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The effect of different materials joint in Vacuum Insulation Panels

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Abstract

During recent years the use of Vacuum Insulation Panels in buildings applications has been improved, because of their both higher performances and lower thickness compared to traditional insulation materials.
These performances are due to the interior vacuum degree, which represent also the main problem connected with the applications of this technological solution in buildings constructions: to maintain the vacuum condition the panels are enclosed in an envelope layer, characterized by an higher thermal conductivity. Moreover they have to be assembled to each other or to additional different joint materials in practical building application, generating a thermal bridging effect.
The aim of present work is to analyse the critical aspects related to this insulation technology for building application.
An experimental campaign through heat flow meter apparatus was carried out with the purpose of assessing the decrease of performance due to the thermal bridges effects considering different joint materials in VIPs assemblies.

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Keywords: vacuum insulation; joint; thermal bridge effects; equivalent thermal conductivity; linear thermal conductivity; heat flow meter.

1. Introduction

During lasts years European Government intensified debates on energetic approach and objectives, proposing several directives that converge in “20-20-20 Strategy” (in actualization of Kyoto Protocol).

This strategy, named also “Climate and energy package” set three key purpose for 2020:

- 20% reduction of CO_2 emissions, compared to 1990 levels;
- 20% improvement in energy efficiency;
- 20% improvement of energy consumption produced from renewable resources.

MSE (italian Ministero Sviluppo Economico) data show that the most percentage of energy employ (about 35-40%) is relative to civil uses: for this reason buildings energy consumption reduction is the sector where is expected a greater margin of improvement. Indeed, as shown in [1], 2010 annual energy savings achieved in building sector was about 50% more than estimated one, but the global energy saving in the same year was 9% less than that imposed by the guideline.

However a reduction in heating and cooling energy consumptions is therefore essential considering the high potential in building energy efficiency improvement. To achieve this goal one of the main issue is to reduce the heat losses through the building envelope, with high performance insulated materials or technologies. Vacuum Insulation Panels (VIPs) are characterized by a thermal conductivity 5-10 times lower than the traditional insulating materials (λ_{cop} is about 0.003-0.005W/mK). However their application is still very braking due to the high cost, high energy demand in the production phase, shorter lasting than buildings life, lack of experience in assembling and little knowledge about their thermal assessment in real building applications.

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Nomenclature

λ_{cop}	Centre of panel thermal conductivity	[W/mK]
λ_{eq}	Equivalent thermal conductivity of VIPs assembly, measured by heat flow-meter	[W/mK]
λ_{joint}	Thermal conductivity of structural joint material	[W/mK]
$\lambda_{eq,air\ cavity}$	Thermal conductivity of air cavity between two adjacent panels	[W/mK]
R_{joint}	Thermal resistance of structural joint material	[m^2K/W]
$R_{eq,air\ cavity}$	Thermal resistance of air cavity between two adjacent panels	[m^2K/W]
ψ	Thermal bridge linear thermal conductivity	[W/mK]
R	Thermal resistance of VIPs assembly, measured by heat flow-meter	[m^2K/W]
A	Panel area	[m^2]
P	Panel semi-perimeter	[m]
s	Panel thickness	[m]
ϑ_{low}	Set point temperature of lower plate of heat flow-meter	[°C][K]
ϑ_{up}	Set point temperature of upper plate of heat flow-meter	[°C][K]
ϑ_{avg}	Average temperature between ϑ_{low} and ϑ_{up}	[°C][K]
$\Delta\vartheta$	Difference between ϑ_{low} and ϑ_{up}	[°C][K]
$\dot{Q}$	Heat flow measured by heat flow-meter	[W]
d	Air cavity width	[m]

2. State of the art

Since 1930 numerous studies on vacuum thermal insulation properties, their possible applications and the resulting effects were carried out. Most of the past literature were related to the optimization of the panel properties, as the type of core ([2]; [3]) and envelope materials ([4]; [5]; [6]). These studies were performed considering also the vacuum degradation due to gas and water vapour permeation, risk of damage (VIP perforation) and environmental impact ([7]). In this phase, panels with fumed silica core and envelope consisting in three barrier layers metalized films result the most used solution. For this type of VIP was found a thermal conductivity reference value equal to λ_{cop}=0.003-0.005W/mK (depending on the vacuum degree) ([3]). However new core materials and envelope solutions are being studied, in order to maximize the VIPs thermal performance.

The big potential of the application of this technological solution generate a second research phase (in progress), to understand its effective thermal behaviour in buildings construction. Several experimental, numerical and analytical investigations were proposed, as well as real measurements on site. Some of them were focused on real performances of a VIP ([4]) while others about VIP assemblies ([6]). But the aspect that has attracted more attention of researchers, concerns the decrease of performance due to the thermal bridges, necessarily caused by the particular shape of the panel. This interest is due to the fact that the greater the material insulating power, the greater the impact on the overall performance of the thermal bridging effect. Simmler and Brunner (2005) [2] mathematically characterized design values for VIPs including thermal bridge and ageing effects.

With greater detail, thermal bridging effects can be divided into three categories: thermal bridges due to VIP envelope, due to air gap between two adjacent envelopes and thermal bridges on the scale of building component due to structural joints. The thermal bridges due to VIP envelope were analytically an numerically investigated in [7], considering four parameters that influences the linear thermal transmittance: laminate thickness, laminate thermal conductivity, core material thermal conductivity and panel thickness.

Other researchers proposed various solutions for thermal bridging effect reduction ([7];[8];[9]).

Finally, the structural thermal bridges has the largest influences on the overall thermal properties of a VIPs assembly. The study on the effect of structural thermal bridge was poorly investigated. To this purpose few case studies of buildings were realized, where VIPs have been used both in energy refurbishment and in new construction (some of them are summarized in [10]). Fantucci et al. [11] characterized by numerical simulation the effect of thermal bridging for VIP panels layers in real current use building applications, where the VIP is typically coupled to other boards.

Moreover these studies did not clearly define relationships between VIPs performances and the effects of assembly joints. The aim of this work is to investigate VIPs thermal behaviour, in relation to thermal bridging effects due to their installation, and the interaction with air joints and other structural joint materials.

2.1. VIPs in real buildings application

There are several use cases of VIP in buildings, both in new construction and refurbishment, in order to improve thermal insulation of building envelope and internal or external partitions, both vertical and horizontal [12].

In case of vertical component insulation, is necessary to provide a mounting and support systems to the structure for VIPs. This can be made (analyzing the literature) with laths and battens in different materials (like MDF and XPS), with metal and plastic rail system, or with plaster and adhesives. For roofs, floors and horizontal surface panels are instead put close each other without additional structural support: so only air joint have to be considered. Additional protection layers (for example polyurethane foam) above and below the panels are necessary to distribute the loads, and a double sealant layer is useful to secure enough moisture sealing on top of the panels.

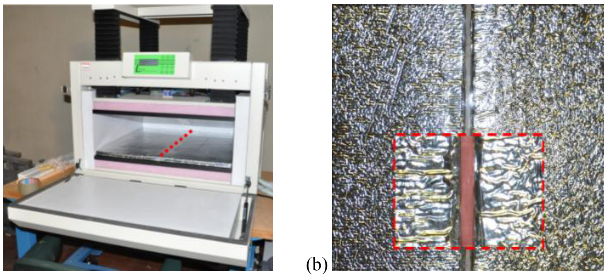
The structure should be suitable for easy replacing, and panels should not be coated with conductive materials on both side, in order to simplify the individuation of damaged VIP (for example with thermography). For the same reason, a dry assembling system is always preferable.

A method to limit damage risk during installation is to encapsulate VIPs into prefabricated elements.

3. Methods and methodology

VIPs assembly thermal properties depends on several geometrical and physical factors, like thermal resistance of VIPs and their dimensions, boundary conditions, assembling methods (air joints or structural joints). In order to assess the effective assemblies equivalent thermal conductivity, an experimental campaign was carried out.

Laboratory measurements were performed to assess the thermal conductivity of different VIPs samples (with different dimensions and conformations). Measures were carried out with a heat flow-meter apparatus in accordance with the international standard UNI - EN 12667:2002 [13]. The apparatus consists in a single heat flow-meter with guarded ring “LASERCOMP FOX600” (Fig. 1) equipped with two plates containing heat flow meters placed above and below the sample.



(a) (b)

Fig. 1. (a) LASERCOMP FOX600; (b) specimens sample

Detailed specifications of the equipment are shown in Table 1.

Table 1. LASERCOMP FOX600 specifications.

Accuracy	~1%
Reproducibility	~0.5%
Temperature control stability	~ +/- 0.03 °C
Thickness measurement precision	~ +/- 0.025 mm
Maximum sample size	~ 610x610 mm
Actual measuring area	254x254 mm

The instrument was designed and realized in accordance with ASTMC518-91 Standard [14], and was calibrated with calibration reference samples “1450b NIST SRM” and EPS sample (high accuracy expanded polystyrene). The samples were previously tested and certified by NIST.

The accuracies of the measured thermal conductivities were determined for each measurement. The resulting accuracy values were within ±2%, according to EN-ISO 12667 (annex B) [13].

The measurement principle was to create a constant temperature difference between the upper plate and lower plate and to measure specific heat flow and surface temperatures in steady state condition.

The hot plate provides the value of the thermal resistance R as a function of measured thickness: to calculate the equivalent thermal conductivity λ_{eq} of the assembly (two panels coupled trough a joint), based on nominal thickness s, it was used the following relation:

$$\lambda_{eq} = \frac{s}{R} \quad (1)$$

To make the thermal properties independent from the size of the panels, it was calculated the linear thermal conductivity ψ:

$$\psi = \frac{\dot{Q} - \frac{\lambda_{cop}}{s} \cdot A \cdot \Delta\vartheta}{l \cdot \Delta\vartheta} \quad (2)$$

where:

$$\dot{Q} = \frac{\lambda_{eq}}{s} \cdot A \cdot \Delta\vartheta \quad (3)$$

Plates size is 600x600mm, but measure area is restricted to a central area of 254x254mm (Fig. 2a).

The surveys were carried out on panels having a size of 600x300mm, and with different types of joint materials: air joint (considering different width), MDF (medium density fiberboard), XPS (extruded polystyrene) and rubber. With the exception of rubber, other materials can be really used in buildings application. Rubber was chosen to analyse the VIP performance with an high thermal conductive joint. Indeed the rubber thermal conductivity λ_{Rubber} is around seven times higher than λ_{XPS}, and three times than $\lambda_{MDF.}$ In structural joints the width was maintained constantly equal to 36mm, in accordance with the results obtained in [15]. In air joints the most influential variable on the VIPs assembly performance is instead the joint width. For this reason four different spacers between the panels were considered.

In order to establish the influence of air gap dimensions on the VIP equivalent thermal conductivity λ_{eq} the experimental measurement of the air joint width was necessary. A photographic survey was carried out for this purpose, as shown in Fig. 2c.

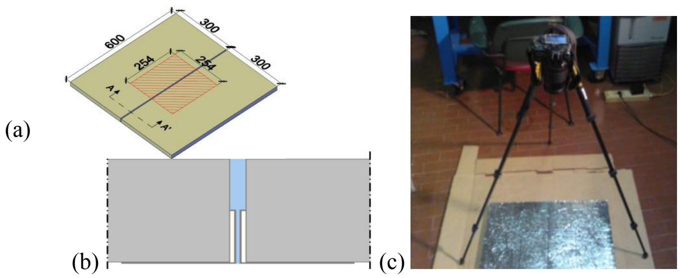


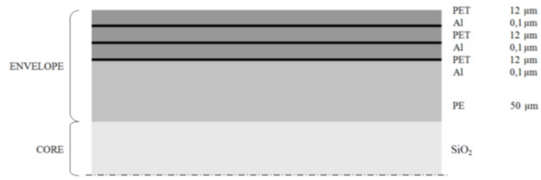
Fig. 2. Experimental investigation: (a) controlled area, (b) section A-A' with individuation of air joint width measured by photographic survey; (c) photographic survey apparatus.

Panels jointed were photographed with an high resolution camera (image sensor of 12.3 megapixels), zoomed on the control area to maximize picture quality. Photos were straightened with a photo editing software, and then imported on CAD software for measurement, joint area was measured by edge retracing with a close polygonal line. To obtain the average width, this area was divided by the only known data, namely the length of the joint (or the measurement area) equal to 254mm.

Considering the welds panels conformation (Fig. 2b), this procedure was performed on the side in which the joint would have greater width.

Tests were done on MF3 panels (envelope composed with three layers of PET + Aluminium and one of PE), which have the thermal properties shown in Table 2.

Table 2. Layers thermal conductivities

Panel section stratigraphy	Panel type **MF3**	**s** [μm]	**λ** [W/mK]
	**PET**	12	0.19
	Al	0.1	160
	PET	12	0.19
	Al	0.1	160
	PET	12	0.19
	Al	0.1	160
	PE	50	0.33
	SiO_2 core	20000	0.004615*

*thermal conductivity in vacuum condition

Thermal conductivities of the various specimens (VIPs and structural joint materials) were severaly previously experimentally determined with heat flow meter apparatus.

Three tests for structural joints and four for air joints were therefore carried out considering 20mm panel thickness.

Set point temperatures were kept constant during all the tests: ϑ_{low}=35°C=308K and ϑ_{up}=15°C=288K (ϑ_{avg}=25°C=298K). No internal and external surface resistances were considered.

In order to prevent condensation between panels during tests, joints were sealed with adhesive tape.

4. Results

The experimental investigation show that the VIPs assemblies thermal behavior strictly depends on physical and geometrical properties. Results are summarized in Table 3 and

Table 4, for structural and air joints respectively.

Table 3. Structural joint: λ_{eq} (panel dimensions 254x254mm) and ψ

s [mm]	Joint Material	λ_{joint} [W/mK]	R_{joint} [m2K/W]	λ_{eq} [W/mK]	ψ [W/mK]
20	XPS	0.0350	5.7090	0.0108	0.0787
	MDF	0.1034	1.9340	0.0206	0.2031
	Rubber	0.2053	0.9742	0.0321	0.3491

Table 4. Air joint: λ_{eq} (panel dimensions 254x254mm) and ψ

s [mm]	d [mm]	d/s [mm]	$\lambda_{Air\ joint}$ [W/mK]	$R_{Air\ joint}$ [W/mK]	λ_{eq} [W/mK]	ψ [W/mK]
20	1.97	0.099	0.093	0.215	0.0066	0.0255
	3.47	0.174	0.111	0.180	0.0069	0.0284
	5.60	0.280	0.120	0.167	0.0077	0.0391
	6.67	0.334	0.123	0.163	0.0087	0.0519

Fig. 3 show the influence of the thermal resistance of the material joint (R_{joint}) both on ψ and λ_{eq}.

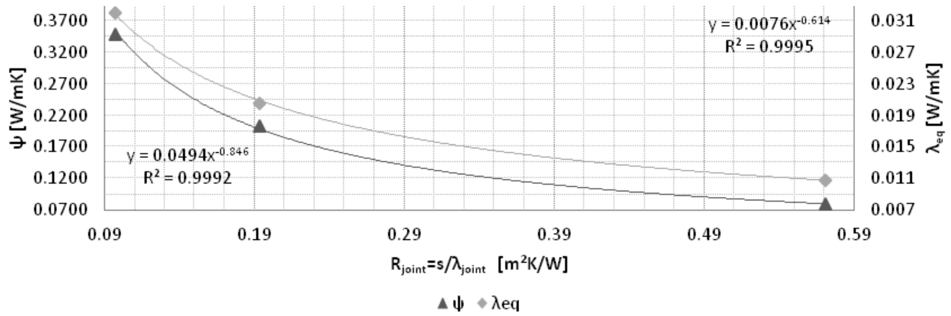


Fig. 3. Structural joint: ψ and λ_{eq} in function of R_{joint} (254mm joint length)

With the increasing of λ_{joint} the assembly thermal properties get worsted. λ_{Rubber} is about 6 times higher than λ_{XPS}: resulting an increasing around 300% for λ_{eq} (for 254x254mm panels) and 450% for ψ.

The most influencing variable for the air joint is the joint width "d". A three time increasing of this element generate an increase of linear thermal transmittance of above 200%, as shown in Fig. 4, where:

- Best Case is used to indicate the thinnest air joint obtained in laboratory (around 2.7mm);
- Realistic Case is the most probable value obtainable in construction site (around 3.5mm);
- Worst Case identify a badly done joint (around 5.6mm).

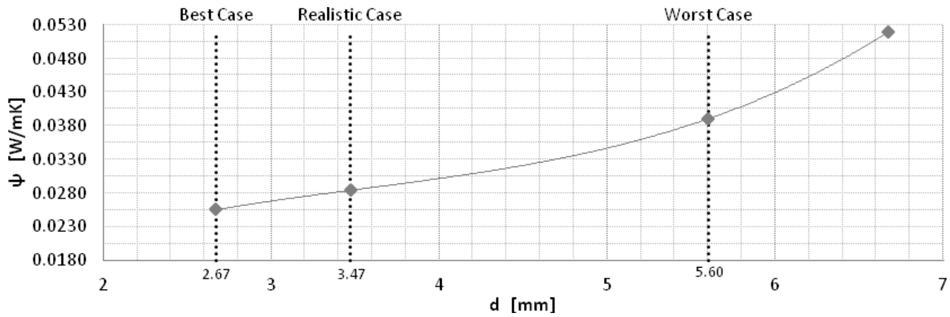


Fig. 4. Air joint: ψ in function of "d" (joint width)

The λ_{eq} results above presented are related to 254x254mm measuring area: in order to obtain values for VIP dimension more realistic at buildings scale, an analysis related to the form factor was conducted. Form factor is the P/A ratio, where P is the panel emi-perimeter [m] and A is the panel surface [m^2]. This survey can be also useful to understand the reliability of $\lambda_{eq\ producer}$=0.007W/mK, which is the λ_{eq} proposed by producer to take into account in a simplify way the thermal bridging effects in VIPs applications. Indeed in Figure 5 is reported the relationship between λ_{eq} and P/A ratio, related to air joints and structural joints (MDF and XPS), where the vertical dot lines are the standard production dimensions, and the horizontal single and double dot dashed line represent the $\lambda_{eq\ producer}$ and λ_{cop} values respectively.

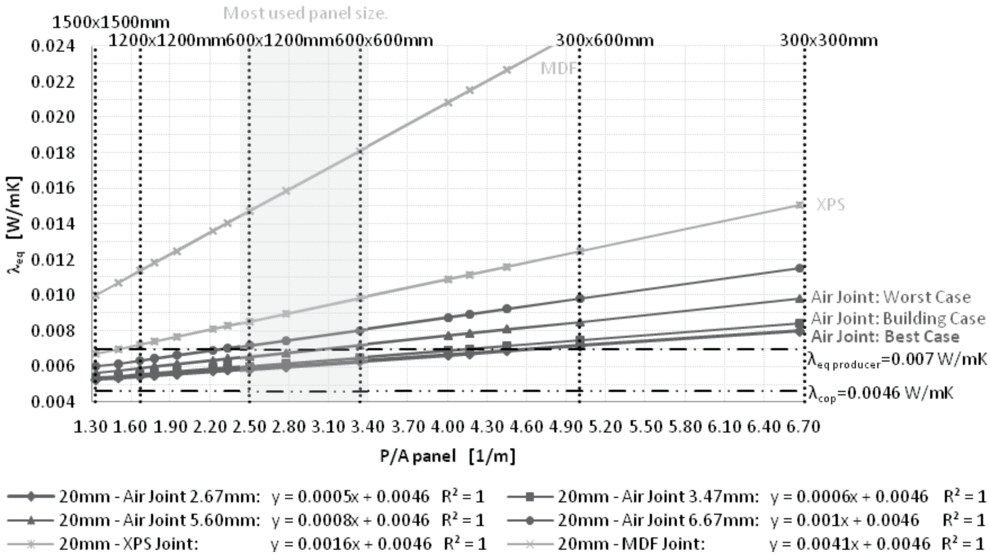


Fig. 5. λ_{eq} in function of panel dimensions P/A, with identification of most used panel size (600x600mm and 600x1200mm)

Complete results are reported in Table 5 and Table 6, where the difference between λ_{eq} and λ_{cop} are calculated for different panels dimensions.

Table 5. Increasing of λ_{eq} compared to λ_{cop} for each type of joint tested, and related to panels dimensions

s [mm]	Panel dimension [mm]	λ_{cop} [W/mK]	Air Joint 2.67mm (Best Case)	Air Joint 3.47mm (Realistic Case)	Air Joint 5.60mm (Worst Case)	Air Joint 6.67mm	XPS Joint	MDF Joint	RUBBER Joint
20	300x300	0.0046	42%	45%	53%	60%	69%	85%	91%
	300x600		36%	38%	46%	53%	63%	81%	88%
	600x600		27%	29%	36%	43%	53%	75%	83%
	600x1200		22%	24%	30%	36%	46%	69%	79%
	1200x1200		16%	17%	22%	27%	36%	59%	72%
	1500x1500		13%	14%	18%	23%	31%	54%	67%

The difference between λ_{eq} and λ_{cop} is always significant and not negligible, and it ranges from a minimum of 13% from a maximum of 91% as a function of types and materials of joint considered. Assuming that VIPs most employed in construction have average dimensions of those analyzed (600x600mm and 600x1200mm), the variation is reduced from around 20% to 80%.

Especially, for structural joints, an extension in panel sizes of 25 times (from 300x300mm to 1500x1500mm) caused a decrease in equivalent thermal conductivity from approximately 70% (Rubber) to 55% (XPS, which is less sensible to the panel size effects for his better thermal resistance). Similar variations were observed changing joint material, from Rubber to XPS, with the same panel dimensions (70% for 300x300mm and 50% for 1500x1500mm). At the typical dimensions for building purposes (600x600mm and 600x1200mm), the λ_{eq} increase respectively approximately from 55% to 45% for XPS joint, and from 75% to 70% for MDF joint.

Air joint caused a lower increase of λ_{eq}, because of their thinner width: considering the references dimensions, variation is from 30% - 25% (2.67mm Air joint – Best Condition) to 45% - 35% (6,67mm Air joint). Increasing the air joint width by a factor 2.5 correspond therefore to a λ_{eq} increase from 45% (smaller panels) to 15% (larger panels, which are less sensible to thermal bridging effects). Furthermore an extension on panel size of 25 times (from 300x300mm to 1500x1500mm) causes a decrease in equivalent thermal conductivity of 35% (in Realistic case).

5. Conclusions

The influence of joints in thermal performances of assemblies is always not negligible, and, for typical panels dimensions (600x600mm and 600x1200mm) causes an increase in λ_{eq} from 25% to 75% (in function of type of joint), compared with λ_{cop}, as shown in Table 6.

Table 6. Increasing of λ_{eq} compared to λ_{cop} for typical building joints and panels dimensions

s [mm]	Panel dimension [mm]	λ_{cop} [W/mK]	Air Joint 3,47mm (Realistic Case)	XPS Joint	MDF Joint
20	600x600	0.0046	29%	53%	75%
	600x1200		24%	46%	69%

Another important consideration concerns the precautionary values $\lambda_{eq\ producer}$=0.007W/mK which producers suggest to use in VIPs applications thermal analysis (Fig. 5). The λ_{cop} value is exceeded in almost all cases, in particular for air joint between panels which have a P/A ratio lesser than around 4.5, and for structural joints. For this reason $\lambda_{eq\ producer}$ is not reliable for practical cases.

The thermal properties of the VIPs are extremely variable depending on many factors (including panels size and joint materials, analyzed in this paper), which can reduce the insulating power of the VIP, thus losing all advantages in using this type of insulating system. For these reasons, a calculation method should be realized, to take into account all the most influential variables, in order to obtain reliable values of λ_{eq} or ψ, usable for the determination of the building components thermal behaviour.

The paper shows how the joint technologies affect the thermal performances of VIPs assemblies. It represent a first step for the definition of an empirical model, based on experimental and numerical results, for the determination of VIPs thermal assessment in real building applications.

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