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Analysis of thermal bridges in insulated masonry walls: a comparison between vacuum insulated panels and expanded polystyrene

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ABSTRACT
The paper presents a comparative study between the thermal performances of a couple of masonry walls with no insulation and then insulated with vacuum insulation panels and expanded polystyrene. The research purpose is to demonstrate the superior thermal performance of the vacuum insulation panels compared to common thermal insulation, in initial state and even after 25 years in service. It also provides the steps to determine the effective thermal resistance of the buildings elements insulated with vacuum insulation panels, considering both local and geometric thermal bridges. Results emphasize that even after 25 years in use, the walls insulated with vacuum insulation panels with reduced thickness possess a greater thermal performance than that of the walls insulated with expanded polystyrene with common thickness. This is one of the reasons for which this material should be improved and developed further for the future buildings envelopes.

KEYWORDS
vacuum insulation panels, thermal bridges, steady-state, effective thermal resistance

INTRODUCTION
Vacuum insulation panels are composite nano insulation materials, consisting of a nanoporous core encapsulated by a sealing envelope with multiple functions such as airproofing, waterproofing and radiation thermal transfer blocking. Their thermal conductivity in initial state is 4 mW/(mK), about 8-10 times lower than those of the common thermal insulation materials such as expanded polystyrene or mineral wool. Also, even if the envelope is damaged and the panel is filled with air, its thermal conductivity is the same as for the core material, i.e. 20 mW/mK for fumed silica, which is still approximately half of that of the expanded polystyrene.

In this paper, a comparative study is made between the thermal performances of several brick masonry walls without insulation and then thermally insulated with expanded polystyrene (EPS) and vacuum insulation panels (VIP), in different thicknesses. For each situation there are determined the effective thermal resistances, taking into account the walls thermal bridges by computing the related linear heat transfer coefficients. There are considered two types of thermal bridges given by the walls corner intersection with a concrete column (see Figure 1) and also by the walls intersection with a balcony slab (see Figure 2). At the same time, there are computed the effective thermal conductivities of the VIP, considering the local thermal bridges developed on their edges. These thermal bridges are analysed and computed in several other studies (i.e. Tenpierik and Cauberg, 2010; Sprengard and Holm, 2014).

The layers of the analysed elements may be observed in the following figures. A levelling rendering is applied on the masonry walls and then the VIP are installed. The panels are protected on their exterior side by a layer of EPS and a decorative rendering. The mounting of the panels on the levelling layer and of the EPS on the panels is made by adhesion. The balcony slab has a width of 1.00 m and is insulated both at its inferior and superior side.

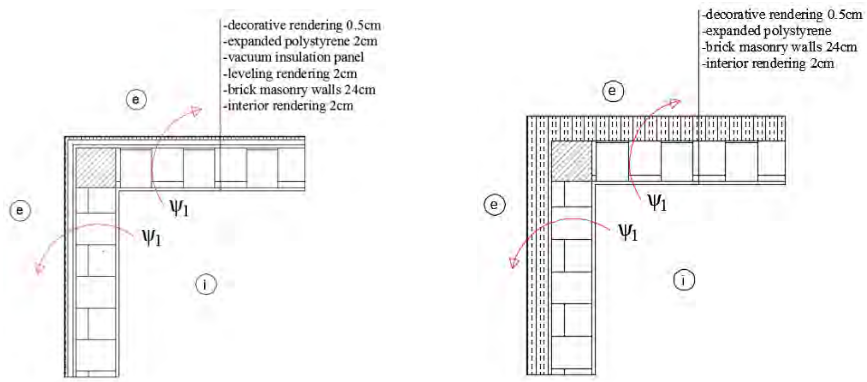


Figure 1. Wall corner intersection - i) insulated with EPS, ii) insulated with VIP

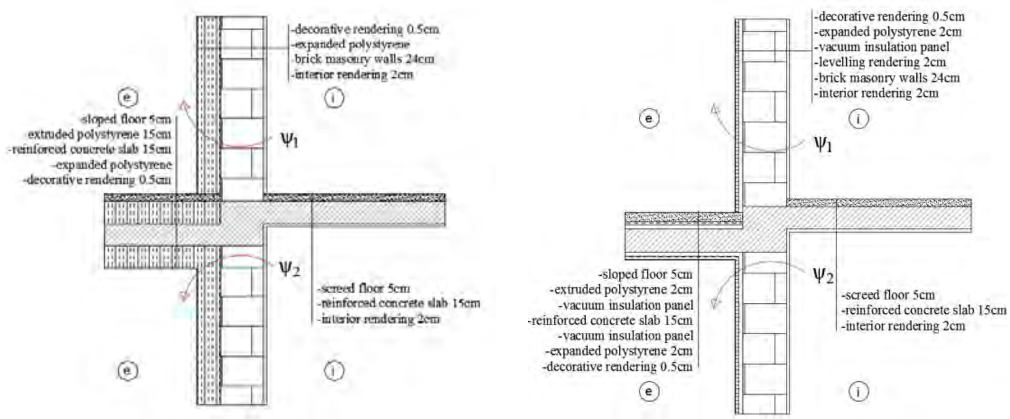


Figure 2. Balcony slab-wall intersection - i) insulated with EPS, ii) insulated with VIP

The analysis is made for the following situations: the walls and balcony slab without thermal insulation, insulated with EPS having a thickness of 10 cm, 20 cm and 30 cm and insulated with VIP of 2 cm, 3 cm and 4 cm, the latter being analysed both in initial state and also after 25 years in service. The maximum chosen thickness of the vacuum insulation panels is the highest one for the adhesion procedure. For larger thicknesses, the material requires a mounting system which develops supplementary local thermal bridges. In the case of balcony slab - exterior wall intersection where EPS is the analysed insulation, on the superior side of the exterior cantilever slab it is considered a layer of extruded polystyrene with a thickness of 15 cm.

METHODS

First of all, there is computed a mean effective thermal conductivity of the VIP. The determination considers the thermal bridges developed on the panel edges using a method from literature (Tenpierik and Cauberg, 2007).

The design value of the centre-of-panel thermal conductivity is λ_{cop}=4 mW/(mK) in initial state after production and λ_{cop}=8 mW/(mK) after 25 years in service, for the panels with envelopes consisting in metallised polymer films (MF) (Heinemann et al, 2010). The difference is given by an inherent decrease of the material thermal performance in time due to the increase of the water content and internal pressure. Two types of panel envelope are considered in analysis: MF2 having a thickness of t_f=84µm and a thermal conductivity of λ_f=0.54 W/(mK) and MF3 having a thickness of t_f =97μm and a thermal conductivity of λ_f=0.39 W/(mK) (Berge and Johansson, 2012). The panels have no gaps or seams between them, therefore their possible influence on the edge thermal bridge is not considered. Having this data, there are computed the linear thermal transfer coefficients ψ_{VIP} related to the thermal bridges developed on the panel edges. Then, there are determined the effective thermal conductivities of the VIP having the following dimensions: 300×600 mm, 600×600 mm and 600×1500 mm and an average value is calculated. The computation is made with the following formula:

$$\lambda_{VIP.eff} = \lambda_{cop} + \frac{\psi_{VIP} \times d \times P}{A} \quad [W/(mK)] \tag{1}$$

where: $\lambda_{VIP.cop}$ [*W/(mK)*] is the design value of the centre-of-panel thermal conductivity, ψ_{VIP} [*W/(mK)*] is the linear thermal transfer coefficient developed on the panel contour, *d* [*m*] is the panel thickness, *P* [*m*] is the panel perimeter and *A* [m^2] is the panel area.

A next step in the analysis is the determination of the linear thermal transfer coefficients ψ related to the considered walls thermal bridges: walls corner and wall-balcony slab intersection. First of all, the unidirectional thermal resistance of the wall is determined:

$$R_{unidir} = \frac{1}{\alpha_{int}} + \sum_i \frac{d_i}{\lambda_i} + \frac{1}{\alpha_{ext}} \quad [m^2 \cdot K/W] \tag{2}$$

where: d_i [*m*] is the layer *i* thickness, λ_i [*W/K*] is the layer *i* thermal conductivity, α_{int} and α_{ext} [W/m^2K] are the superficial heat transfer coefficients at the interior and exterior surface of the wall

Table 1. Thermal conductivities of the materials used (C107/3, 2008)

Material	λ [W/(mK)]
Brick masonry	0.55
Reinforced concrete	1.74
Renderings: interior, exterior, leveling, protection	0.93
Screed floor, sloped floor	0.93
Decorative rendering	0.7
Expanded polystyrene	0.044
Extruded polystyrene	0.04

The determination of the linear heat transfer coefficients ψ is based on a two-dimensional steady-state modelling in Therm software in accordance with EN ISO 6946:2017. The geometric models were designed according to the details presented in Figure 1 and Figure 2, for each layer being given its corresponding thermal conductivity. Also, the models were built taking into account the recommendations of the C107/3 standard which states that the cross section limits have to be placed at minimum 1.20 m relative to the central element. The interior temperature is considered T_i=20°C and the external one T_e=-18°C. The walls superficial heat transfer coefficients are α_{ext}=24 W/m^{2}K (exterior side) and α_{int}=8 W/m^{2}K (interior side). The limits of the cross-sectioned elements (wall, interior slab) are considered to be adiabatic. After the input data is introduced, the software generates the discretization mesh, computing the temperature and thermal flow values in each of its elements, using the Finite Element Method. The model computation is characterised by the following parameters: the maximum dimension of the grid elements is 25 mm, the maximum number of iterations is 50 and the maximum computation error is 1%. Using the program output data, the linear thermal transfer coefficients are computed with the following formula:

$$\psi = \frac{l_{therm}}{R_{therm}} - \frac{B}{R_{unidir}} \; [W/m \cdot K] \quad (3)$$

where: l_{therm} [m] is the thermal bridge length, R_{therm} [m^2K/W] is the output R-value from Therm, B [m] is the effective dimension of the linear thermal transfer coefficients ψ and R_{unidir} [m^2K/W] is the unidirectional thermal resistance

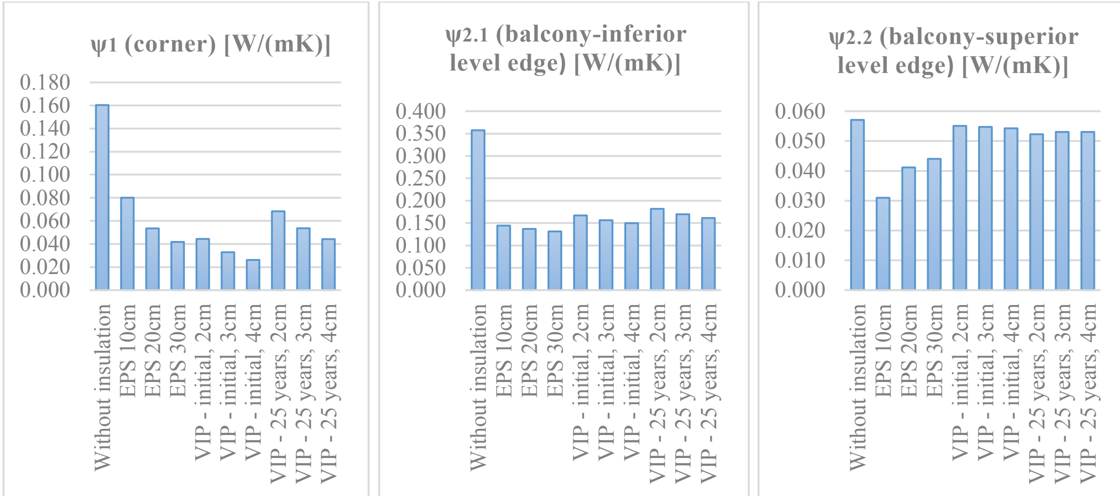
Finally, using the computed linear heat transfer coefficients, the effective thermal resistances of the walls are calculated for a 2 story building in accordance with EN ISO 10211:2017. Each level is composed of four walls having the same geometrical characteristics: two walls of 3m × 3m and two walls of 3m × 6m. Also, the two stories are separated by a reinforced concrete slab with a balcony cantilever on the building contour, having a width of 1m. The balcony slab is at an inferior level compared to the interior slab, according to the analysed details. The layers and thicknesses of the walls and slabs correspond to the ones presented before (see Figure 1 and Figure 2). The analysis is made for two inferior level walls and two superior level walls, the other four walls of the system having the same characteristics. Each wall has a corner thermal bridge for each of their lateral margins. The inferior level walls have a thermal bridge at their superior edge given by the intersection with the balcony slab. In the same way, the superior level walls have a thermal bridge at their inferior edge. The free margins (section margins) of the walls are considered to be adiabatic.

RESULTS

Table 2. Linear heat transfer coefficients ψ related to the panel edges thermal bridges. Effective thermal conductivities λ of the panels considering these thermal bridges

Panel dimensions [mm]	Envelope type	ψVIP -initial- [mW/(mK)]	ψVIP -25 years- [mW/(mK)]	λVIP.eff -initial- [mW/(mK)]	λVIP.eff -25 years- [mW/(mK)]
300 x 600 x 20	MF2	1.33	1.25	4.265	8.250
300 x 600 x 20	MF3	2.05	1.93	4.409	8.386
300 x 600 x 30	MF2	0.95	0.91	4.284	8.273
300 x 600 x 30	MF3	1.47	1.41	4.442	8.423
300 x 600 x 40	MF2	0.73	0.71	4.294	8.284
300 x 600 x 40	MF3	1.15	1.12	4.461	8.448
600 x 600 x 20	MF2	1.33	1.25	4.177	8.167
600 x 600 x 20	MF3	2.05	1.93	4.273	8.257
600 x 600 x 30	MF2	0.95	0.91	4.189	8.182
600 x 600 x 30	MF3	1.47	1.41	4.295	8.282
600 x 600 x 40	MF2	0.73	0.71	4.196	8.189
600 x 600 x 40	MF3	1.15	1.12	4.307	8.299
600 x 1500 x 20	MF2	1.33	1.25	4.124	8.117
600 x 1500 x 20	MF3	2.05	1.93	4.191	8.180
600 x 1500 x 30	MF2	0.95	0.91	4.132	8.127
600 x 1500 x 30	MF3	1.47	1.41	4.206	8.197
600 x 1500 x 40	MF2	0.73	0.71	4.137	8.133
600 x 1500 x 40	MF3	1.15	1.12	4.215	8.209

According to these results, in the following computations a mean effective thermal conductivity is considered: $\lambda_{VIP.eff.0}$ = 4.25 mW/(mK) – for initial state; $\lambda_{VIP.eff.25}$ = 8.25 mW/(mK) – after 25 years in use.



a) b) c)

Figure 3. Linear thermal transfer coefficients of the analysed details
a) wall corner intersection, b) balcony slab-wall intersection – inferior level edge
c) balcony slab-wall intersection – superior level edge

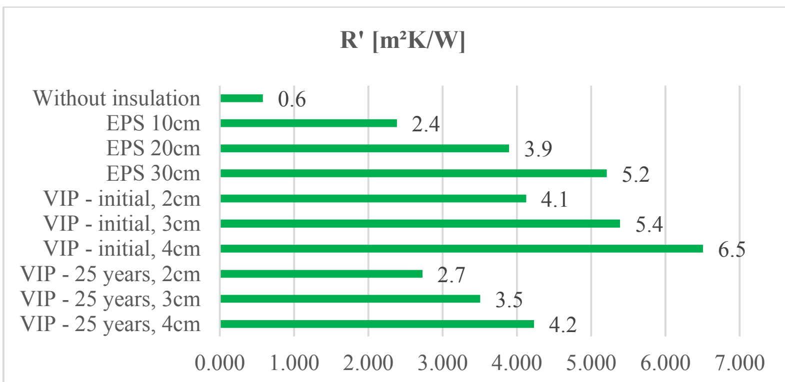


Figure 4. Average effective thermal resistance of the analysed walls

DISCUSSIONS

The results regarding the thermal bridges developed on the panel contour ψ_{VIP} validate the findings from another studies (Tenpierik and Cauberg, 2007; Sprengard and Holm, 2014), for the panels having λ_{cop}=4 mW/(mK), with MF type envelope and with no gaps or seams between them. One may observe that the thermal bridges developed on the VIP edges after 25 years in service are slightly lower (between 2.60%-6.40%) than those of the new panels, a phenomenon which is more prominent as its thicknesses are lower (see Table 2). At the same time, the envelope type influence the panel thermal performance. Between two panels with same geometrical characteristics, the one with MF2 type foil has a lower linear thermal transfer coefficient with about 54-58% than the one with MF3 type foil. Another aspect revealed by the results is that the linear heat transfer coefficients related to the panels edges decrease with the increase of its thickness.

As a consequence of these local thermal bridges, the panels effective thermal conductivity is greater for those with MF3 type foil, compared to that of those with MF2 type (see Table 2). The difference raises with the increase of the panel thickness and decrease with the increase of the panel 2D dimensions: for 300×600mm – difference of 1.5-2%, for 600×600mm – difference of 1-1.5% and for 600×1500mm – difference of 0.8-1%. At the same time, the panel effective thermal conductivity is greater than the centre-of-panel thermal conductivity with 0.124-0.461 mW/(mK) for the new panels and with 0.117-0.448 mW/(mK) after 25 years in service.

The thermal bridges of the analysed details are lowered by the use of thermal insulation (see Table 3). In most cases, the thermal bridges of the wall corner detail (ψ_1) with VIP are lower than those of the same detail with EPS. Also, the thermal bridges at the inferior level edge of the balcony detail ($\psi_{2.1}$) with VIP have similar values to those with EPS. At the same time, the thermal bridges at the superior level edge of the balcony detail ($\psi_{2.2}$) with VIP have a rather constant value, regardless of their thickness or age and they have higher values compared to the details insulated EPS.

The effective thermal resistance of the walls insulated with VIP decrease with about 35% after 25 years in use, compared to their initial state, as shown in figure 4. However, one should note that even in this situation, the thermal performance of VIP is comparable to that of the EPS, but for a reduced insulation thickness of approximately 80%. The walls insulated with the panels having a thickness of 4 cm develop an increased effective thermal resistance which recommend this solution for the higher thermal efficiency building systems.

CONCLUSIONS

One of the directions in this research field is the continuous improvement of the existing thermal insulation solutions and the development of new ones in order to increase the overall thermal performance of the buildings. In this regard, the VIP may represent a leap forward, considering its superior thermal performances.

The study reveals that even the VIP develop larger thermal bridges and their performance decrease over time, the building elements insulated with this solution have a superior effective thermal resistance compared to common solutions such as EPS. Therefore, the VIP may be a suitable replacement for the traditional insulations, especially when there is required a reduced insulation thickness.

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