Vacuum Insulation Panels: Thermal Bridging Effects and Energy Performance in Real Building Applications

Original
Vacuum Insulation Panels: Thermal Bridging Effects and Energy Performance in Real Building Applications / Isaia, F., Fantucci, S., Capozzoli, A., Perino, M.. - In: ENERGY PROCEDIA. - ISSN 1876-6102. - STAMPA. - 83:(2015), pp. 269-278. [10.1016/j.egypro.2015.12.181]

Availability:
This version is available at: 11583/2627127 since: 2016-01-02T15:49:01Z

Publisher:
Elsevier

Published
DOI:10.1016/j.egypro.2015.12.181

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 83 (2015) 269 – 278

Energy Procedia

7th International Conference on Sustainability in Energy and Buildings

Vacuum Insulation Panels: thermal bridging effects and energy performance in real building applications

Francesco Isaia[a], Stefano Fantucci[b], Alfonso Capozzoli[b]*, Marco Perino[b]

[a]*Politecnico di Torino, Corso Duca degli Abruzzi 24, Turin 10129, Italy*
[b]*Department of Energy, Politecnico di Torino,TEBE Research Group, Corso Duca degli Abruzzi 24, Turin 10129, Italy*

Abstract

Due to their very low thermal conductivity, Vacuum Insulation Panels (VIPs) have recently seen a fast development and an increasing penetration in building thermal insulation market.
However, there is still a lack of knowledge about their performance when actually applied in buildings. In fact, the thermal bridging effects that occur in VIP junctions are not easily evaluable while produce a reduction of the global thermal performance.
In this paper, the linear thermal transmittances related to VIP junctions considering different joint materials between VIPs panels and different wall configurations were assessed through a 2D numerical analysis. Finally, through a quasi-steady state simulation, a parametric building case study was analysed, with the aim to evaluate the influence of the thermal bridging effects on the overall building energy need.
The results shows that the thermal bridging effect due to VIPs assemblies have not a negligible influence on the overall building energy performance.

Peer-review under responsibility of KES International
Keywords: Vacuum Insulation Panels; Simulation; Thermal bridge; Joint; Building energy performance; Building application.

1. Introduction

Acting on the existing building stock is a mandatory strategy to reduce the energy consumption at the global scale, firstly because about 40% of the overall energy consumption can be attributed to buildings [1], secondly because many of these buildings are more than 20 years old (70-90% in the EU) [2].

Super insulation materials can give a solution to this issue, since their thermal conductivity is 5-10 times lower

* Corresponding author. Tel.: +39-0110904413.
E-mail address: alfonso.capozzoli@polito.it.

Peer-review under responsibility of KES International
doi:10.1016/j.egypro.2015.12.181

than traditional insulation materials, allowing to refurbish existing building envelope with small insulation thickness increments [3]. In recent year, Vacuum Insulation Panels were studied by several researchers. VIPs technology is still poorly adopted, despite many positive aspects, because of the high costs, short durability (with respect of the building life) and lack of knowledge about thermal behaviour in real building applications (especially for the thermal bridging effects [4], [5]).

Nomenclature

λ	Thermal conductivity	[W/mK]
λ_{eq}	Equivalent thermal conductivity of VIP assembly	[W/mK]
λ_{fict}	Fictitious thermal conductivity	[W/mK]
λ_{COP}	VIP Centre Of Panel thermal conductivity	[W/mK]
λ_{pro}	VIP thermal conductivity declared by producers	[W/mK]
R_i	Thermal resistance of inner bounding layers	[m^2K/W]
R_e	Thermal resistance of outer bounding layers	[m^2K/W]
R_i+R_e	Total thermal resistance of the bounding layers	[m^2K/W]
ψ	Linear thermal transmittance due to thermal bridge	[W/mK]
l	Thermal bridge length	[m]
A	Panel area	[m^2]
P	Panel semi-perimeter	[m]
d	Layer thickness	[m]
$\dot{Q}$	Heat flow	[W]
θ_{up}	Higher set point temperature	[K]
θ_{low}	Lower set point temperature	[K]
$\Delta\theta$	Difference between higher and lower set point temperature	[K]
S	Non adiabatic walls surface	[m^2]
V	Single room apartment volume	[m^3]
S/V	Aspect ratio	[m^{-1}]

1.1. State of the art and aims

Kalnæs and Jelle [6] state that *"VIP consists of a porous core enveloped by an air and vapour tight barrier which is heat sealed"*. Many studies were carried out on VIPs, particularly on its main components, which mainly consist on core material [7] and envelope [8]. These studies were focused on the increasing of thermal conductivity for vacuum loss (due to gas permeation over time) and damaging risk (e.g. puncturing).

Other studies were focused on the thermal bridging effects related to the envelope materials [9], the air gaps or structural joints between the panels and the VIPs assemblies at building scale. A universal conclusion from these researches demonstrate the crucial importance to properly consider the thermal bridging effects in order to correctly assess VIPs thermal performance. The higher the thermal resistance of the insulation layer, the greater is the importance of thermal bridging effects. Even if many studies on this issue were carried out, few investigations were done on thermal bridging effects at the building scale, considering the VIP panels coupled with other materials and inserted in a multi-layered wall [4], [5].

In this paper, thermal bridging effects of VIP panels coupled with a number of different joint materials were assessed, also taking into account several multilayer wall configurations.

In the study, the thermal conductivities of VIP panels and the structural joint materials were first evaluated through an experimental campaign (in accordance with [13]). Then, the linear thermal transmittance and the equivalent thermal conductivity of each configuration was assessed through a 2D numerical analysis (in accordance with [12]). Finally, in order to evaluate the influence of the thermal bridging effect on the heating energy need of a building archetype, a case study was considered and a quasi-steady state simulation was performed according to EN

ISO 13790:2008 standard [16]).

2. Methods and methodology

The linear thermal transmittance ψ and the equivalent thermal conductivity λ_{eq} were assessed through a 2D numerical analysis in order to later evaluate the thermal bridging effect for each VIP assembly (two VIPs coupled with a joint). On the basis of these results the energy performance of a building case study with different aspect ratios through a quasi-steady state simulation was evaluated.

Three wall typologies were selected in accordance with UNI-TS 11300-1 (Italian standard) [14], in order to introduce the most common wall stratigraphy: solid wall, cavity wall and insulated cavity wall. A VIP insulation was then added for each wall typology, considering two different solutions (interior and exterior wall insulation). In the first case, the VIP is placed on the internal side of the existing wall, followed by an extra insulation layer and a drywall panel. In the second case, an exterior insulation finishing system was considered, with the VIP placed on the external side, extra insulation layer and plaster rendering as finishing layer.

Different ways to mechanically joint the panels were considered for both VIP configurations (interior and exterior). In this work, four different materials (used as joints/battens) were taken into account: medium-density fiberboard (MDF), extruded polystyrene (XPS), rubber and aerogel composed blanket. To make the comparison consistent with the results from other studies available in literature [4], [5], joints width of 36mm were considered.

Summarizing, three wall typologies were selected (solid, cavity and insulated cavity); for each typology two insulation configurations were simulated (interior and exterior), considering a possible extra insulation layer characterized by a thermal conductivity λ=0.035 W/mK (0mm, 20mm, 40mm or 60mm thick); the outcomes consist of 24 possible different combinations. For each wall configuration, three different thicknesses of VIP were considered (10mm, 20mm or 30mm) combined with the four possible joint materials, resulting in 288 possible combinations (see Fig. 1).

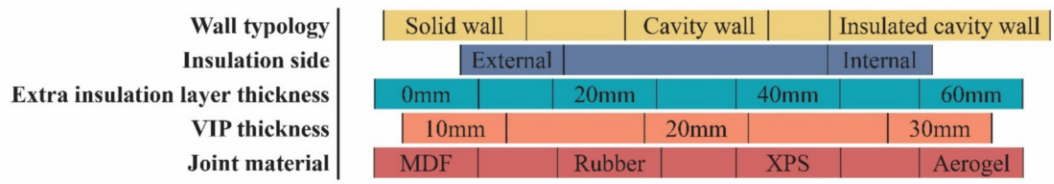

Fig. 1. Possible configurations

Commercially, VIP panels can be found with a variety of different kinds of envelopes, as well as different core materials. A metallized aluminium envelope was considered in this study, consisting in one PE layer covered by three PET + three aluminium layers (Fig. 2).

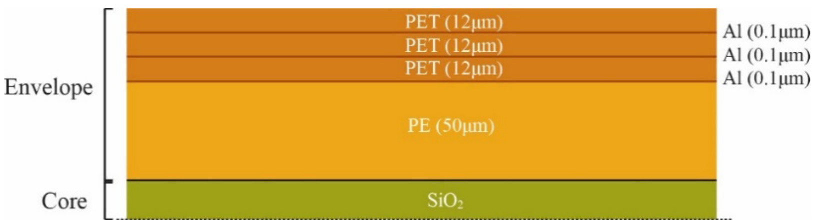

Fig. 2. Metallized aluminium envelope layer

An experimental campaign through a guarded heat flow meter apparatus was carried out to assess the centre of panel thermal conductivities of 10mm, 20mm and 30mm thick VIP panels, which resulted to be 0.00537W/mK, 0.00462W/mK and 0.00479W/mK respectively. The same procedure was performed for different joint materials (Table 1). The thermal conductivity of aerogel was assumed equal to the mean value of a manufacturer declaration

[15].

Table 1. Coupling materials thermal conductivities

Joint material	λ *(W/mK)*
MDF	0.103
XPS	0.035
Rubber	0.205
Aerogel	0.015

2.1. Numerical model for the assessment of VIP and joint thermal properties

The 2D numerical analysis was carried out with the software Physibel BISCO. The mesh was constructed using the Delaunay triangulation and then a bi-dimensional steady-state heat transfer using the energy balance method was applied. Some simplifications were needed to make the numerical analysis faster and more feasible, without compromising the accuracy. For this purpose the multi-layered VIP envelope was considered single-layered and was modelled as in [4], [5]; the same was done with the layers on each side of the VIP panel (Fig. 3). Fictitious thermal conductivities were introduced to these simplified layers to obtain the same thermal resistance:

$$\lambda_{fict,x} = \frac{d_x}{R_x} = \frac{d_x}{\sum_{j=1}^{n} R_{xj}} \tag{1}$$

where R_{xj} are the thermal resistances of all j layers and d_x is the single fictitious layer thickness.

This procedure was done for both the exterior and the interior layers obtaining two fictitious thermal conductivities.

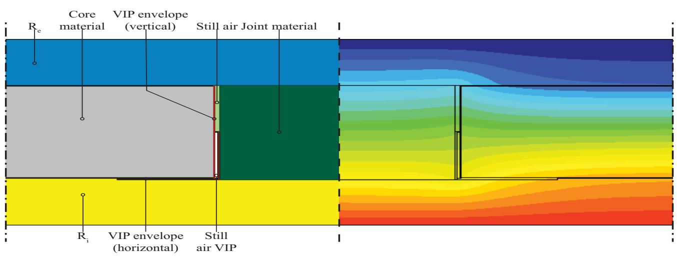

Fig. 3. BISCO model input (left) and isothermal profile as graphical output (right)

Heat flow and temperature values are provided by BISCO as output. Then, using the following equation, the linear thermal transmittance was evaluated (in accordance with [17]):

$$\psi = \frac{\dot{Q} - \frac{1}{R_{TOT}} \cdot l \cdot \Delta\vartheta}{\Delta\vartheta} \tag{2}$$

Where:

$$\frac{1}{R_{TOT}} = \frac{1}{R_i + R_e + \dfrac{d}{\lambda_{COP}}} \tag{3}$$

The equivalent thermal conductivity was calculated as:

$$\lambda_{eq} = \lambda_{COP} + \psi \cdot d \cdot \frac{P}{A} \tag{4}$$

λ_{eq} depends on the panel size, in particular on the semi-perimeter P and the area A, therefore a general value cannot be considered. For this reason, a standard and commercially diffused panel size 500x600mm was considered for this analysis.

2.2. Numerical model for the assessment of building energy performance

A residential building was selected as case study, and the energy performance was evaluated taking into account all wall configurations. The boundary conditions are the following:

- Location: Torino;
- Heating Degree Day=2617 [17];
- Heating Period: October 15th - April 15th
- Inner temperature=20°C (293.15K);
- Inner dimensions: 5x5x2.7m (Fig. 4);
- Window dimensions: 1/8 plan area (minimum for natural light and ventilation according to [19]) (Fig. 4 (a));
- U_w=2W/m^{2}K;
- Ventilation: only natural (0.3h^{-1});
- Floor and ceiling: Adiabatic.

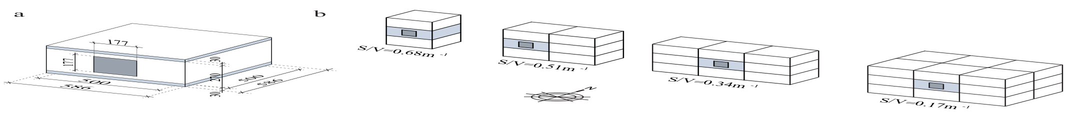

Fig. 4. (a) 3D model of the building case (quotes are in cm); (b) Axonometric view of all four cases: from zero to three adiabatic walls

In order to take into account different aspect ratios, the building energy performance analyses were done considering four configurations (Fig. 4 (b)):

- all walls as external;
- one adiabatic wall;
- two adiabatic walls;
- three adiabatic walls.

To evaluate the influence of the thermal bridging effects, these analyses were carried out:

- considering the equivalent thermal conductivity λ_{eq} for the VIP panel, that takes into account the thermal bridging effects on the basis of 2D numerical analyses;

- considering the thermal conductivity provided by the producer λ_{pro}=0.007 W/mK, that takes into account the thermal bridging effects in a simplified way;
- considering the centre of panel thermal conductivity λ_{COP}, that does not take into account any kind of thermal bridging effect.

Three outcomes were chosen to evaluate the building energy performance, in accordance with [16]:

- H_{tr}: heat transfer coefficient by transmission;
- Q_{Htr}: total energy losses by transmission;
- Q_H: building energy need.

In this way, the results allowed to evaluate the influence of the thermal bridging effects related to the VIP assembly on the building energy performance. To isolate the thermal bridging effect due to VIPs on the building energy performance, other typologies of thermal bridges were not considered in the model.

3. Results and discussion

The linear thermal transmittances and the equivalent thermal conductivities were assessed for all the described wall configurations through the previously described methods. For sake of brevity, only the thermal transmittance related to the configuration with 30mm VIP thickness are shown in Fig. 5 with respect to the total thermal resistance of the bounding layers (which is the total thermal resistance of the multilayer wall, VIP excluded).The percentage differences between the equivalent thermal conductivity and the centre of panel thermal conductivity were calculated in order to evaluate the thermal bridging effects influence.

The energy performance of the building case study was evaluated through a quasi-steady state simulation and the result for a certain wall configuration are shown (in particular the building energy need versus the aspect ratio). Some considerations were then made on the evaluation of the heat transfer coefficient by transmission with different thermal conductivities (λ_{COP}, λ_{pro} or λ_{eq}).

3.1. Linear thermal transmittance and equivalent thermal conductivity evaluation

All the linear thermal transmittances were calculated using equation (2). Moreover all the wall configurations, the VIP thicknesses and their relative joint materials were taken into account.

The linear thermal transmittance variation is represented as a function of the total thermal resistance of the bounding layers. The graph about 30mm VIP is shown in Fig. 5.

In Fig. 5, moving from the left to the right side of the X-axis (which represents the total thermal resistance of the bounding layers R_i+R_e), the linear thermal transmittance of the different wall configurations tend to converge to a narrow range.

Fixing a low value for R_i+R_e, for example 1 m^2K/W (roughly a cavity wall), the range of the linear thermal transmittances goes from 0.013 to 0.037 W/mK (dashed line in Fig. 5). Considering a higher value of R_i+R_e (cavity wall with 40mm of extra insulation layer), the ψ-value ranges from 0.008 to 0.018 W/mK (dotted line in Fig. 5).

A decrease in the linear thermal transmittance ψ can be observed when increasing the total thermal resistance of the bounding layers. This behaviour underlines that the higher the thermal resistance of the bounding layers, the lower the entity of the thermal bridging effects. A best-fit was performed in order to approximate the linear thermal transmittance trend. As a result, fourth grade polynomial curves were chosen.

An important outcome from these results shows that aerogel composed blanket is a particularly suitable material to be used as VIP joint, because of its very high thermal performances. VIP coupling materials are of key importance, given the fact that in a variety of cases they are crucial, for example, as laths and battens in vertical envelopes or to give dimensional flexibility (e.g. corners or discontinuities).

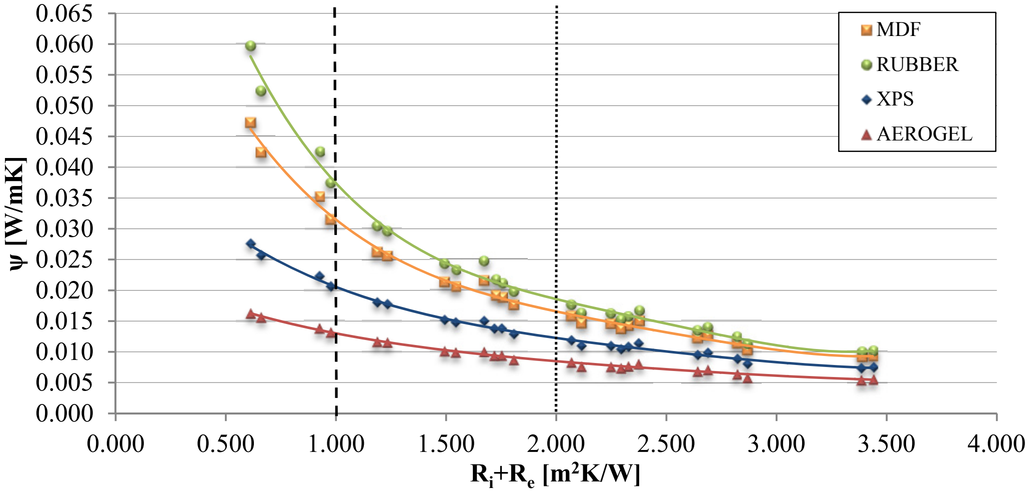

Fig. 5. Linear thermal transmittances (ψ)

The percentage differences between λ_{eq} and λ_{COP} were calculated to make further consideration on the influence of the thermal bridging effects. The results coming from this analysis allow to isolate the thermal bridging effect and to understand its influence in the equivalent thermal conductivity of the insulation material (VIP in this case). A 500x600mm VIP panel was considered, and results are shown in Fig. 6.

The total thermal resistance of the bounding layers values are representative of realistic building envelope configurations (given their vast diffusion in the territory) and cover a pretty big range (meaning that values out of this range are rare exceptions).

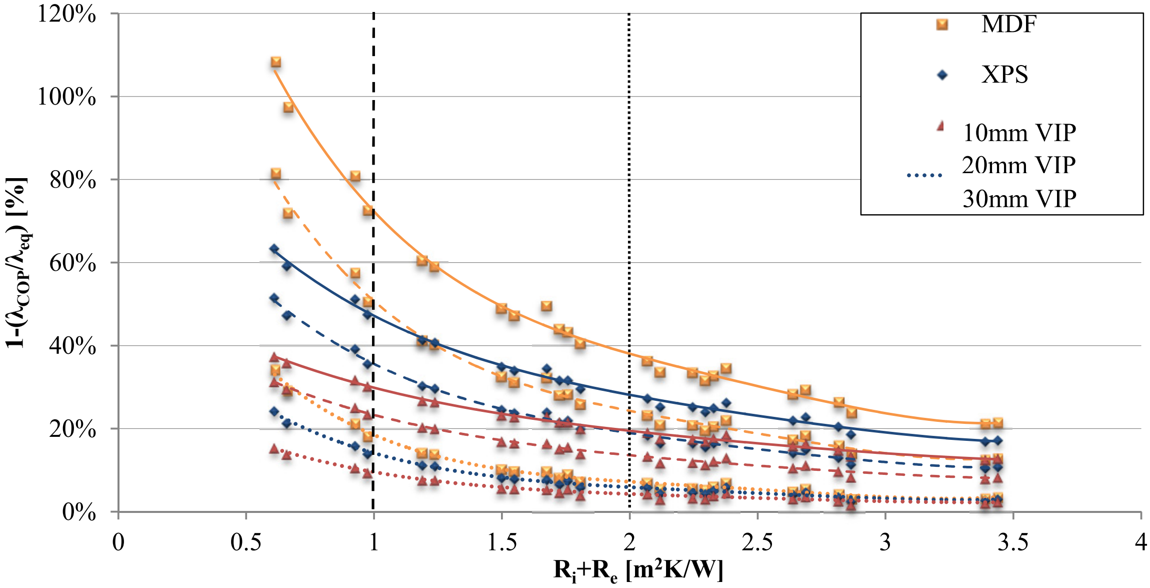

Fig. 6. Percentage difference between different thermal conductivities

In Fig. 6, for R_i+R_e = 1 m^{2}K/W (dashed vertical line), the percentage differences between λ_{eq} and λ_{COP} range from 10% to 75%; for R_i+R_e = 2 m^{2}K/W (dotted vertical line), error values range from 4% to 36%. This indicated that the higher the total thermal resistance of the bounding layers, the lower the error range is.

The curves seem to be split in three groups, were the 30mm VIP curves are on the upper side, the 20mm VIP curves lay in the middle and the 10mm VIP are at the bottom. This is true fixing a certain coupling material; observing all curves at once, it is clear that they cross each other, due to the fact that the coupling materials have extremely different thermal behaviours.

Increasing the VIP thickness, the range between the minimum and the maximum value of the percentage error also increases. For example, considering the XPS joint, for 30mm VIP this range is 46%, for 20mm VIP is 41% and for 10mm is 21%.

Something analogous can be inferred about the range of the percentage error between the thickest and the thinnest VIP panel, considering first a low then a high R_i+R_e value: for MDF joints, this range is equal to 74% in the case of the low R_i+R_e (0,612 m^{2}K/W) value, while the range is 17% for the high R_i+R_e value (3,437 m^{2}K/W).

3.2. Building energy performance evaluation

The building energy performance of a case study was assessed varying the wall typologies and the VIP configurations. The building energy need Q_H per square meter (normalized on net floor area) is shown versus the aspect ratio in Fig. 7, considering (for sake of brevity) the results relative to an internal insulation in a solid wall with 20mm of additional insulation material.

The percentage differences between H_{tr} (heat transfer coefficient by transmission) calculated considering λ_{COP} or λ_{pro} instead of λ_{eq} was also evaluated to understand the influence of the thermal bridging effects on this parameter. This was done for 20mm VIP, XPS joints and for all different aspect ratios (Fig. 8 and Fig. 9).

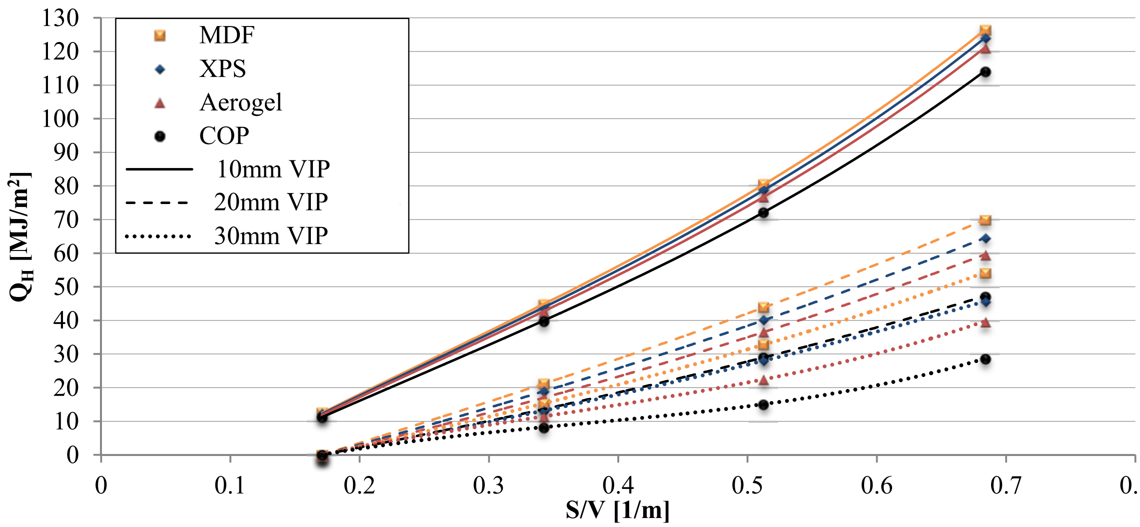

Fig. 7. Q_H variation for different VIP thickness and different surface to volume ratio *S/V* (R_i+R_e=1,232m^{2}K/W)

Observing Fig. 7 it is clear that the coupling joint material does not affect significantly the Q_H value for 10mm VIP (see continuous lines on the upper part of the graph). On the other hand, for 20mm and 30mm VIP, the joint materials influence is significant. According to this conclusions, the higher the VIP thickness (and consequently its thermal resistance), the higher is the thermal bridging effects influence.

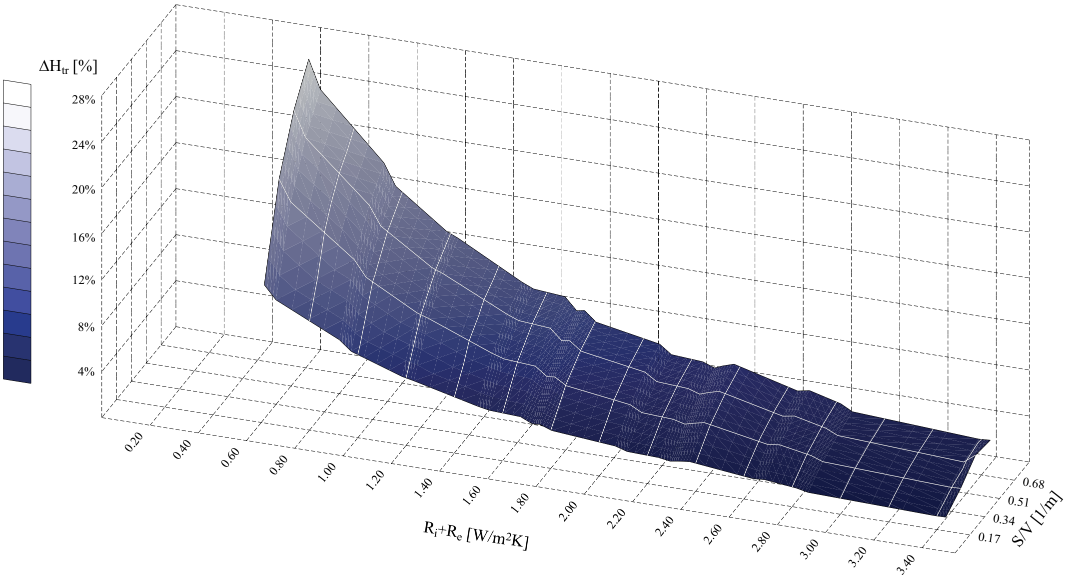

Fig. 8. Percentage difference between H_{tr} calculated with λ_{eq} and λ_{COP} - XPS joint

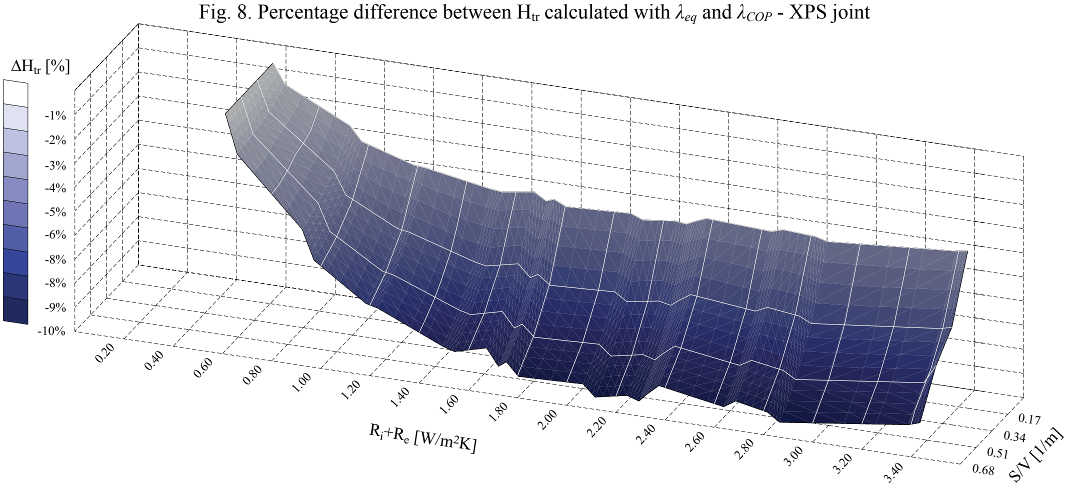

Fig. 9. Percentage difference between H_{tr} calculated with λ_{eq} and λ_{pro} - XPS joint

Fig. 8 shows the percentage difference between H_{tr} (heat transfer coefficient by transmission) calculated with λ_{COP} and the same coefficient calculated with λ_{eq}. This was done for 20mm VIP coupled with XPS joints. All the percentage values are positive because λ_{eq} is always higher than λ_{COP}, since it takes into account the thermal bridging effects. The percentage difference increases with the decreasing of the total thermal resistance of the bounding layers and with the increasing of the aspect ratio. Even though the percentage differences reach low values for high R_i+R_e values, the resulted errors cannot be considered negligible.

Fig. 9 shows a similar graph than Fig. 8, with the main difference that the percentage difference is between H_{tr} calculated with λ_{pro} instead of λ_{eq}. In this case, all the values are negative, since λ_{pro} is always higher than λ_{eq}, meaning that producers underestimate their product's thermal performance. The percentage differences reach not negligible absolute values, as in the previous case.

From the analyses can be inferred that the thermal bridging effects in VIPs strongly affect the value of the heat transfer coefficient by transmission H_{tr}. Excluding the rubber joint case, the percentage differences can reach values up to 51% (in the case of external insulation in a solid wall using 30mm VIP coupled with MDF joints).

4. Conclusions

Vacuum Insulation Panel is a promising technology, especially in the building energy refurbishment field. The thermal properties of this technology allow to obtain high insulated building envelopes with low thickness.

On the other hand, the current situation does not allow this technology to reach a significant market penetration. Further researches need to be carried out to reach a clear and comprehensive understanding of this technology behaviour in building applications.

Linear thermal transmittance values are poorly affected by the variation of the joint typology for high total thermal resistance of the bounding layers ($R_i+R_e>2m^2K/W$). In these cases, it is worthless to use well thermally performing materials as VIP couplings.

The heat transfer coefficient by transmission is a key parameter in the definition of a building energy performance. The analyses performed in this work demonstrate that H_{tr} can increase up to 50% when the thermal bridging effects are considered. This figure occurs with high VIP thickness, low joint thermal conductivity and low R_i+R_e. Therefore, the thermal bridging effects are significant also at the building scale.

The thermal bridging in VIP are never negligible and need to be considered when assessing a building energy performance. The two most effective ways to reduce their influence consists in increasing the total thermal resistance of the bounding layers and reducing the thermal conductivity of the VIP coupling materials.

Acknowledgements

The authors express their gratitude to Simona Paduos for the support given to calculate the building energy need.

References

[1] Costa A., Keane M. M., Torrens J. I., Corry E., *Building operation and energy performance: Monitoring, analysis and optimization toolkit.* Applied Energy 2013;101:310-316

[2] Bittner B., Lechner R., *A policy framework for Energy Performance Assessment for existing dwellings.* EPA-ED 2014

[3] Johansson P, Geving S, Hagentoft C-E, Jelle BP, Rognvik E, Kalagasidis AS, Time B, *Interior insulation retrofit of a historical brick wall using vacuum insulation panels: Hygrothermal numerical simulations and laboratory investigations*, Building and Environment (2014), doi: 10.1016/ j.buildenv.2014.04.014

[4] Lorenzati A., Fantucci S., Capozzoli A., Perino M., *The effect of different materials joint in Vacuum Insulation Panels*. Energy Procedia 2014; 62: 374-381

[5] Capozzoli A., Fantucci S., Favoino F., Perino M., *Vacuum Insulation Panels: Analysis of the Thermal Performance of Both Single Panel and Multilayer Board.* Energies 2015; 8: 2528-2547. doi:10.3390/en8042528

[6] Kalnæs S. E., Jelle B. P., *Vacuum insulation panel products: A state-of-the-art review and future research pathways.* Applied Energy 2014; 116:355-375

[7] Simmler H., Brunner S., *Vacuum insulation panels for building application. Basic properties, aging mechanism and service life.* Duebendorf, 2005

[8] Ghazi Wakili K., Bundi R., Binder B., *Effective thermal conductivity of vacuum insulation panels. Building Research and Information.* 2004.

[9] Tenpierik M. J., van der Spoel W., Cauberg J. J. M., *Analytical models for calculating thermal bridge effects in high performance building enclosure.* 2008

[10] IEA/ECBCS. Annex 39 Subtask A – B. *High thermal Insulation System (HiPTI) – Vacuum Insulated Products (VIP).* Duebendorf; January 22-24, 2001.

[11] Johansson P., Hagentoft C.-E., Kalagasidis A. S., *Retrofitting of a listed brick and wood building using vacuum insulation panels on the exterior of the façade: Measurements and simulations.* Energy and Buildings 2014;73:92:104

[12] EN ISO 6946, *Building components and building elements – Thermal resistance and thermal transmittance – Calculation method-* 2007

[13] UNI EN 12667, *Prestazione termica dei materiali e dei prodotti per edilizia - Determinazione della resistenza termica con il metodo della piastra calda con anello di guardia e con il metodo del termoflussimetro - Prodotti con alta e media resistenza termica.* 2002

[14] UNI-TS 11300-1, *Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale.* 2008

[15] http://www.aerogel.com/products-and-solutions/all-insulation-products/

[16] EN ISO 13790, *Energy performance of buildings – Calculation of energy use for space heating and cooling.* 2008

[17] EN ISO 14683, *Thermal bridges in building construction – Linear thermal transmittance – Simplified methods and default values.* 2007

[18] D.P.R. 26 agosto 1993, n. 412, *Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia, in attuazione dell'art. 4, comma 4, della legge 9 gennaio 1991, n. 10*

[19] Decreto ministeriale Sanità 5 luglio 1975, *Modificazioni alle istruzioni ministeriali 20 giugno 1896, relativamente all'altezza minima ed ai requisiti igienico-sanitari principali dei locali di abitazione*

[20] IEA/ECBCS, *Annex 39, Subtask B. High Performance Thermal Insulation (HiPTI) – Vacuum Insulation in the Building Sector. Systems and Applications.*