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VIPs thermal conductivity measurement: test methods, limits and uncertainty

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Abstract

Super Insulating Materials, such as Vacuum Insulation Panels (VIPs), are characterized by lower thermal conductivities in comparison to traditional building materials. Because of this property the experimental measurement methods and criteria for VIPs may be affected by an higher measurement uncertainty and a reduced trustworthiness. This is due to the low thermal flux through the sample material during experimental assessing. The aim of this research is to verify the reliability and the accuracy of existing testing and measuring methods when are applied to VIPs, showing their drawback and limits, and proposing possible correcting criteria and guidelines.

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Keywords: Vacuum Insulation Panels; thermal conductivity; heat-flux meter; measurement uncertainty.

1. Introduction

The European policy about the energy consumption reduction is more and more restrictive, particularly regarding the building sector. In this case the objective of reaching the Nearly Zero Energy Buildings (NZEB) involves the development of highly performing materials, and of course proper energy saving strategies. In this context several investigations on Super Insulating Materials (SIMs) were carried out, with the outlook of buildings applications.

SIMs main characteristic is their low thermal conductivity (about five times less than those of traditional insulating materials). Despite their excellent thermal characteristics, SIMs are still not widely used because of the lack of knowledge about reliable testing methods and assessment procedure of their actual thermal performances.

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Among SIMs different typologies (such as Vacuum Insulation Panels - VIPs, Advanced Porous Materials - APMs, Gas Filled Panels - SFPs) in this paper the attention was focused on VIPs.

VIPs properties were already investigated from different points of view: intrinsic characteristics (core material typology [1,2] and envelope [3]), criticism [4,5] and environmental impact [6]. To assess VIPs real thermal behaviour in buildings constructions several experimental and numerical investigations were carried out, and also measurements on site. The main topic of those researches was the characterization of VIP assemblies (VIP panels coupled with a joint made of different materials), considering the decrease of performance due to the thermal bridges along panel edges [7,8,9,10]. In [11] VIPs assemblies were insert between adjunctive thermal resistances, to evaluate their contributions on the overall thermal performances of the joint, as if they were plugged into a wall stratigraphy.

However, few in-depth analysis have to be carried out to verify if the measurement test conditions are useful to obtain reliable VIPs thermal characterization. The reference standard for the experimental assessment of thermal resistance of materials with medium and high thermal resistances is the UNI EN 12667:2001 [12]. However if the criteria are also suitable for SIMs was not yet demonstrated.

The aim of this research was to contribute to fill this lack of knowledge with preliminary investigations on experimental test conditions. For this reason, several experimental campaigns were carried out through an heat flux meter apparatus, varying the set point temperatures, in order to evaluate the influence of this input parameter on the VIP thermal performance measurement and to identify the correct test boundary conditions.

2. Methods and methodology

Laboratory measurements were performed to assess the center of panel thermal conductivity of a VIP sample (600x600mm size). A set of experimental measurements was carried out with heat flux meter apparatus, in accordance with the UNI EN 12667:2001 international standard [12].The apparatus, a Lasercomp FOX600, consists of a single sample guarded heat flux meter device with two plates containing the heat flux meters placed above and below the sample (Fig. 1).

The instrument was designed and set up in accordance with the ASTMC518, 1991 standard [13] and was calibrated with “1450b NIST SRM” calibration reference sample and an EPS sample (expanded polystyrene) previously certified by NIST.

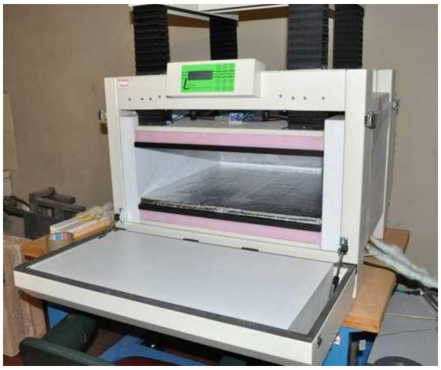

Fig. 1. Guarded heat flow meter apparatus.

As known the measurement principle is to create a constant temperature difference between the upper and the lower plates, and to measure the specific heat flux and surface temperatures in steady state conditions. The center of panel thermal conductivity λ_{cop} [W/mK] was then calculated using Equation (1).

$$\lambda_{cop} = (s \cdot \phi) / \Delta\theta \qquad (1)$$

Where: s is the sample thickness [m], Φ is the specific heat flux [W/m^2] and $\Delta\theta$ is the temperature difference between the two faces of the plates [°C].

Two kinds of investigation were carried out:

- *CAMPAIGN A*: 6 tests varying the average temperature θ_{avg} between upper and lower plate (θ_{upper} and θ_{lower} respectively), but maintaining the same temperature difference $\Delta\theta$ (= 25°C). Thickness of the sample s=20mm;
- *CAMPAIGN B*: 14 tests varying the $\Delta\theta$ values and maintaining constant the average temperature θ_{avg} (=30°C). Thickness of the sample s=30mm.

Campaign B was also carried out with the aim to evaluate the influence of temperature difference $\Delta\theta$ (and consequently of the heat flux through the sample) on the relative uncertainty $\Delta\lambda$. The uncertainty was evaluated in accordance with UNI CEI ENV 13005:2000 [14], considering the four factors which influence the experimental evaluation of center of panel thermal conductivity λ_{cop}: measured thickness s [mm], temperature gradient $\Delta\theta$ [°C], electrical signal from thermo-flux meters E [μV] and calibration factor S_{cal} [(W/m^2)/μV].

3. Results and discussions

3.1. Campaign A

The thermal conductivity of a material is generally a function of the average operating temperature to which the material is subjected. For most of building materials, the law which connect the two variables (thermal conductivity and temperature) is a linear relation, or slightly not linear. In Fig. 2 the experimentally assessed relation between the centre of panel thermal conductivity λ_{cop} and average temperature θ_{avg} is shown. A non-linear dependence was observed.

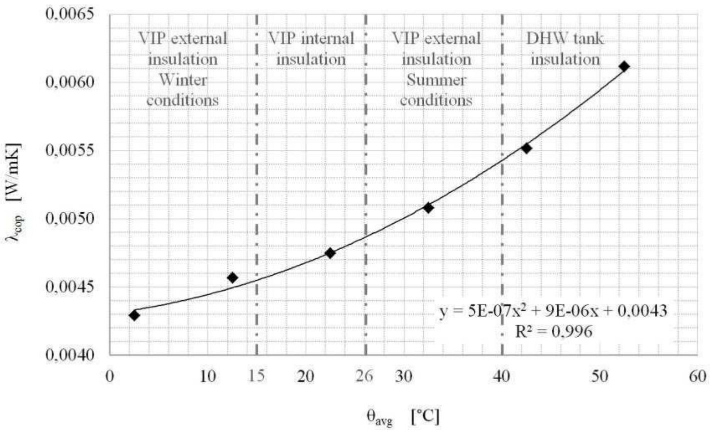

Fig. 2. Relation between λ_{cop} and θ_{avg}.

The not linear dependence of the λ_{cop} from θ_{avg} generate variable thermal performance responses at different temperatures. Indeed, at the same $\Delta\theta$ corresponds a lower λ_{cop} for colder average temperatures that for hotter ones. For example between 40 and 50°C (average temperature gradient $\Delta\theta_{avg}$=10°C) the difference between the centre of panel thermal conductivities $\Delta\lambda_{cop}$ is around equal to 0.0005W/mK, which corresponds to 9% of the relative $\lambda_{cop\_avg\,(40\text{-}50°C)}$=0.0057W/mK. The same reasoning between 10 and 20°C (maintaining $\Delta\theta_{avg}$=10°C) generate a $\Delta\lambda_{cop}$≅0.0002W/mK, that corresponds to 4% of the relative $\lambda_{cop\_avg\,(10\text{-}20°C)}$=0.0046W/mK.

At the same time, the thermal conductivity at θ_{avg}=40°C is about 25% higher than the λ_{cop} at θ_{avg}=10°C, and this is a not negligible gap.

The results obtained from the experimental test demonstrate that VIP thermal conductivity is strictly dependent from the panel temperature. For this reason the value of λ_{cop} could ranges from 0.0043 W/mK at 2.5°C (VIPs external insulation in winter condition) to 0.0061 W/mK at 52.5°C (VIPs external insulation in summer condition, or domestic hot water tank insulation).

This phenomenon can be related to the internal structure of the insulation material. Inside the core material there is some leftover filled air: the vacuum degree could be not perfect, with an average value of about 3hPa but however less than 10hPa [15], and decrease with ageing of the VIP.

The modes of heat transfer inside VIP include solid, convective, radiation and gaseous conduction. If internal pressure of VIP is lower than a certain value, the convective heat transfer can be suppressed. So the total thermal conductivity of a VIP core remains the following [16]:

$$\lambda_{\text{core}} = \lambda_S + \lambda_R + \lambda_G + \lambda_{cv} + \lambda_{coupling} \tag{2}$$

Where:

- λ_{core}: VIP core thermal conductivity [W/mK];
- λ_S: solid thermal conductivity [W/mK];
- λ_R: radiative thermal conductivity [W/mK];
- λ_G: gaseous thermal conductivity [W/mK];
- λ_{cv}: gaseous convection within pores [W/mK];
- $\lambda_{coupling}$: coupling effects thermal conductivity [W/mK].

All of these effects must be minimized in order to obtain a low value of λ_{core}:

- λ_S: in solid conduction the heat is transferred through the physical contact of the constituent particles of the core material, so the materials with a low density allow a smaller solid conductivity;
- λ_R: radiative heat transfer can be reduced by adding opacifier to the core material;
- λ_G: this term depends on the ratio of mean free path of gas molecules and the pore size of the material (see the following section for further details), and it's negligible for materials with pore nanometric dimensions;
- λ_{cv} and $\lambda_{coupling}$: their effects becomes evident at higher pressures for powders and fibre materials due to interaction between them in the VIP core.

The internal pressure is influenced by the temperature. The variation of pressure and temperature have the effect to modify the relative weight of the terms in Equation (2). This phenomenon influence the λ_{core} and so on the λ_{cop}.

The not linear behaviour of VIPs could be caused mainly from the presence of the air inside the VIP, air with low pressure and sensible to temperature variations, following the Equation (2).

3.2. Campaign B

The relation between λ_{cop} and temperature can be observed from another point of view: if λ_{cop} is variable in function of the average temperature, it will be also dependent from the temperature difference $\Delta\theta$. Indeed, with the increasing of $\Delta\theta$ increase also the heat flux through the panel: the greater the flux from which the thermal conductivity λ is calculated, the lower the relative uncertainty $\Delta\lambda$. Fig. 3 shows this relationship ($\Delta\theta$=10°C is the minimum temperature difference between guarded hot plates according to UNI EN 12667:2002 [12]).

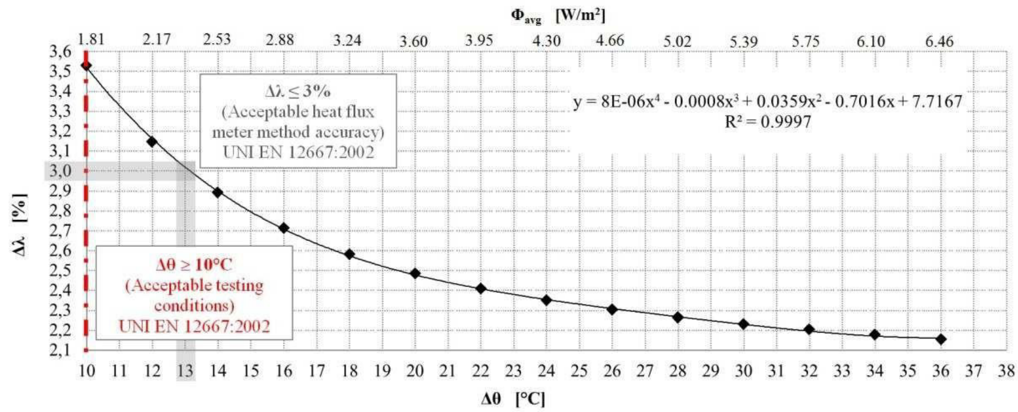

Fig. 3. Percentage uncertainty $\Delta\lambda$ in function of $\Delta\theta$, and relative heat flux Φ_{avg}.

It's clearly demonstrated the preview reasoning: between a 10°C and 24°C of $\Delta\theta$, the relative uncertainty $\Delta\lambda$ decreasing is equal to 34%, while for $\Delta\theta$ from 24°C to 36°C the relative uncertainty variation is only 10%. It means that for higher temperature difference $\Delta\theta$ the λ_{cop} value, measured by heat flow meter, is more stable and reliable (with asymptotic trend for higher $\Delta\theta$ values). Fig. 4. Shows that the λ_{cop} value decrease with the increasing of the $\Delta\theta$, and further confirms the relationship between $\Delta\lambda$ and $\Delta\theta$. The λ_{cop} values measured for low temperature gradients (from 10°C to 24°C) are extremely variable as a function of the $\Delta\theta$ considered. Otherwise, for higher $\Delta\theta$ (from 24°C to 36°C), that determine a lower relative uncertainty $\Delta\lambda$, the λ_{cop} values measured are less scattered and less sensible to $\Delta\theta$ variation.

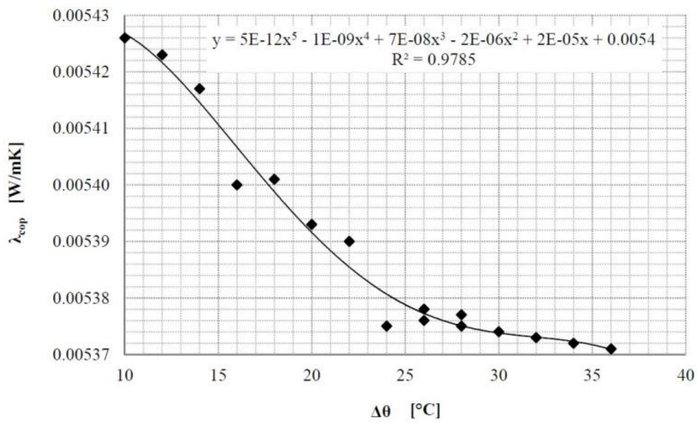

Fig. 4. Thermal conductivities λ_{cop} as a function of $\Delta\theta$. (Tests with $\Delta\theta$ equal to 26 and 28°C were repeated twice.)

4. Conclusions

UNI EN 12667:2002 [12] gives some temperature acceptable values and reference accuracy, for characterizing high thermal resistant materials both by guarded hot plate (Annex B) and heat flux meter methods (Annex C). In case of heat flux meter these limit values are:

- Lower recommended limit for temperature difference through the specimen when determining an unknown relationship 5°C;

- Upper recommended limit for temperature difference across the specimen 10°C;
- Expected heat flux meter method accuracy (when the mean temperature of the test is near the room temperature) ±3 %.

On the basis of the experimental analysis performed in order to obtain a measurement accuracy better than ±3 % the temperature difference between lower and upper plate $\Delta\theta$ must be at least equal to 13°C or more.

For the reasons the necessity of an implementation of measurement procedure suggested by the European standard is recommended. In particular different temperatures limits for Super Insulating Materials characterization need to be considered to obtain reliable values of thermal conductivities in actual conditions.

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