from this standard are only valid for weak thermal bridges and should not be used when VIPs are involved.

[vi] Since the outer dimensions of the EPS encapsulated VIP are fixed, the thickness of the EPS top and bottom layer decreases with increasing VIP thickness. This in turn implies that the combined resistance of the boundary layer between EPS and air and of the EPS top or bottom layer decreases as well with increasing VIP thickness. As a consequence, the modified boundary heat transfer coefficient, α^*, calculated as $\alpha^* = \left(1/\alpha + d_{eps}/\lambda_{eps}\right)^{-1}$, decreases with increasing VIP thickness.