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Article

Vacuum Insulation Panels: Analysis of the Thermal Performance of Both Single Panel and Multilayer Boards

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Abstract: The requirements for improvement in the energy efficiency of buildings, mandatory in many EU countries, entail a high level of thermal insulation of the building envelope. In recent years, super-insulation materials with very low thermal conductivity have been developed. These materials provide satisfactory thermal insulation, but allow the total thickness of the envelope components to be kept below a certain thickness. Nevertheless, in order to penetrate the building construction market, some barriers have to be overcome. One of the main issues is that testing procedures and useful data that are able to give a reliable picture of their performance when applied to real buildings have to be provided. Vacuum Insulation Panels (VIPs) are one of the most promising high performing technologies. The overall, effective, performance of a panel under actual working conditions is influenced by thermal bridging, due to the edge of the panel envelope and to the type of joint. In this paper, a study on the critical issues related to the laboratory measurement of the equivalent thermal conductivity of VIPs and their performance degradation due to vacuum loss has been carried out utilizing guarded heat flux meter apparatus. A numerical analysis has also been developed to study thermal bridging effect when VIP panels are adopted to create multilayer boards for building applications.

Keywords: vacuum insulation panel; thermal insulation; thermal bridge; joint effects; numerical simulation; application of VIPs in buildings

1. Introduction

In recent years, a great deal of effort has been dedicated to developing new technological solutions with the aim of reducing the heating and cooling energy consumption of buildings. One of the most promising solutions for the construction sector is the use of super insulation materials, such as vacuum insulation panels (VIPs) and Areogel-containing materials, in building envelope components. They allow optimal thermal insulation levels to be achieved, while keeping the total thickness of the envelope components below a certain thickness. Nevertheless, some barriers have to be overcome in order to penetrate the building construction market and to be widely adopted by designers. In fact, although these materials show remarkable potential for reducing energy consumption, few investigations have been carried out so far to evaluate their effectiveness in real building applications. In particular, the effects of the configuration adopted for their installation, in terms of design and materials, and the procedures used to evaluate their overall performance need to be investigated in more detail. A number of researches have recently focused attention on:

(1) vacuum degradation and ageing by means of gas and water vapor permeation [1–3];
(2) the risk of damage (perforated VIPs) [1,4];
(3) thermal bridge effects [5–10].

Binz *et al.* [1], and more recently Johansson [7,11–14], have drawn up reviews of case study buildings where VIPs have been used for both retrofit applications and new constructions. As far as thermal bridge effects are concerned, the data available in literature mainly refer to the following three topics:

(a) thermal bridging due to the VIP envelope alone;
(b) thermal bridging due to air gaps between two adjacent panels;
(c) thermal bridge effects at a building component scale.

In relation to topic (a), Tenpierik *et al.* [5] and Johansson [7] have investigated the influence of the VIP envelope properties, evaluating the effective thermal conductivity of VIPs that "cumulatively" takes into account thermal bridging.

These studies were conducted by means of numerical simulations, and the authors found that thermal bridging depends primarily on four parameters: the laminate envelope thickness, the laminate envelope thermal conductivity, the thermal conductivity of the core material and the thickness of the VIP. Some other studies have proposed various solutions for the reduction of the thermal bridging effect in VIPs (topic "c"): a double layer of VIPs with non-continuous joints was proposed in Ghazi Wakili *et al.* [15], while Tenpierik and Cauberg [16] analyzed the encapsulation of VIPs in an expanded polystyrene (EPS) envelope. As highlighted in these studies, thermal bridging is a key issue that should to be taken into account in the assessment of the actual performance of a VIP. In fact, the higher the quality of the insulation layer, the higher the influence of the thermal bridging effect on the overall building energy performance.

However, the researches so far developed have mainly focused on the thermal bridging effect in VIP panels, just taking into account their material properties and the air gap between adjacent boards [17], while the influence of the overall structure of the multilayer wall, together with the structural thermal joints between panels, has seldom been investigated (see e.g., [6,7,18,19]).

Finally, it should be considered that the low equivalent thermal conductivity of the panels, which is typically in the 15×10^{-3} to 45×10^{-3} W/mK range [20], also poses some challenges as far as its measurement is concerned. The usually adopted procedures make use of guarded heat flux meter apparatus, whose lower detection limit is in fact around the value of the equivalent thermal conductivity of the best performing materials currently on the market.

Aims

Considering the situation outlined in the introduction, a research activity has been carried out focusing attention on VIP panels (with fumed silica as the core material [20]). The studies were aimed at:

- investigating the performance of VIP materials when they were applied as an ideal continuous layer (*i.e.*, measurement of the Centre-Of-Panel, COP, equivalent thermal conductivity). In particular, this phase of the research was focused on verifying the accuracy and reliability of the laboratory measurement procedures adopted for the panel rating, and on the analysis of the thermal properties of some commercial materials;
- analyzing the degradation of performance due to vacuum loss (punctured VIP);
- characterizing, by means of numerical simulations, the effect of thermal bridging in real building applications in which VIP panels were used (where the super-insulation material was usually coupled to other layers, e.g., multilayer board performance, and jointed/fixed to proper frames). In particular, the effective VIP thermal conductivity, considering the thermal bridge, was evaluated through a numerical analysis by varying:
    - the thermal resistance of the additional layers adjacent to the VIP board (R_i, R_e);
    - the size/shape of the VIP panel;
    - the thermal conductivity of the VIP envelope;
    - the type of structural joint.

2. Experimental Section

2.1. Measurement of the Center-of-Panel Thermal Conductivity

The Centre-Of-Panel (COP) thermal conductivity of the VIP boards was measured by means of typical guarded heat flux meter apparatus, applying the standardized procedure used to rate traditional insulation materials for building applications [21]. The aims of such measurements were:

(1) to test the reliability, repeatability/reproducibility and accuracy of the measurement procedure;
(2) to verify the nominal λ_{COP} of some commercial VIP boards, with particular emphasis on the constancy of the properties between boards of the same type (homogeneity of the delivered performance).

In relation to item 1, it should be underlined that although this kind of measurement procedure is considered trivial, and is performed using well known equipment and "oiled" techniques, the high thermal resistance of the material under test put the experimental system under extreme stress. The nominal lower limit of the measurable thermal conductivities of test rigs is usually around 0.0015 ÷ 0.0020 W/mK. Moreover, the very low value of the heat flux that is generated during the tests is demanding as far as measurement accuracy is concerned.

The data presented in this paper were collected using a LASERCOMP FOX 600; a guarded heat flux meter apparatus based on heat flux meters. The features and technical specifications of this equipment are: 610 mm × 610 mm heating plates, 254 mm × 254 mm measurement area, −15 °C to 85 °C test temperature range, and 0.0015 ÷ 1 W/mK range of measurable thermal conductivity.

A nominal accuracy of ±1% is declared by the manufacturer of the apparatus for typical insulation materials. Nevertheless, the actual measurement accuracy for the λ_{COP} measurement was assessed for each single test, accordingly to [22].

Seven different type/shape of VIP panels were tested. All the samples refer to commercially available materials, easily found on the EU market. Features and shape of the tested panels are summarized in Table 1.

Table 1. Features of the tested VIP panels and λ_{COP} measurement results.

Test N°	Manufacturer	Panel Type	Sample N°	Thickness [mm]	$T_{average}$ [°C]	ΔT_{nom} [°C]	λ_{COP} [W/(mK)]	Accuracy $\Delta\lambda$ [%]
1 (*)	A	1 (470 mm × 970 mm)	1	13.32	24.00	20.0	0.0047	2.2
2	A	1 (470 mm × 970 mm)	2	13.92	24.00	20.0	0.0027	2.5
3 (*)	A	1 (470 mm × 970 mm)	3	13.79	24.00	20.0	0.0033	2.3
4	A	1 (470 mm × 970 mm)	4	14.05	24.00	20.0	0.0026	2.5
5	A	2 (370 mm × 770 mm)	1	12.88	24.02	20.0	0.0020	2.6
6 (*)	A	2 (370 mm × 770 mm)	2	13.16	24.02	20.0	0.0018	2.8
7	A	3 (270 mm × 670 mm)	1	13.13	24.00	20.0	0.0056	2.1
8	A	3 (270 mm × 670 mm)	2	13.48	24.00	20.0	0.0062	2.1
9	A	4 (420 mm × 820 mm)	1	13.09	24.02	20.0	0.0024	2.5
10	A	4 (420 mm × 820 mm)	2	12.28	24.02	20.0	0.0022	2.5
11	A	4 (420 mm × 820 mm)	3	12.57	24.02	20.0	0.0021	2.6
12	A	5 (420 mm × 540 mm)	1	12.67	24.02	20.0	0.0022	2.6
13	A	5 (420 mm × 540 mm)	2	13.36	24.02	20.0	0.0021	2.6
14	A	5 (420 mm × 540 mm)	3	13.75	24.02	20.0	0.0020	2.7
15	A	5 (420 mm × 540 mm)	4	13.39	24.02	20.0	0.0017	2.9
16 (*)	B	1 (500 mm × 300 mm)	1	12.48	24.02	20.0	0.0028	2.4
17	B	1 (500 mm × 300 mm)	2	12.67	24.03	−20.0	0.0029	2.3
18	B	1 (500 mm × 300 mm)	3	12.67	24.02	−10.0	0.0028	2.7
19 (*)	C	1 (520 mm × 420 mm)	1	11.86	24.02	20.0	0.0033	2.3

The tests with * have been carried out twice.

Three producers (named A, B, and C in the following) were chosen. Several types of panels were analyzed for two of the producers (a total of 19 samples were studied). The size of the analyzed VIP panels spanned from 300 mm × 500 mm to 420 mm × 820 mm. All of the panels used fumed silica as the core material. The features and structure of the panel envelope were not known, and the manufacturers refused to supply detailed information for data confidentiality reasons.

Table 1 summarizes the obtained results together with the calculated accuracies (which ranged from 1.7% to 2.9%). A total of 19 experiments were performed at a nominal average temperature of 24 °C (between the upper and lower plate) and with a nominal temperature difference between the plates of 20 °C. For all the tests, with the exception of test 17 and 18, the upper plate was the hot side. Tests 17 and 18, instead, were conducted warming the lower plate (and, for test 18, the measurement was carried out with a nominal temperature difference of 10 °C).

As is possible to see (Table 1), five different types of board were considered for manufacturer "A". In case of board types "1" and "5", the measurements were repeated for five different (nominally identical) samples; in relation to board types "2" and "3", the measurements were repeated for two different samples, while for board type "4", attention was focused on three samples. In relation to manufacturers "B" and "C", only one kind of board was analyzed, but two different samples were studied for manufacturer "B".

In order to judge the accuracy and repeatability of the measurements, some tests have been carried out twice, that is, samples No. 1, 3, 6, 16 and 19 (highlighted with * in Table 1). The results of this analysis are summarized in Figure 1, where the measured λ_{COP} is plotted together with the respective accuracy bar.

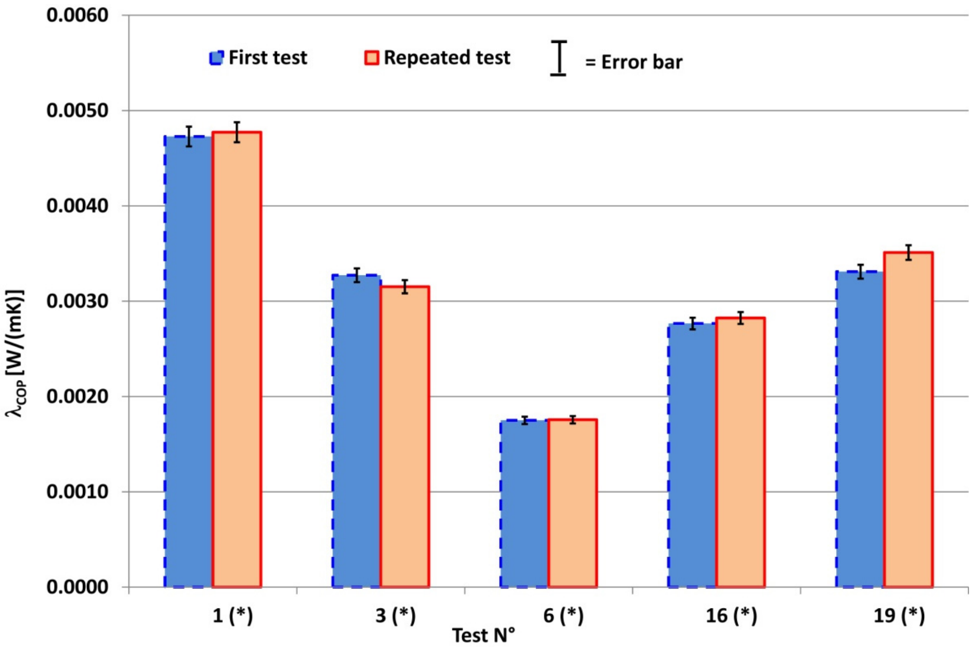

Figure 1. Repeatability of measurements—Results from repeated tests on the same sample—λ_{COP} [W/(mK)].

As it is possible to see, the repeatability/reproducibility of the tests is excellent; only for test 19 is there a borderline situation in which the accuracy interval of the measurement, around ±2.3%, is slightly smaller than the variability between the two tests, which is around 5%. For all the other cases, the variability of the measured λ_{COP} for the two tests is always much lower than the uncertainty interval.

This preliminary study was essential in order to be able to correctly understand the results of the tests conducted on materials related to different manufacturers and/or to different samples of the same type of board. The λ_{COP} values measured for the nineteen considered samples are graphically resumed and shown in Figure 2.

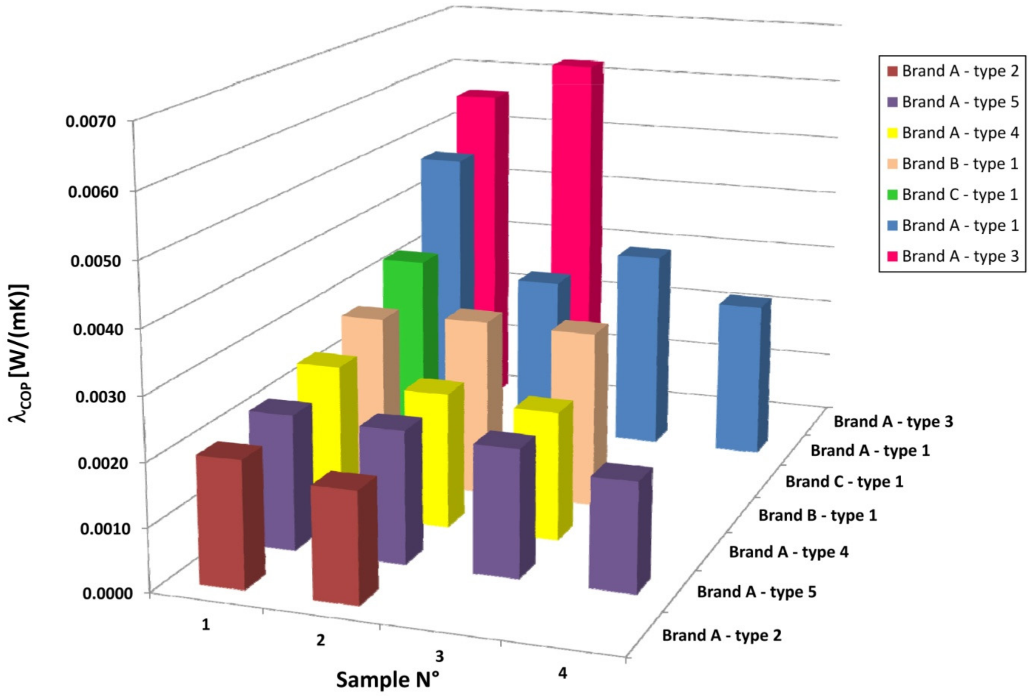

Figure 2. Measured values of the λ_{COP} for various samples.

In this plot, each series on the horizontal (right) axis represents a different type of board, while the series on the other horizontal axis refers to different samples of the same type of board.

As expected, there is quite a large variability of performance of the VIP materials when either the manufacturer and/or the board type is changed (as also highlighted in [6,18]). In the present study, the best performing material showed a minimum λ_{COP} value equal to 0.0017 W/mK, while the worst sample provided a λ_{COP} of 0.0062 W/mK.

A rather unexpected outcome was the variability of the properties for the different samples of the same board type. This fact is quite obvious for the results related to "Brand A-type 1" (see Table 1 and Figure 2). For this product, tests repeated over 5 different panels of the same type provided a λ_{COP} value that spanned from a minimum of 0.0026 W/mK to a maximum of 0.0047 W/mK, with a standard deviation between the measured values of 0.0010 W/mK. This variability was less pronounced in other cases, but still present (for example, in the case of "Brand type 5", the variability of the 5 tested samples was equal to 0.0002 W/mK, with a difference between the maximum and minimum measured value of 0.0004 W/mK).

2.2. Performance Decay Due to Damage

Another important issue that has to be considered when using a VIP in buildings is the risk of losing the vacuum due to external agents, such as puncturing of the envelope. The most recurrent piece of information in the scientific literature is that, in the case of damage to the envelope, the thermal conductivity increases about five times compared to the pristine material, reaching values that are half those of traditional insulation materials [1,4].

Given the importance of this topic, an experimental analysis on performance decay, related to the loss of vacuum, was carried out during the second stage of the research. For this reason, experimental tests on punctured VIPs were performed utilizing the guarded heat flux meter apparatus for brand "C" and for another board (manufacturer "D") (see Table 2).

Table 2. Effect of vacuum loss on punctured VIPs.

Sample	Thickness [mm]	T_{avg} [°C]	T_{up} [°C]	T_{low} [°C]	λ_{COP} [W/(mK)]	$\Delta\lambda$ [%]
Intact VIP-C	12.0	24.02	14.02	34.02	**0.0034**	2.3
Punctured VIP-C	17.8	24.02	14.02	34.02	**0.0228**	2.0
Intact VIP-D	24.7	24.0	14.0	34.0	**0.0060**	2.0
Punctured VIP-D	28.1	24.0	14.0	34.0	**0.0230**	2.3

These findings are coherent with those reported in the literature [1] and highlight the importance of a proper protection of the VIP materials from external mechanical risks when they are adopted in building envelope components.

3. Multilayer Walls with VIP Panels—Numerical Analysis of the Overall Thermal Performance

The very low center of panel thermal conductivity of VIPs, λ_{COP}, makes them very promising for the construction of highly efficient energy walls.

Nevertheless, it should be taken into account that VIPs cannot simply be installed as they are manufactured. These super-insulation materials are supplied in rectangular elements of finite size and, to "cover" a wall, they need to be properly coupled to each other and to be fixed onto a supporting layer. These actions frequently require the use of some sort of frame that is able to hold the panels in place and to allow their reciprocal connection.

As a result, the overall thermal performance of the wall not only depends on an excellent λ_{COP} value, but is also influenced by the thermal bridging caused by the framing system.

Thermal bridging can have a significant influence on the heat flux that crosses the building envelope and can seriously compromise the effectiveness of the super-insulation materials. A proper evaluation of the thermal bridge and of the overall performance of the multilayer walls is therefore necessary.

In [5], this issue was approached by modifying the surface heat transfer coefficients of the VIP panels. In such a way, it was possible to take into consideration both the thermal resistance of the inner/outer surfaces and the additional thermal resistance of the panels between which the VIP was located.

In the present paper, however, the additional insulation introduced by the outer and inner bounding panels has been modeled together with the structural joints that border the super-insulation material in order to better predict the thermal field distortion at the VIP edges.

The overall performance of the multilayer wall has been assessed by means TRISCO software, which is based on the energy balance method (following a procedure similar to the one suggested in [15]). The reference configuration assumed for this study consisted of Figures 3 and 4:

- a typical VIP panel without spacers and with symmetrical joints;
- a linear structural joint between the panels;
- two layers (one external and one internal) which bound the super-insulation panel;
- a single layer type edge (without overlapping).

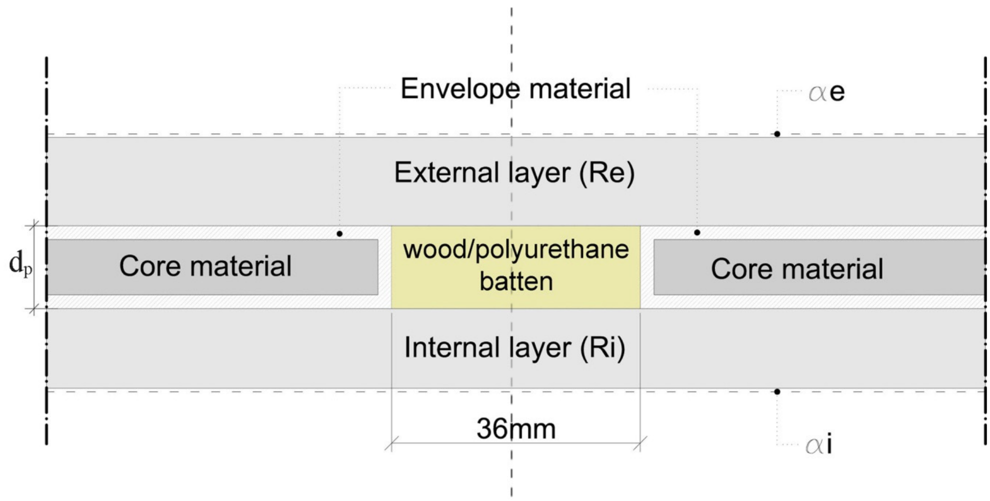

Figure 3. Model for the numerical calculation of the effective thermal conductivity of VIPs.

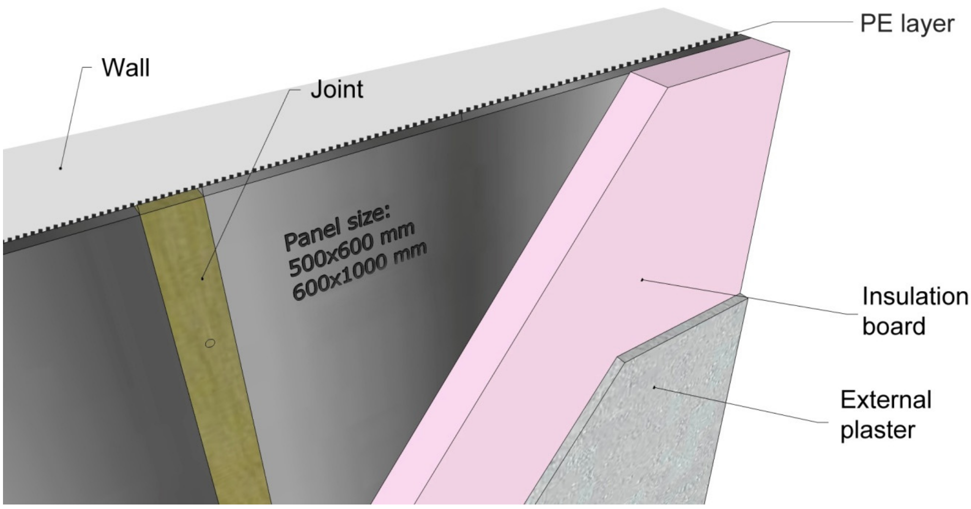

Figure 4. 3D scheme of a typical building insulation configuration.

The VIP panel was 500 × 600 mm and the value of the equivalent thermal conductivity (λ_{COP}) used for the numerical simulations was the same one measured for brand B (see Section 2).

The numerical analysis was repeated for different thermal properties of the membrane that is used to bind the VIP panel. A parametric analysis was carried out considering three different types of envelope [20]:

- a metal foil, consisting of a central aluminum barrier layer, laminated between an outer PET layer (for scratch resistance) and an inner PE sealing layer (case: a);
- a metalized film, made of one layer of aluminum coated PET film and an inner PE sealing layer (case: b);
- a metalized film, made of three layers of aluminum coated PET film and an inner PE sealing layer (case: c).

Figure 5 schematically shows the envelope structure and summarizes its main features.

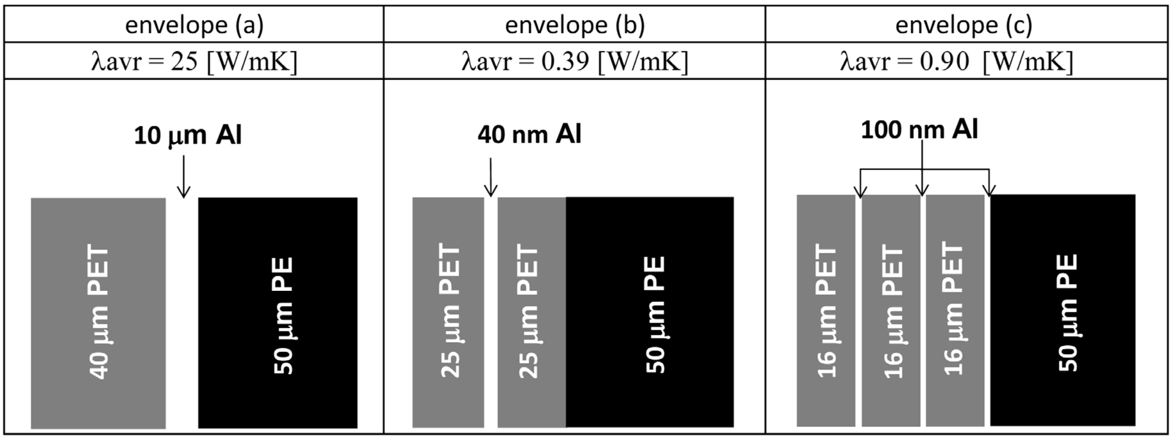

Figure 5. Envelope configurations considered for the numerical simulations [6].

As far as the structural joints are concerned, various arrangements for real building applications were found taken from a literature review (see e.g., [1,18,23]).

In the present study, two typical systems were considered: wood (λ_{wood} = 0.14 W/mK) and polyurethane batten (λ_{PU} = 0.026 W/mK) interposed between two adjacent VIPs, as shown in Figures 3 and 4. The joints are used in practice to fix additional insulation panels, through dowels, onto a VIP and to fix the VIP onto the rear wall.

Finally, since the thermal bridging is affected by the presence of the two boundary layers (internal, R_i, and external; R_e—Figures 3 and 4), different simulations were carried out varying the additional thermal resistance of these two additional layers (R_{tot}) in the range between 0 to 3.83 m^2K/W.

In other words, the total additional thermal resistance, R_{tot}, was divided between the external and internal layers, R_i and R_e, respectively. Calculations were then repeated changing these last two parameters in discrete steps, as shown in Table 3.

The internal and external surface resistances, α_i and α_e, for the horizontal heat flux were assumed to be fixed, and their values were chosen in accordance to EN ISO 6946 [24]. The temperatures of the external and internal environments adopted in the simulations were always set at 0 °C and 20 °C, respectively.

Table 3. Thermal resistance of the additional panels (R_i, R_e)—values assumed for the simulations (the values related to R_i and R_e are shown in bold in the first row and first column, respectively. The values of $R_{Tot} = R_i + R_e$ are shown in the table).

$R_i + R_e$ [m^2K/W]	**R_i [m^2K/W]**				
R_e [m^2K/W]	**1.87**	**0.87**	**0.37**	**0.12**	**0.00**
1.96	3.83	2.83	2.33	2.08	1.96
0.96	2.83	1.83	1.33	1.08	0.96
0.46	2.33	1.33	0.83	0.58	0.46
0.21	2.08	1.08	0.58	0.33	0.21
0.00	1.87	0.87	0.37	0.12	0.00

A first set of simulations was performed for an ideal case in which there were no boundary panels (external and internal, that is: $R_i = R_e = 0$ m^{2}K/W) and no structural joints. In such a configuration, the thermal bridge is only caused by the presence of the VIP envelope ("no joint" cases) (It is worth noting that this configuration is the one that is usually investigated and reported in the literature). The aims of this analysis was to compare the results obtained with the numerical model used in this paper with those available in literature [6], for validating the model itself.

Subsequently, the effect of thermal bridging was assessed taking into consideration the combined influence of both the "VIP panel-edge" node (thermal bridge at the "VIP level", due to the panel envelope) and the "VIP—joint" node (thermal bridge at the "building level", due to the structural joints).

In order to quantify these phenomena, the linear thermal transmittance of the thermal bridge (EN ISO 14683 [25]), was calculated on the basis of the results obtained by means of a steady-state numerical model.

Finally, starting from the knowledge of the linear thermal transmittance and the centre of panel thermal conductivity of VIP, λ_{COP}, a suitably modified U-value of the VIP panel (effective thermal transmittance, U_{eff}) was assessed, which globally took into account the heat flux through both the structural joints and the multilayer structure.

The calculation procedure, which was conducted accordingly to standard EN 10211-1 [26], started with the identification of the portion of the panel that was influenced by the thermal bridge, that is with the assessment of the value of "b" (Figure 6).

The length "b" was chosen to include the entire region in which the heat flux departs from the one-dimensional conditions in the geometrical domain of the model (this check was done on the basis of the results of the numerical model).

The linear thermal transmittance of the thermal bridge between two adjacent panels, ψ_{VIP}, was then calculated through the following equation:

$$\psi_{VIP} = \frac{\dot{Q} - \dot{Q}_{COP}}{l_p \cdot (\theta_i - \theta_e)} = \frac{q - q_{COP}}{(\theta_i - \theta_e)} \quad (1)$$

where, referring to the calculation scheme shown in Figure 6; $\dot{Q}$ is the overall (actual) heat flux that crosses the surface Sp (dashed area in Figure 6) of the panel with the thermal bridge (of length l_p). θ_i and θ_e are the internal and external temperatures, respectively; and q_{COP} is the centre of panel heat flux per unit length, $\frac{\dot{Q}_{COP}}{l_p}$ ($\dot{Q}_{COP}$ is the heat flux that would cross an ideal panel with the same area, S_p, but made only of homogeneous VIP material).

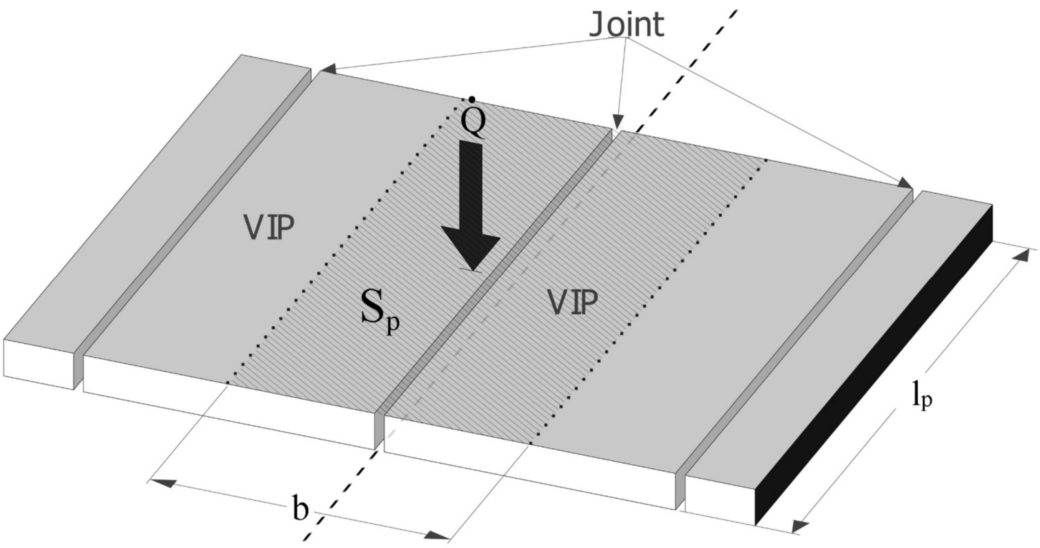

Figure 6. 3D scheme of the numerical calculation of the effective VIP thermal conductivity.

The 1-D thermal transmittance of the ideal envelope component without joints, U_{1D}, can be written as (according to the EN ISO 6946 standard [24]):

$$U_{1D} = \frac{1}{\alpha_i + R_i + \frac{d_p}{\lambda_{COP}} + R_e + \alpha_e} \tag{2}$$

where d_p is the VIP thickness; R_i and R_e are the thermal resistance of the internal and external additional layers, respectively (see Figures 3 and 6); and α_i and α_e are the thermal resistances of the internal and external surfaces.

U_{1D} is the thermal transmittance of a multilayer board, in the absence of any kind of thermal bridge, b is the width, in the 2-D geometrical model, over which the U_{1D} value applies (*i.e.*, the simulated panel width).

Equations (1) and (2) clearly highlight that the influence of the thermal bridge depends on the features of the various layers of the wall, as well as on the VIP material, and on the heat transfer coefficients of the surface.

In order to obtain a parameter that is able to describe the overall performance of a multilayer wall with VIP panels, an effective thermal transmittance, U_{eff}, can be defined as:

$$U_{eff} = \frac{\dot{Q}/S_p}{(\theta_i - \theta_e)} \tag{3}$$

Recalling Equations (1) and (2), it is then possible to write:

$$U_{eff} = U_{1D} + \frac{l_p}{S_p} \cdot \psi_{VIP} \tag{4}$$

Finally, an effective thermal conductivity of the VIP panel, $\lambda_{eff,VIP}$ (which accounts for both the "undisturbed" homogeneous material and the thermal bridge at the edges), can be derived from Equation (4).

It is also possible to write U_{eff} as:

$$U_{eff} = \frac{1}{\alpha_i + R_i + \frac{d_p}{\lambda_{eff,\,VIP}} + R_e + \alpha_e} \quad (5)$$

and hence:

$$\lambda_{eff,VIP} = \frac{d_p}{\left(\frac{1}{U_{eff}} - \alpha_i - \alpha_e - R_i - R_e\right)} \quad (6)$$

$\lambda_{eff,VIP}$ is of practical importance since it allows an easy and immediate comparison to be made between the performance of an ideal, homogeneous panel and that of a real panel with joints.

As already mentioned, a numerical model was built with TRISCO. Due to the thermal symmetry, only one half of the configuration reported in Figures 4 and 6 was modelled. In this way, the model provided one half of the linear thermal transmittance $\Psi_{VIP}/2$.

The model was tested during a preliminary phase to assure a grid independent solution (this was done accordingly to the EN ISO10211 standard) [26]. Its reliability was then verified considering the "no joint" configurations and comparing the ψ-values calculated with the TRISCO (the calculations were made for similar conditions—$\lambda_{env,VIP}$, λ_{COP}, panel thickness—as the cases published in literature) model with those available in literature (see e.g., Baetens *et al.* [6]). The results are not shown here for the sake of brevity).

After these (positive) tests, the numerical model was used to study various configurations. Figures 7 and 8 summarize the obtained results.

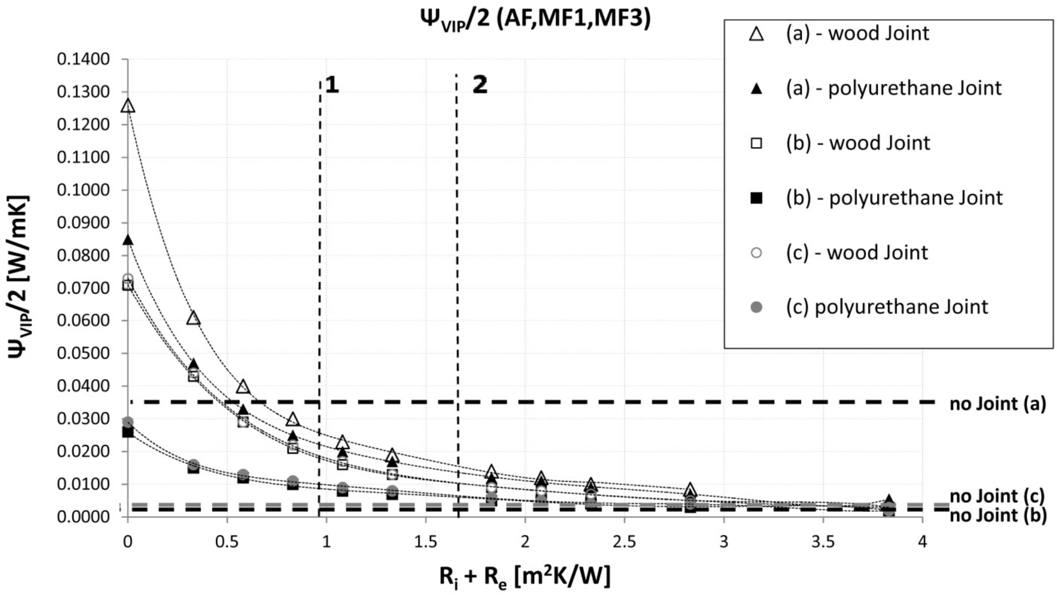

Figure 7. $\psi_{VIP}/2$ values (1000 mm × 600 mm VIP panel).

In particular, the linear thermal transmittance of the thermal bridge, $\psi_{VIP}/2$, is plotted *versus* the total thermal resistance of the internal and external boundary layers (that is, R_i and R_e) in Figure 7. Figure 8 instead shows analogous profiles of the effective thermal conductivity of the VIP panel, $\lambda_{eff,VIP}$.

Various curves are plotted on these figures, each of which refers to a different case/configuration (different envelope materials—(a), (b), (c)—and different structural joints—Wood, Polyurethane).

Moreover, for comparison, the values related to the cases without any structural joint and without additional layers (*i.e.*, $R_i + R_e = 0$) are also shown as horizontal dashed lines ("no joints" cases).

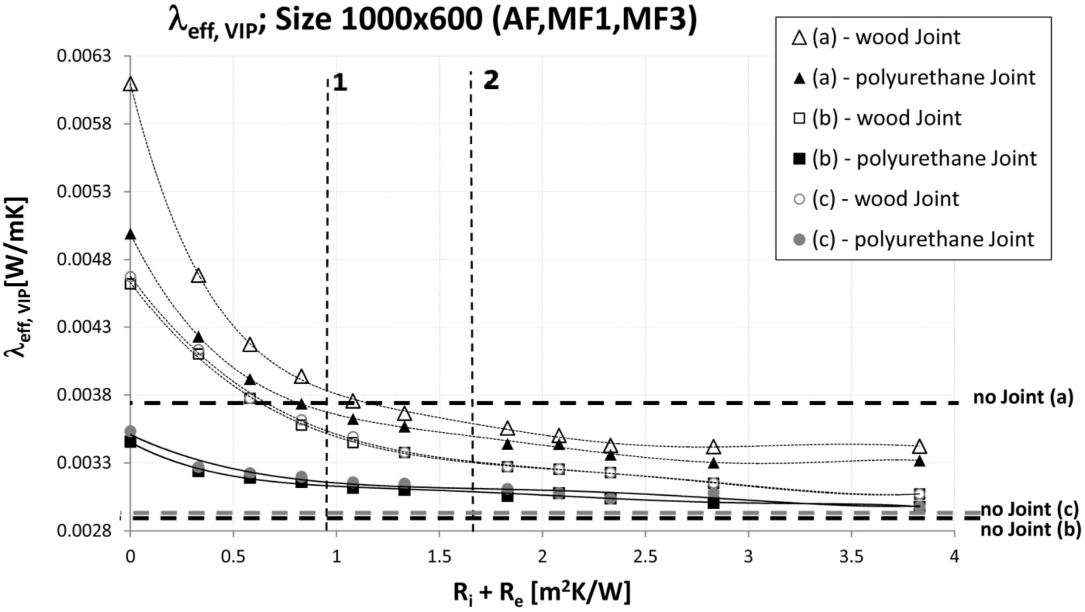

Figure 8. λ_{eff} values (1000 mm × 600 mm VIP panel).

4. Discussion

The results of the numerical analysis demonstrate that the influence of thermal bridging due to the structural joints is remarkable compared to the effects of the VIP envelope alone, without the joints (these last cases are represented by horizontal dashed lines in Figures 7 and 8).

Considering all the cases without additional layers apart from the VIP panel (that is for $R_i + R_e = 0$, *i.e.*, points lying on the Y-axis), it is possible to see (Figure 7) how the introduction of a structural joint significantly lowers the performance of the super-insulation materials. Depending on the VIP envelope conductivity (a, b, c), the $\psi_{VIP}/2$ value for the configurations with a wood joint is about 3.5 ("a", high conductive VIP envelope) to 25–35 times (for "c" and "b" respectively) higher than that of the case with the envelope alone (no joint case). When the polyurethane joint is considered, a smaller increase of the $\psi_{VIP}/2$ value is observed, especially when the VIP envelope has a lower conductivity level (b, c).

As previously mentioned, this configuration is the one that has been investigated most frequently so far. However, it should be considered that it is also the one which is unlikely to be found in practice, that is, where the VIP panels are located inside a multilayer wall for installation purposes and protection from accidental damage.

If the effects of the layers that bound the super-insulation panels are considered, it is visible from Figures 7 and 8, that the behavior of the wall package can change significantly.

As expected, the $\psi_{VIP}/2$ parameter (Figure 7) assumes the maximum value for null additional resistances ($R_i + R_e = 0$, for just the VIP panel alone and the joints) and tends to decrease as the thermal resistance of the bounding layers increases.

For the (b) and (c) cases, $\psi_{VIP}/2$ approaches the values shown for the "no joint" configurations when the additional thermal resistance exceeds 4 m^2K/W (which, to have a practical idea, corresponds to a total thickness of a good traditional insulation material of about 15 cm). Instead, when the (a) configuration is used for the VIP membrane, $\psi_{VIP}/2$ becomes lower than the "no joint" values for an additional total thermal resistance of about 0.50–0.75 m^2K/W.

As expected, the polyurethane joints (Figure 7) show better insulation properties than those of the wood joints. However, the difference depends to a gear extent on the type of the VIP envelope material and on the wall structure. The less the envelope is conductive, the less the difference in performance between wood and polyurethane.

The relative decrease in $\psi_{VIP}/2$, when switching from wood to polyurethane joints, is plotted in Figure 9 *versus* the total thermal resistance of the additional layers. One curve (square symbols) refers to the case of an (a) envelope, while the other (diamond symbols) is related to a "b" envelope. A reduction of about 65% is achieved for the case with an (a) envelope when there are no boundary layers ($R_i + R_e = 0$). This figure reduces to about 35% if the envelope is made of (b).

Besides the effect of the membrane material, the difference in $\psi_{VIP}/2$, between the polyurethane and wood joints, also decreases as the total thermal resistance of the layers surrounding the VIP increases (*i.e.*, when the influence of the thermal bridge due to the joints become less important). For an Ri + R_e of about 3 m^2K/W, the previous percentages become 40% and 13% for (a) and (c), respectively.

Therefore, the use of polyurethane as a structural joint results to be particularly beneficial when either a high performing material is used for the VIP membrane or the total thermal resistance of the boundary layers is low (see Figures 7 and 9).

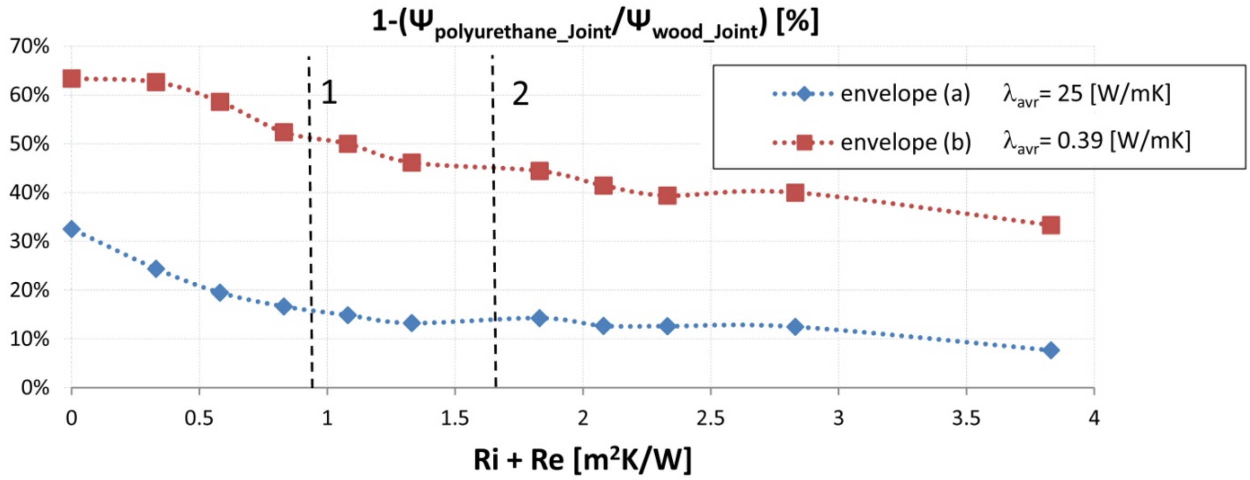

Figure 9. Difference between ψ values for wood and polyurethane joints considering (a) and (b) envelopes (1000 mm × 600 mm VIP panel).

In order to have an idea of the effects of the various joint configurations on the performance of realistic wall structures and which could be used for typical building renovations and/or constructions, two multilayer components were considered.

- Case 1 consisted of 0.25 m thick concrete and 0.03 m XPS (corresponding to an additional total thermal resistance, besides the VIP panel, of: $R_i + R_e = 0.98$ m^2K/W);
- Case 2 consists of a 0.30 m brick cavity wall (0.12 m each brick layer and 0.06 m air cavity), 0.03 m XPS and three plaster layers with a thickness of 0.02 m each (corresponding to an additional total thermal resistance, bedsides the VIP panel, of: $R_i + R_e = 1.63$ m^2K/W).

The values of the total additional thermal resistance of such configurations are given in Figures 7–9 by means of vertical dashed lines, denoted with the labels "1" and "2".

It is possible to see (Figure 7) that the $\psi_{VIP}/2$ values for the (a) envelope with joints are lower than those related to the "no joints" reference case (it is worth recalling that the "no joint" configurations refer to a case without any additional thermal resistance), as the first is in the range of about 0.0014–0.025 W/mK and the second is around 0.035 W/mK.

The situation is instead reversed for the (b) and (c) envelopes. For (b), the ψ_{VIP} related to walls "1" and "2", considering the wood joint, is around nine and five times higher than the values of the "no joint" case (the latter being around 0.002 W/mK) (for the polyurethane joint these figures become 4.5 and 3.5 times higher, respectively).

Similar results were found for the (c) envelope. Analogous conclusions can be drawn when the $\lambda_{eff,VIP}$ values are analyzed (Figure 8).

This parameter has the advantage of giving/offering a direct and prompt comparison of an ideal case of a wall made with a homogeneous layer of VIP panels and the actual case of a wall with VIP panels installed with structural joints.

The rationale behind this quantity is that the effect of the thermal bridge, instead of being accounted for by means of its linear transmittance ψ (as usually done), is taken into consideration by virtually increasing the equivalent thermal conductivity of the material (as if the thermal bridge were evenly "spread" over the entire panel).

The calculation of $\lambda_{eff,VIP}$ requires a hypothesis on the incidence of the thermal bridges (that is, their total length) over the whole panel surface. An assumption about the shape and the size of the VIP panels is therefore needed. For the analysis here presented, a 1000 mm long and 600 mm wide board was used.

It is worth noting (Figure 8) that the combination of the thermal bridge effect (related to the envelope and the structural joints) and of the boundary layers leads to an effective "overall" thermal conductivity of the super-insulation material than spans from about 0.0030 to 0.0034 W/mK for the best configurations (corresponding to the case in which a very high total thermal resistance of the additional boundary layers is adopted: $R_i + R_e \approx 4$ m^{2}K/W).

Compared to the equivalent centre of panel thermal conductivity, λ_{COP}, (which is around 0.0028–0.0029 W/mK, for the materials considered for this analysis), the effective thermal conductivity is about 7% to 21% higher. $\lambda_{eff,VIP}$ could be as high as 0.0060 W/mK if a configuration with an (a) envelope, wood joints and no additional layers were used.

In the case of more realistic configurations (*i.e.*, cases "1" and "2"), the percentage increase of $\lambda_{eff,VIP}$ compared to λ_{COP} is about 31%–25% using polyurethane joints and about 39%–29% for a wood joint.

Finally, the influence of the shape and size of the VIP panel on the overall performance of the wall is shown in Figure 10, where the relative variation of the actual, effective U-value of the wall (*i.e.*, U_{eff}) with respect to the U_{1D} value, is plotted *versus* the total thermal resistance of the boundary layers ($R_i + R_e$).

As expected, as the number and the extent of the linear thermal bridges are lowered, the performance of the super-insulation material increases. The board shape/size becomes more and more influential as the thermal resistance of the boundary layers becomes lower and the thermal properties of the VIP envelope and of the structural joints become poorer.

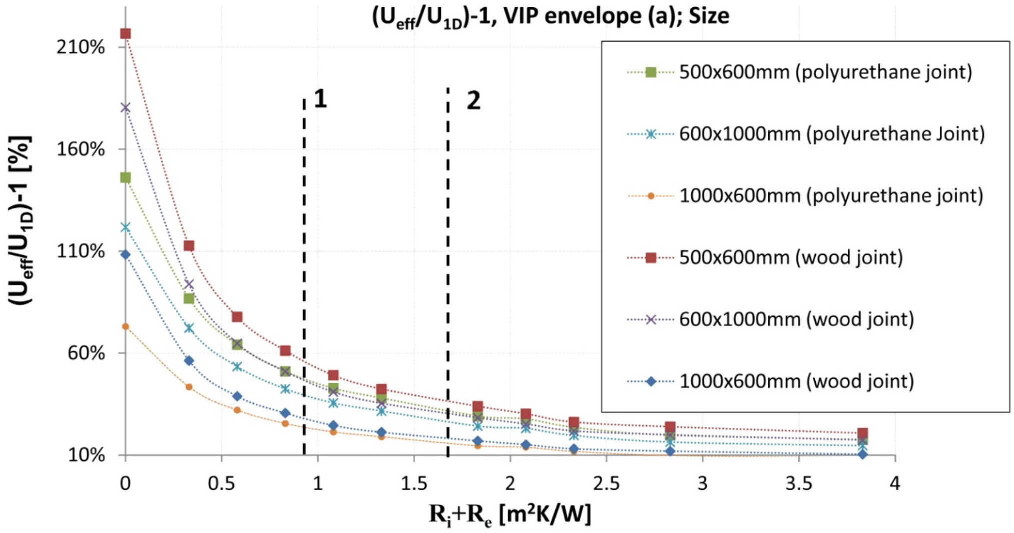

Figure 10. (U_{eff}/U_{1D})-1 values for VIP panel envelope (a) for three different sizes and shapes.

5. Conclusions

Super-insulation materials show promising features and can be/constitute an effective solution for the energy retrofitting of existing buildings as well as for the construction of new highly efficient houses, without compromising space utilization. They, in fact, allow very low U-values to be reached with reduced wall thicknesses.

Nevertheless, the use of VIPs also represents a challenge for engineers and architects. The rating of the performance of the material, through the center of panel equivalent thermal conductivity alone, is insufficient to provide designers with information that is useful to represent the actual behavior of VIPs when applied to real buildings. Moreover, the laboratory measurement of λ_{COP} can reveal to be tricky, due to its very low value. On the basis of the outcomes obtained from the research developed so far, it is possible to highlight that the following key points need to be considered carefully when VIP panels are used in wall construction:

(1) reliability of the declared nominal thermal conductivity of the panel;
(2) durability and performance decay due to vacuum loss;
(3) assessment of the overall, actual performance of the whole wall system (with multiple layers and joints).

As far as the first topic is concerned, it should be pointed out that the measurement of the equivalent thermal conductivity at the center of panel (a parameter which is typically/frequently used to label traditional insulation materials), though apparently trivial, is in practice quite difficult to carry out in an accurate way. The very low thermal conductivity of the material under analysis, in fact, poses many challenges to certified laboratories and the resulting measurement accuracy needs to be assessed carefully during each test (for all the tests performed in the present study, the accuracy was around 2%–3%). In order to assure a proper accuracy and repeatability of the tests, care needs to be taken in the choice of the sample size, sample positioning and measurement conditions (e.g., temperature differences).

The experience attained on five different VIP panels has shown that the measurement repeatability was almost always satisfactory (just for one case was the variability between two tests similar to the measurement accuracy). However, it should be underlined that measurements repeated for different samples of/on the same VIP material (same manufacturer, same panel type) sometimes provided significantly dissimilar values of λ_{COP}. The most evident case is the one related to "Manufacturer A—panel type 1". For this material, tests performed on five, theoretically identical samples showed λ_{COP} values ranging from 0.0026 W/mK to 0.0047 W/mK. The results for the other panel types also presented a remarkably high variability of the samples.

The reason for such behavior can be due to both the construction process (not sufficient constancy of the manufacturing process, e.g., a probable degree of vacuum that can change from one panel to the other) or to a variability of the measurement conditions. As far as this last issue is concerned, it should in fact be noted that the surface of VIP panels is never perfectly even or flat, and this could determine a variability of the contact thermal resistances between the hot/cold plates of the measurement apparatus and the sample under test. Such variability can determine a non-negligible variation of λ_{COP} for different samples of the same material.

Further research is needed in relation to this point, since λ_{COP} is a parameter that is universally adopted to score the performance of super-insulation material and which therefore has a huge impact on the material market and on the design processes.

The performance decay due to loss of vacuum (which can occur either during the installation process, because of mechanical damage, or during the operational phase, for ageing) implies an increase in the equivalent thermal conductivity of the super-insulation panel of about 400%–500% with respect/compared to the pristine material. The findings obtained during the present research have confirmed some previous studies and point out that attention should be paid to VIP durability.

Nevertheless, it is worth noting that, even when damaged, a VIP panel has a lower equivalent thermal conductivity than the best traditional insulation materials currently on the market.

Finally, the effects of the actual installation process, which implies the use of structural joints to fix the boards and at least one external and one internal layer between which the VIP panel is located/positioned, are significant for the ultimate performance of a wall and must be assessed properly.

It has been demonstrated that a significant underestimation of VIP performance, at the building level, is obtained if this assessment is not conducted in an appropriate way.

The most important parameters that can affect the ψ values of the thermal bridges, due to structural joints, in actual applications are: the overall thermal resistance of the wall, the thermal properties of the joint and the thermal conductivity of the VIP envelope.

In short, in order to correctly evaluate the economic and energy effectiveness that can be achieved using high performance insulation materials in real building applications, it is impossible to either disregard the thermal bridging effect or neglect the specific structure of the wall in which the panel is inserted.

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Author Contributions

The research presented in this paper was a collaborative effort made by all the authors. All the authors contributed to the literature review, development, implementation, experimental and numerical analyses.

Nomenclature

B	Panel width [m]
d_p	VIP panel thickness [m]
l_p	Thermal bridge length [m]
$\dot{Q}$	Actual heat flux through the panel with joints [W]
$\dot{Q}_{COP}$	Center of panel heat flux (heat flux through a homogeneous panel without joints [W]
R_{Tot}	Total thermal resistance of the two boundary layers $R_i + R_e$ [m^2K/W]
R_i	Thermal resistance of the internal boundary layer [m^2K/W]
R_e	Thermal resistance of the external boundary layer [m^2K/W]
S_p	Surface of the panel [m^2]
U_{eff}	Effective thermal transmittance [W/m^2K]
U_{1D}	Thermal transmittance of the homogeneous panel (center of panel thermal transmittance) [W/m^2K]
α_i	Internal surface thermal resistance [m^2K/W]
α_e	External surface thermal resistance [m^2K/W]
λ_{COP}	VIP center of panel equivalent thermal conductivity [W/mK]
$\lambda_{eff,VIP}$	Effective thermal conductivity [W/mK]
λ_{PU}	Polyurethane thermal conductivity [W/mK]
λ_{wood}	Wood thermal conductivity [W/mK]
Ψ_{VIP}	Linear thermal transmittance of the thermal bridge [W/mK]
θ_i	Internal temperature [°C]
θ_e	External temperature [°C]
$q = \frac{\dot{Q}}{l_p}$	Heat flux per unit length [W/m]
$q_{COP} = \frac{\dot{Q}_{COP}}{l_p}$	Center of panel heat flux per unit length [W/m]
i	Internal
e	External

Conflicts of Interest

The authors declare no conflict of interest.

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