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The effect of temperature on thermal performance of fumed silica based Vacuum Insulation Panels for buildings

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Abstract

Vacuum Insulation Panels are characterized by very low thermal conductivity, which makes them alluring for building and civil sectors. However, considering the structure and composition of these materials, their application in buildings may be defined by a number of issues which need to be properly taken into account. The real performance of VIPs can be influenced by the boundary conditions (e.g. temperature) at which they work during their operation. In this paper experimental analyses aimed at characterising the relationship between the centre of panel thermal conductivity and average temperature were carried out. The experiments were performed on two VIP samples with different thickness. Moreover a comparison with non-evacuated panels and a traditional insulating material was performed.

Peer-review under responsibility of KES International.
Keywords: Vacuum Insulation Panels; fumed silica pressed board, thermal conductivity; temperatures; guarded heat-flux meter.

1. Introduction

In the last years Vacuum Insulation Panels (VIPs) are gaining relevant interest in the building sector and, in particular, in the energy efficient refurbishment of buildings, where space saving is becoming an important aspect to be considered in the selection of insulating materials.

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Vacuum Insulation Panels (VIPs) are generally composed by silica powder, a core material of polyurthane foams or glass/mineral fibres, and a sealed barrier envelope in which a certain vacuum degree (generally between 0.1 and 10 mbar) is created.

The heat transfer mechanism in porous media (such as the VIPs core) is generally described in the literature [1,2,3,4] as the sum of the contribution of the solid thermal conductivity (λ_s), the radiative thermal conductivity (λ_r), the gaseous thermal conductivity (λ_g) and the coupling effect (λ_{cpl}), as shown in Eq.1:

$$\lambda_{tot} = \lambda_s + \lambda_r + \lambda_g \left(+ \lambda_{cpl} \right) \quad (1)$$

The basic principle of VIPs technology is to evacuate the core material to reach pressure values low enough to obtain Knudsten number $Kn \geq 1$ (the Knudsten number is calculated as the ratio of the mean free path of the gas molecule and the characteristic size of the porous media). In this way the gaseous thermal conductivity (λ_g) can be neglected and the resulting total thermal conductivity mainly depends on the contribution of the solid conduction and the infra-red radiation in the pores.

The application of VIPs in the building sector may be characterised by a series of issues which need to be properly faced and analysed in order to investigate their impact and to find potential solutions. In particular, the evaluation of the actual thermal performance of VIPs, when they are used in real building applications, could be very different from the performance measured in laboratory in terms of centre of panel thermal conductivity.

The following two main phenomena influencing the performance of VIPs have been investigated in literature in the last few years: i) the thermal bridging effect determined by the relatively higher thermal conductivity of envelope and/or materials used to couple the panels, and ii) the ageing effect.

The thermal bridging effect in VIPs was widely discussed in literature at both material/component level [5,6,7] and building level [8,9,10,11].

The service life of VIPs when they work in real building applications remains a key issue to face. The ageing mechanism could produce a rapid decay of total thermal conductivity due to the increase in pressure and moisture content inside the panel over time [12,13]. Several works were focused on the prediction of VIPs service life, and on the development of linear model for the determination of the increase in moisture content [14].

A further aspect to be properly investigated is the effect of relatively high temperatures on the actual thermal performance of panels. VIPs can reach high temperatures when they are exposed to the external environment (e.g. in sun-exposed façade VIPs could work at temperatures also higher than 60°C). Temperatures in the range 30 – 60°C (typical in building applications) could negatively affect the thermal conductivity of VIPs and this phenomenon needs to be further investigated through experimental analyses. Moreover, it can be observed that at constant pressure the main factor which determines an increase of the total thermal conductivity is assumed to be the radiative contribution [15].

In this paper, results of numerical simulations and experimental campaigns conducted by means of a Guarded Heat Flux Meter apparatus (GHFM) on fumed silica based VIPs are presented. The objective of this research activity is to experimentally demonstrate that, also in the typical range of values in building applications, the centre of panel thermal conductivity of fumed silica VIP is influenced by the boundary temperature at which it can work [16]. For this purpose, a preliminary numerical analysis was conducted to find the area of influence of the edge and lateral thermal losses effects for the analysed VIPs. This kind of analysis is useful to verify that a correct measurement of centre of panel thermal conductivity can be performed considering exclusively the centre of panel area. After that, a set of measurements of centre of panel thermal conductivity of different VIPs were carried out, considering different temperatures of hot and cold plates of GHFM while maintaining the same temperature difference. Moreover, the same analysis was conducted for non-evacuated insulating materials (fumed silica pressed board and extruded polystyrene – XPS) in order to investigate the different thermal behaviour of thermal conductivity as a function of average temperature.

Nomenclature

λ_s	solid thermal conductivity	[W/mK]
λ_r	radiative thermal conductivity	[W/mK]
λ_g	gaseous thermal conductivity	[W/mK]
λ_{cpl}	thermal conductivity (coupling effect)	[W/mK]
λ_{tot}	total thermal conductivity	[W/mK]
λ_{cop}	centre of panel thermal conductivity	[W/mK]
ϑ_{avg}	average temperature	[°C]
$\Delta\vartheta$	temperature difference	[°C]
φ	specific heat flux	[W/m^2]
A_m	instrument metering area	[m^2]
ϑ_{hot}	hot plate temperature	[°C]
ϑ_{cold}	cold plate temperature	[°C]
s	specimen thickness	[m]
u	measurement uncertainty	[%]
$\Delta\lambda$	variation of thermal conductivity	[W/mK]

1.1. State of the art on Fumed Silica based VIPs

One of the most common materials used as VIPs core is represented by nanoporous silica materials. This family of materials includes fumed silica, precipitated silica and granular aerogel. Fumed Silica (FS) has his largest pore size of ~ 300 nm that is in the same order of magnitude of the mean free path of the air molecule at ambient temperature and pressure. For this reason, the gas conduction λ_g is drastically reduced even at atmospheric pressure [2,15]. Moreover, since opacifier (silicon carbide powder, or titanium dioxide) contribute to reduce the radiative heat transfer, a total thermal conductivity in the range 0.019 - 0.020 W/mK can be reached (lower than the conductivity of dry air ~ 0.025 W/mK) [17].

Due to the small pore size, a gas pressure below 10 mbar is in general sufficient to suppress the λ_g, while in other materials (foams and fibres) a pressure value below 0.2 mbar is needed to obtain this effect [17].

Thanks to their properties, fumed silica based VIPs show many advantages in building applications, as the followings [3]:

- High life expectancy is poorly sensitive to the increase in pressure because the critical pressure value ranges between 10 and 20 mbar. This value is considerably higher than the critical pressure needed with other core materials.
- In case of total loss of vacuum (e.g. puncturing), the thermal conductivity remains relatively low considering that fumed silica is characterized by a value of thermal conductivity which is half compared to traditional insulating materials.

In recent years several studies aimed at investigating the heat transfer mechanism in fumed silica based VIPs are reported in literature [15,17,18,19,20]. The dependence of thermal conductivity on the internal gas pressure for different core materials is reported in [21], while the variation of thermal conductivity over time for different VIP envelope typologies is analysed in [22]. All the studies show values of λ_{s+r} ranging between 3.6 and 4.4 mW/mK, while a value of 0.04 mW/mK at pressure level of 1 mbar is reported for λ_g. Anyway, most of the manufacturers declare a $\lambda_{tot} \leq 5$ mW/mK for FS based VIPs (which is a typical value at a pressure of 10 mbar) [23].

2. Methods and methodology

The objective of this study is to investigate through experimental measurements the relationship between the average temperature and centre of panel thermal conductivity of fumed silica VIPs, considering the typical range of temperatures in building applications.

In order to carry out a comprehensive analysis, two specimens of fumed silica based VIPs characterised by two different thicknesses (10 and 30 mm) were analysed. The performance of samples were measured in two different stages: when they were fresh (as delivered by the producer), and after they were stored in a laboratory for 32 months at a temperature ranging between 18 and 30°C. Also non-evacuated insulating materials were measured, in order to compare their thermal behavior with that one of the VIPs.

For this purpose two different investigations were carried out:

- Numerical 2D simulations were performed in order to quantify the area influenced by edge effects and lateral heat losses for the analysed samples. This analysis was useful to verify if lateral heat losses and thermal bridging effect could produce a deviation from the 1D heat flux in the metering area of GHFM. This numerical analysis was carried out considering the same boundary conditions adopted in the subsequent experimental measurements.
- Experimental analyses were carried out to measure the centre of panel thermal conductivity of different insulating materials under several average boundary temperature conditions.

2.1. Numerical analysis on edge and lateral heat losses effects

A significant criticism in the measurement of centre of panel thermal conductivity by means of GHFM is represented by potential heat losses through the edges of the specimens. For this reason the apparatus plates consist of a central metering area (A_m), into which the thermocouples and heat flow sensors are distributed, surrounded by an outer guard ring that reduces the lateral heat losses. Indeed, the apparatus is equipped with a hermetic closure and insulation in order to prevent interactions with the external laboratory environment.

Some numerical analyses were carried out to verify whether the specimen surfaces were characterized by a constant temperature distribution in correspondence of the GHFM apparatus metering area.

This kind of analysis became necessary because the experimental measurements of VIPs thermal conductivity were performed with an average temperature of the plates much higher than the temperature of the surrounding environment (laboratory).

The objective was to determine whether, in case of VIPs, the lateral heat losses and the thermal bridging effects (due to the relatively high thermal conductivity of envelope) can be considered negligible in the metering area.

The numerical model was developed through the Physibel BISCO software, according to the same criteria explained in [5]. Half GHFM was modelled (symmetric configuration), considering a thermal conductivity for the outer insulation guard ring of 0.05 W/mK and a temperature of the laboratory equal to 20°C (Fig. 1). Temperatures of plates were imposed equal to the hottest and coldest values of average temperature considered in the experimental campaigns (ϑ_{avg} = 2.5°C and 52.5°C with $\Delta\vartheta$ = 25°C). Both the 10 mm and 30 mm thick specimens were analysed.

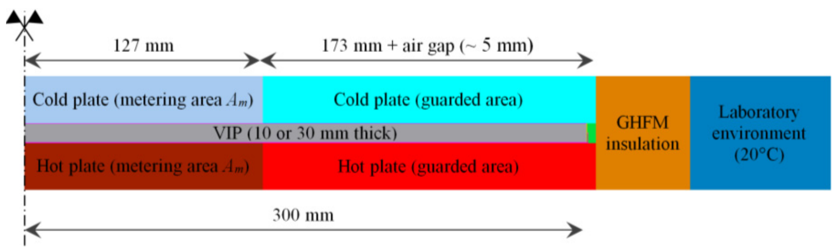

Fig. 1. Model for 2D numerical analyses.

2.2. Experimental measurement of the thermal conductivity

The experimental investigations were carried out by means of a “Lasercomp FOX600” Guarded Heat Flux Meter. The GHFM method defines the global heat transfer through flat slab specimens and the calculation of its thermal properties (resistance and conductivity) in accordance with EN ISO 12667:2001 [24].

The general measuring method is based on the one-dimensional Fourier-Biot law:

$$\varphi = \lambda_{cop}\left(\frac{\Delta\vartheta}{s}\right) = \lambda_{cop}\left(\frac{\vartheta_{hot} - \vartheta_{cold}}{s}\right) \quad (2)$$

where φ is the measured specific heat flux through the sample in the metering area (A_m) [W/m^2], λ_{cop} is the sample thermal conductivity [W/mK], $\Delta\vartheta$ is temperature gradient between the hot and cold plates [°C] and s is the sample thickness [m] measured by the apparatus.

The main objective of the experiments was to assess the effect of the temperature on the centre of panel thermal conductivity for different VIPs (evacuated and non-evacuated) and for a traditional insulating material. In particular, the tests were carried out on fresh VIPs (as delivered by the producer) and on the same panels after they were stored in the laboratory for 32 months. Moreover, a comparison with non-evacuated insulating materials (punctured VIP, fumed silica pressed board and extruded polystyrene - XPS) was performed.

Each sample was measured at different average temperatures ϑ_{avg} (mean temperature between hot and cold plates of the GHFM) ranging between 2.5°C and 52.5°C, maintaining the same temperature difference between the plates. The temperature difference $\Delta\vartheta$ was kept equal to 20°C for fresh VIP$_S$ and to 25°C for aged VIPs and all the other samples (non-evacuated insulating materials).

These temperature differences were selected in accordance with [16], so as to ensure a level of uncertainty $\Delta\lambda$ [%] lower than the limits suggested by the international standard EN ISO 12667:2001 [24].

The uncertainty analyses were carried out in accordance with CEI ENV 13005:2000 [25] considering composite uncertainty that takes into account the measured factors which influence the experimental evaluation of centre of panel thermal conductivity λ_{cop}.

2.3. Description of specimens

In Table 1 the main characteristics of the VIP samples analysed in this study are reported, as declared by the producer.

Table 1. Characteristics of FS based VIPs declared by producer

Material	Dimensions		Composition			Properties (given by producer)			
	Area	s	SiO_2	SiC	Other	ρ_p	$\lambda_{cop\text{ - }(22.5°C)p}$	p_p	Envelope type
	[mm]	[mm]	[%]	[%]	[%]	[kg/m^3]	[W/mK]	[mbar]	
VIP	600 x 600	10 30	80	15	5	150 - 300	≤ 0.005	≤ 0.5	MF3 [2]

The thermal conductivity of fresh VIPs considering a mean temperature of 22.5°C (the same temperature condition of manufacturer declaration) was first measured by means of the GHFM. In order to obtain a complete comparison with the manufacturer data, the densities were also estimated by weighting the samples. Table 2 shows the assessed characteristics of the VIPs.

The measured thermal conductivities are in good agreement with the values declared by the producer ($\lambda_{cop\text{ - }(22.5°C)p} \leq 0.005$ W/mK). The small difference that occurs between the λ-values lies within the measurement uncertainty (around 2.1% in case of 10 mm VIP thickness and 2.5% in case of 30 mm VIP thickness). The declared density was also confirmed, in both cases its value lied in the range between 150 and 300 kg/m^3. These results demonstrate that the adopted experimental procedure is robust and reliable.

Table 2. VIPs experimentally assessed characteristics.

Material	Dimensions		Properties (experimental)			
	Area	s	ρ_{VIP}	ρ_{core}	$\lambda_{cop\text{ - }(22.5°C)}$	p
	[mm]	[mm]	[kg/m^3]	[kg/m^3]	[W/mK]	[mbar]
VIP	600 x 600	10	~ 200	~ 170	0.0051 ± 0.0001	≤ 0.5
		30	~ 190	~ 180	0.0050 ± 0.0001	

To investigate the influence that the vacuum degree inside the panel has on the correlation between the thermal conductivity and the average temperature, experimental tests were also conducted on non-evacuated insulating materials. In particular the following specimens were analysed:

- Punctured VIP, dimension 600 x 500 x 25 (thickness) mm, density ~ 214 kg/m^3, to evaluate the effects of a complete loss of vacuum) on the behavior of the panels thermal conductivity at different temperatures;
- Fumed Silica pressed board (VIP core material), dimension 600 x 500 x 25 (thickness) mm, density ~ 198 kg/m^3, to verify whether the high conductivity VIP envelope can be an influent factor on the VIPs thermal conductivity behavior;
- Extruded polystyrene (XPS), dimension 600 x 600 x 20 (thickness) mm, density ~ 30 kg/m^3, to have a reference trend (λ- ϑ characteristic curve) for a traditional macro-porous insulating material.

Fig. 2. Samples: (a) VIP 10 and 30 mm thick; (b) punctured VIP and VIP core material; (c) XPS.

3. Results and discussion

3.1. Numerical analyses

Several simulations were performed considering the model described in Section 2.1. Different values of temperatures for the hot and cold plates of the GHFM were considered. The results of the most relevant numerical simulation (worst condition: 30 mm VIP and ϑ_{avg} = 52.5°C) are reported in Fig. 3. As it can be seen, the temperature profile is influenced by the thermal bridging effect and lateral heat losses only for around the firsts 5 cm from the edge of the sample. This result demonstrated that in this case the metering area of the GHFM was not affected by any kind of impact, and hence the measurement of the centre of panel thermal conductivity can be correctly evaluated.

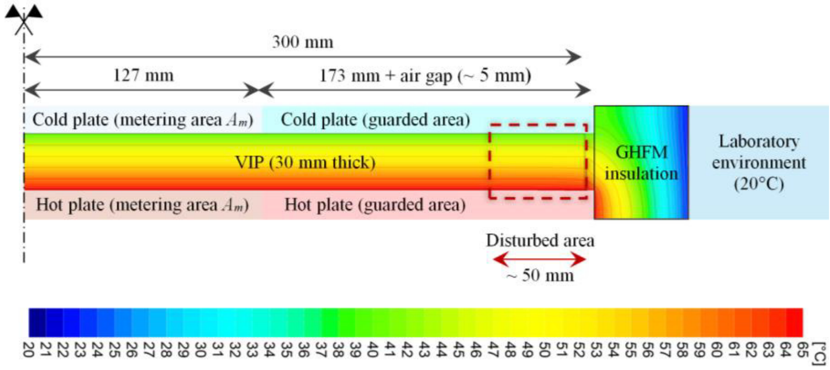

Fig. 3. Output of the numerical 2D analysis: 30 mm VIP, ϑ_{avg} = 52.5°C.

3.2. Experimental analysis: the influence of temperature on thermal conductivity

The experimental tests were carried out in two separate stages with different boundary conditions. In the first stage, experimental measurements were performed on two fresh VIPs characterised by the two different thicknesses (10 and 30 mm). Three different values of average temperature ϑ_{avg} (mean temperature of cold and hot plates) were analysed considering a fixed temperature difference between the plates of 20°C. Results of the experiments related to the variation of thermal conductivity as a function of average temperature are summarized in Table 3 together with the estimated experimental uncertainties.

Table 3. Experimentally assessed characteristics of fresh VIPs.

		10 mm VIP - Fresh		30 mm VIP - Fresh	
ϑ_{avg}		λ	u(λ)	λ	u(λ)
[°C]		[W/mK]	[%]	[W/mK]	[%]
10		0.0048	2.2	0.0046	2.7
25		0.0052	2.1	0.0051	2.6
40		0.0058	2.1	0.0059	2.4
$\Delta\lambda_{(max-min)}$	[W/mK]	0.0010		0.0013	
$\Delta\lambda_{(max-min)}$	[%]	20.4%		28.7%	

Table 4. Thermal conductivity depending on average temperature, and measurement uncertainty of different insulating materials.

		10 mm VIP		30 mm VIP		Punctured VIP		FS core		XPS	
ϑ_{avg}		λ	u(λ)	λ	u(λ)	λ	u(λ)	λ	u(λ)	λ	u(λ)
[°C]		[W/mK]	[%]	[W/mK]	[%]	[W/mK]	[%]	[W/mK]	[%]	[W/mK]	[%]
2.5		0.0050	2.1	0.0047	2.4	0.0213	2.0	0.0211	2.0	0.0307	2.0
12.5		0.0052	2.1	0.0050	2.4	0.0215	2.0	0.0212	2.0	0.0317	2.0
22.5		0.0054	2.1	0.0052	2.3	0.0216	2.0	0.0213	2.0	0.0327	2.0
32.5		0.0058	2.0	0.0056	2.3	0.0218	2.0	0.0214	2.0	0.0337	2.0
42.5		0.0063	2.0	0.0061	2.2	0.0221	2.0	0.0216	2.0	0.0348	2.0
52.5		0.0070	2.0	0.0069	2.2	0.0224	2.0	0.0219	2.0	0.0361	2.0
$\Delta\lambda_{(max-min)}$	[W/mK]	0.0020		0.0022		0.0010		0.0009		0.0054	
$\Delta\lambda_{(max-min)}$	[%]	40.4%		45.8%		4.8%		4.1%		17%	

In the second stage, experimental tests considering a wide range of average temperatures were carried out on the same panels after that they were stored in laboratory for 32 months. Moreover the same kind of analysis was conducted on a punctured VIP, Fumed Silica pressed board (namely VIP core material) and an XPS board (Table 4).

The thermal conductivity values were evaluated at the centre of panel and hence no thermal bridging or edge effects were taken into account in the measurements.

Analysing Table 3 and Table 4, it can be observed that the thermal conductivity strictly depends on the average temperature both for fresh and aged VIPs. Considering the range of average temperature from 10 to 40°C the thermal conductivity of fresh VIPs increases of about 20% (10 mm thickness) and 29% (30 mm thickness). With the same difference of average temperatures (30°C) the centre of panel thermal conductivity of aged VIPs increases of about 16% and 17/18% for 10 mm and 30 mm thickness respectively (~ 0.002 W/mK). Moreover, from 2.5°C to 52.5°C, the thermal conductivity of aged VIP worsened of about 40% and 46% for 10 mm and 30 mm VIP thick, respectively (Fig. 4(a) and (b)). Moreover, it is possible to observe that, in comparison to fresh samples, the ageing effect caused an average increase of thermal conductivity of 5% and 4%, respectively for 10 mm and 30 mm thick.

Considering the measurement uncertainty, results pointed out that a temperature difference between the plates of 25°C provides more reliable data than $\Delta\vartheta$ = 20°C. This is due to the higher heat flux that cross the specimen in the case of higher temperature gradient [16].

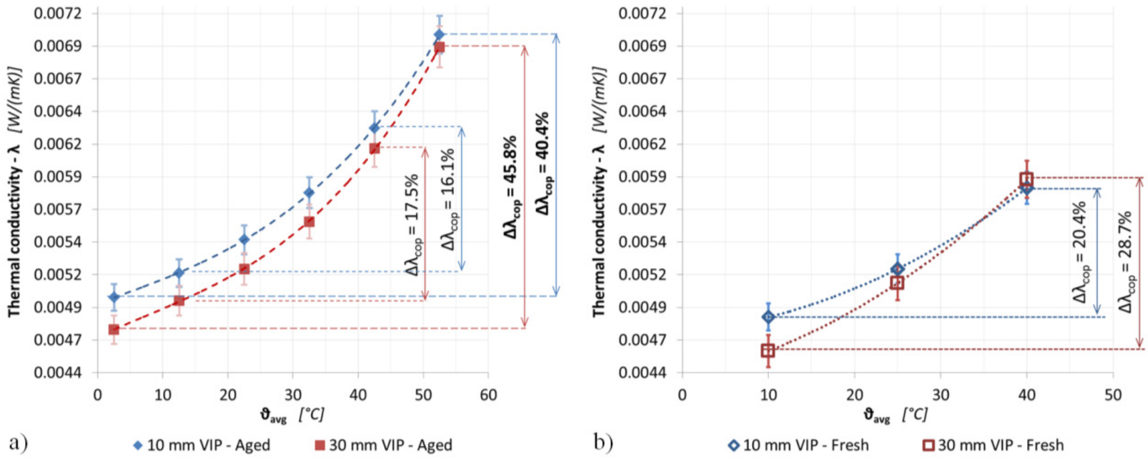

Fig. 4. Centre of panel λ depending on the mean testing temperature: (a) aged VIPs after 32 month of storage; (b) fresh VIPs.

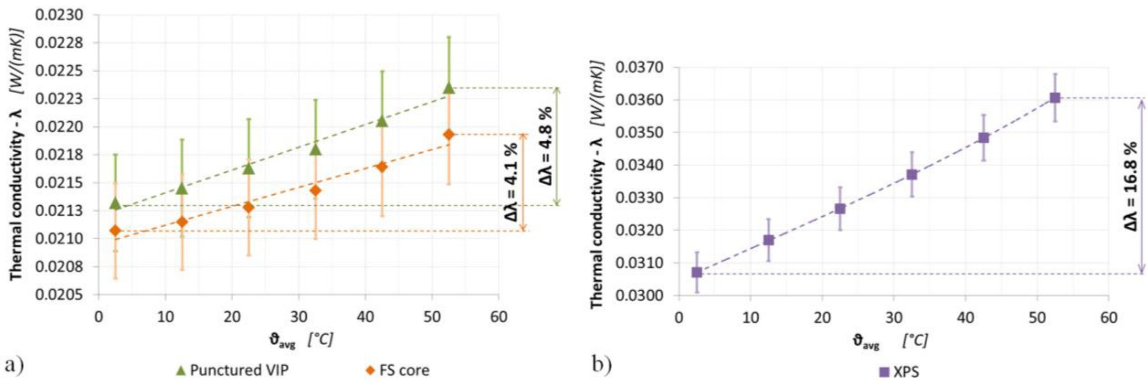

Fig. 5. λ depending on the mean testing temperature: (a) punctured VIP and FS core; (b) XPS.

The punctured VIP and the fumed silica core material were instead characterized by an approximated linear trend and a lower variation of thermal conductivity with the increasing of average temperature (Fig. 5(a)). The increase in thermal conductivity was equal to about 0.001 W/mK for both punctured VIP and Fumed Silica core material.

The wide variation of VIPs centre of panel thermal conductivity, measured with different average temperatures, is related to the weights of the different heat transfer contributions presented in Eq. (1). Firstly, the radiative heat transfer contribution λ_r could increase considering that it is a function of the cube of the mean temperature. Secondly, the increase of average temperature could influence the internal pressure of fumed silica based VIPs. In the critical pressure range, the centre of panel thermal conductivity may increase, influenced by the gaseous thermal conductivity λ_g which cannot be considered completely suppressed at high temperatures. Moreover, a further increment of the internal pressure could be due to the effect of high temperature on the eventual residual water content inside the VIP.

Instead, in case of punctured VIP and FS core, the thermal conductivity increase is not sensibly influenced by the variation of gaseous thermal conductivity, considering the constant internal pressure. This could explain the difference experimentally observed between the increment of VIP thermal conductivity (~ 0.002 W/mK) and the increment in punctured VIP and FS core (~ 0.001 W/mK) in the same range of temperatures.

From Fig. 5(a) it is also possible to observe that the thermal conductivity of the punctured VIP was always slightly higher than that of the FS core material. This difference is about 0.004 W/mK, and it could be due to the more conductive VIP envelope. However, the effects of VIP envelope on heat losses can be considered negligible.

In Fig. 5(b) the variation of centre of panel thermal conductivity as a function of the average temperature is shown also for a traditional insulating material, i.e. extruded polystyrene (XPS). In this case, similarly to the case of non-evacuated VIP (with or without the envelope), a linear trend was observed, but with a more marked variation of thermal conductivity (about 17%) in the same range of average temperature (2.5°C - 52.5°C). This variation could be due to the radiative effect, considering also the absence of opacifier. Moreover the large dimension of XPS pores could increase the effect of the average temperature on the gaseous thermal conductivity.

4. Conclusions

The present work investigates through experimental analyses the influence of boundary temperatures at which VIPs can be subjected during operating conditions on the centre of panel thermal conductivity.

Two specimens of fumed silica based VIPs characterised by two different thicknesses were analysed. The performance of the samples was measured when they were fresh (as delivered by the producer) and after they were stored in a laboratory for 32 months. The experimental analyses shown that thermal conductivity can increase up to 45% when the average temperature ranges from 2 to 50°C. Considering this behaviour, the manufacturers should provide different values of thermal performance of VIPs for different average temperatures. In this way a more realistic performance, which takes into account the real temperature conditions at which the panels could work, are obtained.

A comparison with a punctured VIP (with a complete loss of vacuum), and fumed silica pressed board (VIP core material), was carried out to investigate the influence of the internal vacuum degree. A quasi linear trend between thermal conductivity and temperature was found with a very limited variation of thermal conductivity as a function of temperature (4 - 5%).

Moreover, the same experiment was also conducted for a traditional insulating material (extruded polystyrene). In this case trend similar to the case of non-evacuated VIP was observed, but with a more marked variation of thermal conductivity (about 17%), due to the different internal structure.

The wide increment of VIPs centre of panel thermal conductivity can be associated to the variation of the relative weights of the different heat transfer contributions with the average temperature. The increase of temperature influences the radiative thermal conductivity (λ_r) and the gaseous thermal conductivity (λ_g). However, the causes of the thermal conductivity behaviour will be further investigated by the authors in order to have a comprehensive understanding of the physical phenomenon observed through these experimental analyses.

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