Numerical Investigation on Thermal Bridge Effects in Vacuum Insulating Elements

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Abstract

The requirements regarding the heat insulating quality for both new buildings as well as for the refurbishment of old buildings are increasing permanently. Therefore, there comes substantial meaning to the thermal bridge effects of a construction. Concerning the estimation of thermal bridges in vacuum insulating elements, their joints represent the most interesting (risk afflicted) part of the construction, which is to be examined in detail and thus estimated.

On the basis of computational micro- and macro-structural analysis the complex interactions regarding the thermal bridges of vacuum elements are simulated and illustrated.

Investigations are carried out both for standalone vacuum elements (VIP and VIS) as well as for complete vacuum insulated constructions. Special attention is paid to the influence of the covering material on the resulting heat fluxes. Additionally geometrical variations of the joints are taken into account.

The results, which are

- linear thermal transmittances Ψ for different joint designs and
- equivalent thermal conductivities λ and thermal resistances R for the complete layer,

are evaluated to meet the requirements of real life situations. The obtained results allow a simplified consideration of vacuum insulated layers with calculation of energy consumptions of buildings as well as an estimation of thermal bridge influences.

1 Introduction

In general, vacuum elements are not a single material but a compound of the core material and the envelope. Their core is made of microporous precipitated silica. The function of this core is to provide physical support to the envelope (static equilibrium) and to reduce the free mean path of the remaining gas molecules. The envelope, which consists of a metal film or a multilayer metallized film with VIP and of stainless steel with VIS, covers all surfaces of the element and especially the edges. Because of the relatively high thermal conductivity of the envelope material, the heat flux increases at the edges. Further information on vacuum insulation in general can be found for example in (Willems 2004) or (Willems, Schild 2005a).

2 Thermal conductivity of the cover material

2.1 Vacuum Isolation Panels (VIP)

The envelope material covers the VIP element and has to be an effective barrier against gases and moisture. With VIP elements, this envelope is made of multilayer metallized films or, in some cases, very thin metal films. Some exemplary cross-sections are described in figure 1.

Metal film (AF): A central aluminium layer with a thickness up to 10 μm. The aluminium layer is laminated between an outer PET layer (that offers some scratch resistance) and an inner PE sealing layer.

Metallized films (MF): They also have an inner PE layer for sealing purposes. To this layer, up to three layers of PET film with a one-side aluminium coating are laminated. The thickness of each aluminium coating usually varies from 20 to 100 nm.

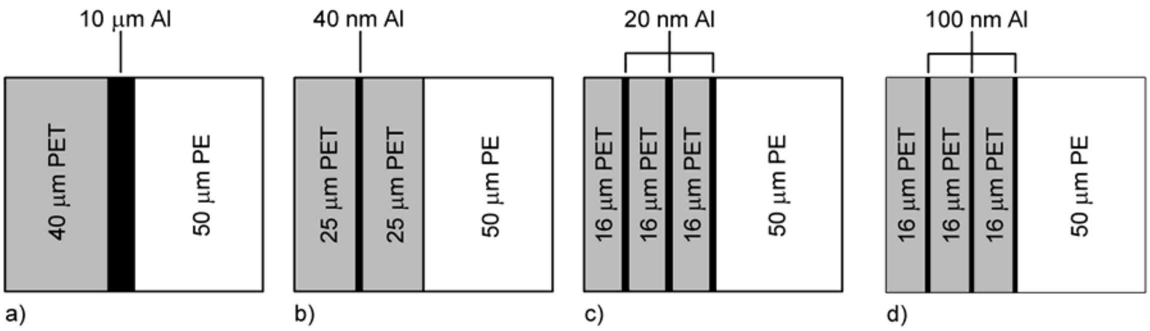


Figure 1: Cross section of some typical envelope materials for Vacuum Isolation Panels: a) metal film (AF-VIP) b) single-layer metallized film (MF 1-VIP) c / d) three-layer metallized film (MF2-VIP and MF 3-VIP)

The complex calculation of the edge effects of VIP elements is restricted to the exactness of the calculation method. Because of the great differences of the layer-thicknesses (varying between a nanometer scale for the aluminium layers and a centimetre scale for the core leading to absolutely unacceptable model sizes and excessive calculation times), it is inevitable for general thermal bridge studies, to replace the multilayered barrier envelope by a single layer with similar material properties.

For replacing the multilayered barrier, micro structural examinations of the heat transfer were carried out. The geometrical and material values for the calculations are listed in table 1. The obtained value for the heat flow was converted to an equivalent thermal conductivity λ_{film} for a single-layer barrier film with the same thickness. Properties of influence are the thermal conductivities both of the aluminium layer and the PE/PET-layer but also the element thicknesses, see also (Wakili, Bundi, Binder 2004).

Table 1: geometrical and material values used for the calculations with VIP elements

Envelope material	AF-VIP	MF 1-VIP	MF 2-VIP	MF 3-VIP
Thickness of the PE / PET layer $d_{PE / PET}$ [μm]	90	100	98	98
Thickness of the aluminium layer d_{AL} [μm]	10	0,04	0,06	0,30
Entire thickness of the envelope [μm]	100,00	100,04	98,06	98,30
$\lambda_{PE / PET}$ [W / (m•K)]	0,30			
λ_{AL} [W / (m•K)]	200			
λ_{CORE} [W / (m•K)]	0,008			

It can be stated, that an effective thermal conductivity λ_{film} can be specified for MF-VIPs. These MF models features a constant value from a specific element thickness onwards. Concerning the standard VIP element thicknesses these models can be calculated with effective values: MF1: 0,38 W/(m·K), MF2: 0,42 W/(m·K), MF3: 0,90 W/(m·K). The AF-VIPs show much higher and thickness dependent thermal conductivities. This has to be mentioned for further calculations.

In summary, one can say that a minimization of the aluminium layer thickness is inevitable for the reduction of the thermal bridge effect of the barrier envelope.

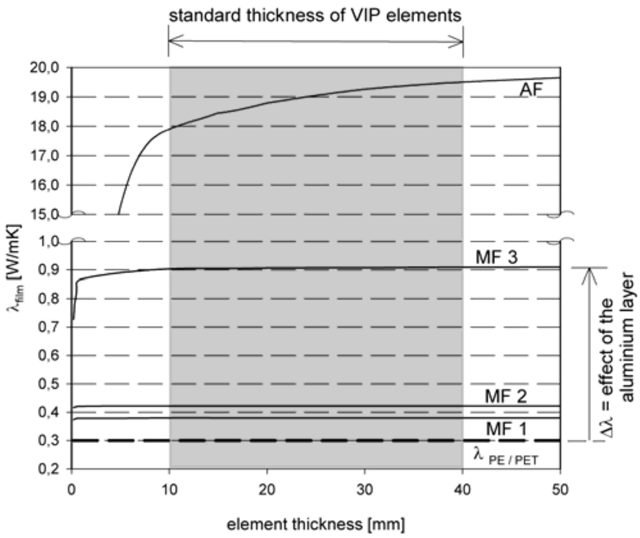


Figure 2: Effective thermal conductivity λ_{film} of different materials (see figure 1)

2.2 Vacuum Insulating Sandwiches (VIS)

The counterparts to the VIP elements are the Vacuum Insulating Sandwiches (VIS). Microporous silica is used as core material as well. The surfaces and the edge membrane are made of stainless steel with a thermal conductivity of 15 W/(m·K). In the calculations that have been carried out, different edge designs for VIS elements have been tested. Apart from the standard design shown in Figure 2a, three improved alternatives (Figure 2b-d) have been investigated to get the best solution from a thermal point of view. Besides using a thinner edge membrane, an extension of the membrane length was covered. Some other investigations on this topic were described in (Thorsell 2005).

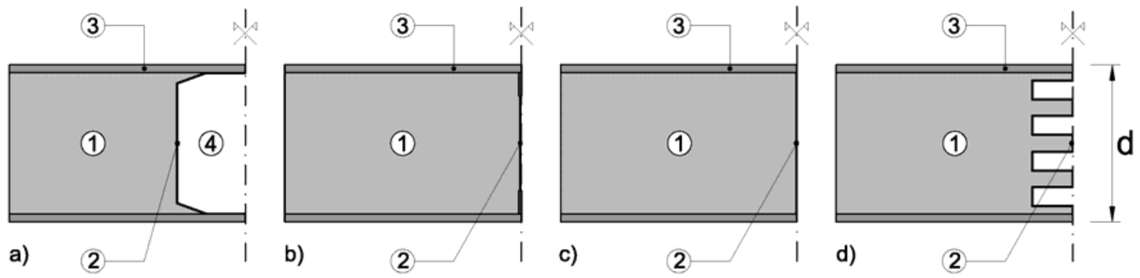


Figure 2: Cross-sections of typical VIS elements

a) Standard element:	**① Core, ② membrane: d = 0,1 – 0,3 mm, ③ covering plate: 0,1 mm steel, ④ air-gap**
b) Variation 1:	**① Core, ② membrane: d = 0,1 – 0,3 mm; 0,3 mm at the edges, ③ covering plate: 0,1 mm steel**
c) Variation 2:	**① Core, ② membrane: d = 0,1 – 0,3 mm, ③ covering plate: 0,1 mm steel**
d) Variation 3:	**① Core, ② membrane: d = 0,1 – 0,3 mm; membrane length maximized for decreasing the heat losses (air-gaps are take into account), ③ covering plate: 0,1 mm steel**

3 Linear thermal transmittance of VIP and VIS elements

For the following calculations, the centre-of-panel thermal conductivity λ_{COP} for VIP elements is assumed as 0,008 W/(m·K) (see (va-q-tec 2004)) and for VIS elements as 0,006 W/(m·K) (see (FIW 2004)). The primary aim was to quantify the influences of different edge designs and geometrical imperfections (i.e. air gaps) on the additional heat losses at the edges.

3.1 Standard VIP and VIS elements

With λ_{COP} and the calculated values for λ_{film}, different parameter studies have been carried out to obtain linear thermal transmittances for both VIP and VIS elements. Some results are presented in table 2 and 3. The different edge designs for VIS elements have been checked for feasibility and therefore are possible alternatives for a thermal improved element design.

Table 2: Linear thermal transmittance ψ [W/(m*K)] of the VIP elements

	AF (λ_{film} = var.)	MF 1 (λ_{film} = 0,38)	MF 2 (λ_{film} = 0,42)	MF 3 (λ_{film} = 0,90)
d_{VIP} [mm]	No imperfections estimated			
10	0,049	0,011	0,011	0,020
20	0,047			0,017
30	0,042	0,010	0,010	0,014
40	0,038			0,013

Table 3: Linear thermal transmittance ψ [W/(m*K)] of the VIS elements

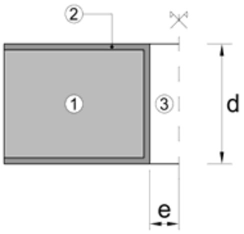
	VIS_1			VIS_2			VIS_3			VIS_4		
	$d_{membrane}$ [mm]											
d_{VIS} [mm]	0,10	0,20	0,30	0,10	0,20	0,30	0,10	0,20	0,30	0,10	0,20	0,30
10	0,069	0,085	0,096	0,085	0,102	0,109	0,079	0,099	0,109	0,043	0,061	0,074
20	0,069	0,090	0,105	0,067	0,095	0,112	0,064	0,093	0,112	0,044	0,065	0,082
30	0,066	0,084	0,099	0,053	0,079	0,097	0,051	0,078	0,097	0,042	0,062	0,079
40	0,063	0,079	0,093	0,044	0,067	0,084	0,043	0,043	0,084	0,040	0,058	0,074

3.2 Additional calculations for VIP elements

3.2.1 VIP elements with imperfections

Some VIP elements show an edge with some curvature instead of straight edges. That leads to additional losses due to air gaps. At least, air gaps can occur due to fabrication tolerances or inexactly laying. The tolerances of VIP elements (manufacturer values) are ± 2 mm for automated manufacture and ± 5 mm for hand made panels.

In dependence on the air gap thickness the thermal transmittance ψ of the VIP elements are calculated (see Figure 3). The thermal conductivity λ_{air} of the air cavity is calculated according to DIN EN ISO 10211.



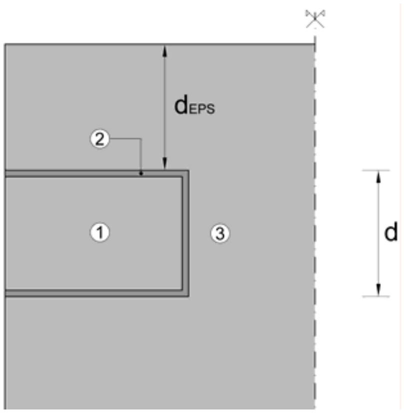
<table>
<tr><td></td><td colspan="2">AF
(λ_{eff} = var.)</td><td colspan="2">MF 1
(λ_{eff} = 0,38)</td><td colspan="2">MF 2
(λ_{eff} = 0,42)</td><td colspan="2">MF 3
(λ_{eff} = 0,90)</td></tr>
<tr><td></td><td colspan="8">e_{air} [mm]</td></tr>
<tr><td>d_{VIP} [mm]</td><td>2,5</td><td>5,0</td><td>2,5</td><td>5,0</td><td>2,5</td><td>5,0</td><td>2,5</td><td>5,0</td></tr>
<tr><td>10</td><td>0,054</td><td>0,058</td><td rowspan="4">0,016</td><td rowspan="4">0,021</td><td rowspan="4">0,016</td><td rowspan="4">0,021</td><td>0,025</td><td>0,027</td></tr>
<tr><td>20</td><td>0,053</td><td>0,058</td><td>0,021</td><td>0,024</td></tr>
<tr><td>30</td><td>0,047</td><td>0,052</td><td>0,019</td><td>0,022</td></tr>
<tr><td>40</td><td>0,043</td><td>0,049</td><td>0,017</td><td>0,020</td></tr>
</table>

Figure 3: left: Cross-section of standard installed VIP element: ① Core, ② barrier envelope, ③ air gap (resulting of imperfections); right: Linear thermal transmittance Ψ [W/(m·K)] of VIP elements with air-gaps

The increase of the linear thermal transmittance of the AF models ranges from 10 up to 19 %, with MF models even from 50 up to 60 %. That means: The better the thermal resistance of the barrier envelope, the worser an air gap influences the additional total heat loss.

3.2.2 VIP elements with EPS layer

In some cases the VIP elements are installed between other materials such as wood or insulation material. For an examination on the influences of such an installation on the edge losses, the MF 1 model is modelled with an additional EPS layer. The thickness of this layer is varied from 10 to 30 millimetres.



	MF 1 (λ_{eff} =0,38)		
	d_{EPS} [mm]		
d_{ELEM} [mm]	10	20	30
10	0,020	0,025	0,027
20	0,017	0,021	0,024
30	0,014	0,019	0,022
40	0,013	0,017	0,020

Figure 4: left: Cross-section of VIP installed in insulation layer: ① Core, ② barrier envelope, ③ EPS; right: Linear thermal transmittance Ψ [W/(m·K)] of the VIP panel

With a modification like this, the additional heat losses are increased between 30 and 100%. Nevertheless, one has to take into account that also the thermal resistance of the whole construction does increase. The doubling of the thermal transmittance ψ therefore depends on the higher thermal resistance R of the whole panel (calculated in the centre).

4 Determination of equivalent material values of VIP and VIS elements

To calculate the equivalent thermal conductivity λ_{equ} of a vacuum construction, one has to equal the heat loss Φ_{1D} of an idealized equivalent 1-dimensional construction

$$\phi_{1D} = U_{equ} \cdot A \cdot \Delta\theta$$

and the heat loss Φ_{2D} of the real 2-dimensional thermal bridge effected construction.

$$\phi_{2D} = \left(U^{1D} \cdot A + \psi \cdot P\right) \cdot \Delta\theta \qquad \text{; P perimeter length of the vacuum panel}$$

By doing this, one gets

$$U_{equ} \cdot A \cdot \Delta\theta = \left(U^{1D} * A + \psi \cdot P\right) \cdot \Delta\theta \qquad \Leftrightarrow \qquad \frac{\lambda_{equ}}{d} \cdot A = \frac{\lambda_{COP}}{d} * A + \psi \cdot P \, .$$

Solving this equation leads to the well known formulation

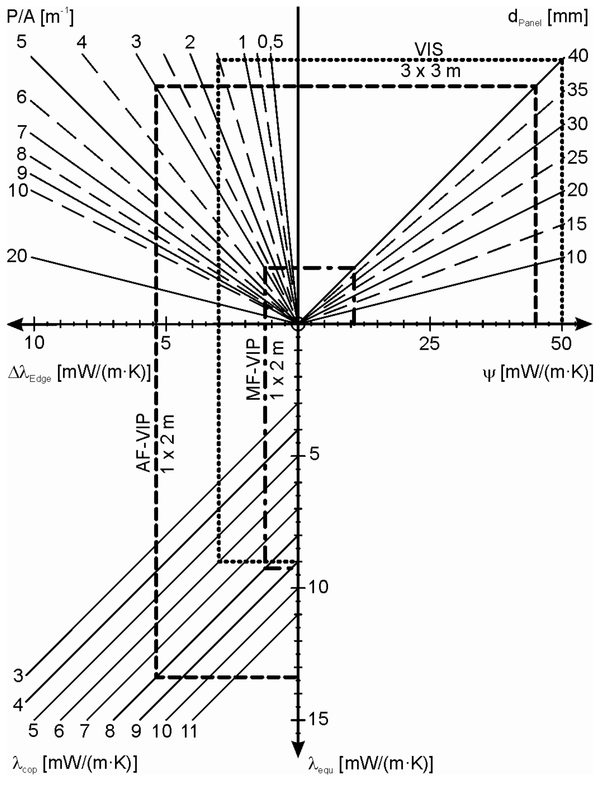
$$\lambda_{equ} = \lambda_{COP} + \psi_m \cdot d \cdot \frac{P}{A}$$

From this, an equivalent thermal resistance R_{equ} can be derived like

$$R_{equ} = \frac{d}{\lambda_{equ}} \, .$$

Figure 5 shows the nomographical solution of the equivalent thermal conductivity λ_{equ} of vacuum insulated elements. The calculation of λ_{equ} is demonstrated by three examples. Using the panel measurements and the thermal values listed in chapter 1 and 2, a direct comparison between a VIS element (3,0 x 3,0 m) and two VIP panels (1,0 x 2,0 m) is pointed out.

Figure 5: Nomographical solution for the equivalent thermal conductivity λ_{equ} of vacuum insulated elements



The equivalent thermal resistances R_{equ} for both VIP and VIS elements are portrayed in figure 6. Depended on the element thicknesses (10 to 40 mm) and the element sizes (taken into account by the ratio P/A) the resistances of the different VIP and VIS models are calculated. Additionally the different thermal transmittances ψ were varied. In the diagram these variations are represented by areas using "bad" (lower border) and "good" (upper border) values for ψ (compare variations in chapter 3).

For the simple reason that the production sizes between VIP and VIS elements differ very much from each other, only the interval from P/A = 1,8 to 2,5 can directly be compared.

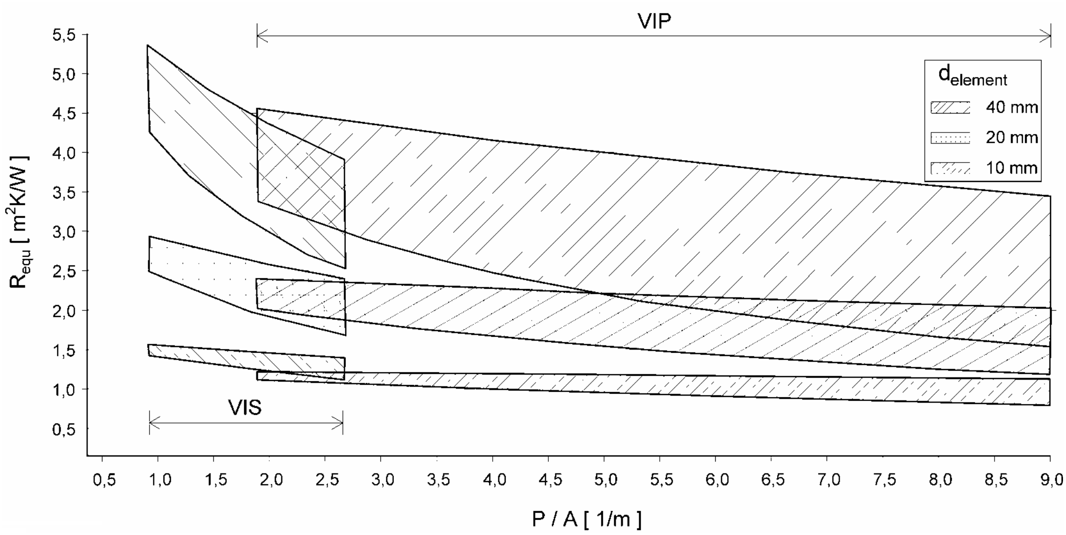


Figure 6: Equivalent thermal resistances of the examined VIP and VIS elements classified after the element thicknesses

5 Conclusion

Vacuum insulations can be used in many different fields of application in the building envelope. In general, they are used to replace or add to a conventional insulation layer. Some exemplary cross sections of building applications can be found in (Willems, Schild 2005b). Because vacuum insulated elements do not represent a homogenous material layer, additional heat losses due to thermal bridges at the perimeter of the elements have to be taken into account.

These thermal bridge effects with vacuum insulated elements have been examined and the results are presented in this paper. For the estimation of these effects, the joints of VIP and VIS elements were examined under micro- and macro-structural analyses.

One pre-condition for further calculations is the replacement of the multilayer envelope of VIP elements by a layer of an equivalent homogenous material. Calculations for the determination of such a layer have been carried out and validated. As a result, envelope materials with thick metal or metallized layers show significant higher thermal conductivities than a homogenous PE or PET layer.

With those equivalent thermal conductivities linear thermal transmittances for both VIP and VIS elements have been calculated for different geometrical and structural variations. The obtained results allow the conclusion that by using both VIS and MF-VIP very low equivalent thermal conductivities can be achieved. Compared to this, the AF-VIPs show much higher conductivities.

In summary, one can say that including aging effects and additional heat losses at the edges, vacuum insulated elements show thermal conductivities that are up to four times better than those of conventional insulation materials.

6 References

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