Innovative thermal insulation panels with air channels

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Abstract. The research has been carried out in the direction of developing a new design of building materials with improved thermal insulation properties, by applying different geometries of air channels inside the materials, increasing thus porosity and lowering the density. The solution that was proposed consisted in perforating extruded polystyrene (XPS) panels. Perforation was performed horizontally and at an angle of 45°. The method is simple and cost-effective. Perforated and simple XPS panels were subjected to three different temperature regimes. There was an increase in thermal conductivity with the increase in average temperature in all studied cases. The presence of air channels reduced the thermal conductivity of the perforated panels. The reduction was more significant at the panels with inclined channels. The differences between the thermal conductivity of simple XPS and perforated XPS panels are small, but the latter can be improved by increasing the number of orifices and lowering the air channels diameter. Also, the higher the thermal conductivity of the base material, the more significant is the presence of the channels, reducing the effective thermal conductivity. A base material with low emissivity may also reduce the thermal conductivity.

1. Introduction

In recent years, the population's interest in thermo-insulation of the buildings has considerably increased, being an effective method of reducing energy consumption in winter, but also providing comfort during summer. The main factors influencing heat transfer through a material between two temperatures is the thickness of the material and its thermal properties: thermal conductivity and specific heat. In thermal insulation, porous materials are commonly used. The porous structure utilizes the low thermal conductivity of the gas in the pores. At the same time, heat radiation and gas convection is hindered by the solid structure [1].

The latest researches were conducted towards inventing and developing new thermal insulating materials. Jelle et al. [2] proposed innovative and robust highly thermal insulating materials. Such advanced insulation materials (AIM) are: vacuum insulation materials (VIMs), gas insulation materials (GIMs), nano insulation materials (NIMs), and dynamic insulation materials (DIMs). These materials have closed pore structures (VIMs and GIMs) or either open or closed pore structures (NIMs). A vacuum insulation material (VIM) is basically a homogeneous material with a closed small pore structure filled with vacuum with an overall thermal conductivity of less than 4 mW/(mK) in pristine condition. Maintaining the vacuum inside the pores during a long service life may be the most difficult or challenging task for the VIMs. A gas insulation material (GIM) is basically the same as a VIM, except that the vacuum inside the closed pore structure is substituted with a low-conductance gas. That is, a GIM is a homogeneous material with a closed small pore structure filled with a low-conductance gas with an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition [3].
Other thermal insulation materials are vacuum insulation panels (VIPs) which represent evacuated, open-porous materials that are enveloped into a multilayer film. It is the best material in terms of thermal conductivity in pristine condition: 3-4 mW/mK. It also has a low thickness compared to traditional thermal insulation materials, i.e. polystyrene. The necessary building insulation thickness may be decreased with a factor of 5 up to 10. But, it has some disadvantages, like being fragile, recording a significant decrease of performance with time and being not adaptable for construction sites without losses in thermal conductivity. But, combining VIPs with other materials is beneficial. Among the core materials applied in VIPs are fumed silica, silica aerogels, open cell expanded polystyrene, polyurethane foams, fibreglass, composite materials. A nano-structured core material in combination with the pressure reduction is favorable to be used in VIPs. The use of conventional insulation as a core material for VIPs results in the necessity of a very high quality of vacuum (~0.1 mbar). Common organic envelope materials cannot maintain this inner pressure for a long period: a rapid intake of air through the envelope will occur, resulting in a fast increase of the thermal conductivity. Solutions to maintain this high quality of pressure almost always go together with an envelope material with a higher thermal conductivity. However, VIPs are not in the wide-spread use in buildings because of their high cost, susceptibility to perforation and the effects that worsen their performance [4, 5].

Gas-filled panels (GFPs) try to minimize all parameters of heat transfer by using a low-conductive gas as the main insulator to influence both the gaseous thermal conductivity and the thermal conductivity of the solid structure. The thermal conductivity through the gas is the most important heat transfer in a GFP. As a result of the cellular structure of the GFP, the total panel has a thermal conductivity close to the still-gas thermal conductivity of the fill [5].

Some authors [6] proposed a simple, effective model for prediction of the effective thermal conductivity of VIPs. The effective thermal conductivity of VIPs is function of the thermal conductivity of the core materials, the equivalent thermal conductivity of the rarefied gas embraced in the core and the equivalent thermal conductivity of radiation. The micro structure of the porous core materials and vacuum degree were taken into consideration. Three VIPs were made from the polyurethane foam materials, fibrous materials and nano-granular silica materials as the core materials.

Surveying the excess of bulk materials now available, some materials scientists promoted a method of combining existing materials with geometric features to create multifunctional hybrid materials. By studying natural materials, the performance of simple constituent materials is improved by manipulating their internal geometry at different length scales. Craig and Grinham [7] described a method for designing building materials as heat exchangers, so that incoming fresh air can be efficiently tempered with low-grade heat while conduction losses are kept to a minimum. Any base material can be used in principle, so long as it can be manufactured with millimeter-scale air channels.

Imbabi [8] introduced a new Void Space Dynamic Insulation (VSDI) technology that couples low cost conventional insulation materials with efficient ventilation to deliver low loss building envelopes and high indoor air quality in thin wall construction. VSDI is a new type of dynamic insulation in which the air flow is confined within a co-planar void space bounded by one or more layers of insulation material and the wall structure. The advantages of VSDI are that it eliminates the risk of interstitial condensation and the risk of over-heating during extreme summer months.

The present research aimed at developing new design of building materials with improved thermal insulation properties, by applying different geometries of air channels inside the materials, increasing thus porosity and lowering the density. The method is simple and cost-effective.

2. Materials and methods

2.1. Experiment

Extruded polystyrene (XPS) was used as base material. The overall dimensions of the panel (L×l×g) were 0.6×0.6×0.03 m. The length and width of the panel correspond to the dimensions required by the experimental equipment-heat flow meter (Netzsch HFM 436/6 Lambda), used to measure the
thermal conductivity of the polystyrene panel. The heat flow meter method is based on the European standards EN 12667 [9] and EN 12939 [10].

Experiments were carried out for three temperature regimes, as indicated in table 1.

| Hot plate temperature (°C) | Cold plate temperature (°C) | Average temperature (°C) | Temperature difference between the two control thermocouples (°C) |
|---------------------------|-----------------------------|--------------------------|---------------------------------------------------------------|
| -10                       | 20                          | 5                        | 30                                                            |
| 10                        | 20                          | 15                       | 10                                                            |
| 35                        | 20                          | 27.5                     | 15                                                            |

Different designs of the polystyrene panel were proposed by perforating it and creating air channels inside, aiming at increasing the porosity of the existing panel. Figures 1 and 2 show the horizontal distribution of the air channels and the distribution of the air channels inclined at 45°.

Figure 1. XPS panel with horizontal air channels: a) front view of panel; b) view section.

Figure 2. XPS panel with inclined air channels.

The perforation was manually carried out by means of a pin on the surface of the panel, penetrating the panel. The diameter of the each orifice was $D = 2$ mm. The orifices were equally spaced at $x = 20$ mm distance of the centers. The distance between the center of a marginal orifice and the border of the panel is $x$ as well. The experimental measurements were performed on the simple, not
perforated XPS test panel and on perforated panels in agreement with the three operating conditions indicated in table 1.

2.2. Effective thermal conductivity calculation

The effective thermal conductivity ($\lambda_e$) of the designed porous materials can be calculated by using the thermal conductivity of the solid ($\lambda_s$), the thermal conductivity of the air ($\lambda_{air}$) from the channel-pores, the number of orifices ($n$) and the diameter of an orifice ($D$), as:

$$\lambda_e = \left(1 - \frac{n \pi D^2}{4} \right) \lambda_s + \frac{n \pi D^2}{4} \lambda_{air}$$

The equation was derived from the steady, one-dimensional heat transfer by pure conduction in a multilayer panel, considering the heat flux perpendicular to the panel surface.

The diameter of an orifice is limited to a few millimeters in order that air flow inside channels due to temperature gradients is reduced and therefore it is neglected. The assumption is made that the air is still and its thermal conductivity depends on the average panel temperature.

Equation (1) is similar to that indicated by Kan et al. [6] for VIPs, where the effective thermal conductivity of a porous medium is expressed as a function its porosity ($\xi$), thermal conductivity of the solid matrix ($\lambda_s$), thermal conductivity of the rarefied gas ($\lambda_g$), and thermal conductivity of radiation ($\lambda_r$), as follows:

$$\lambda_e = (1 - \xi) \lambda_s + \xi \lambda_g + \lambda_r$$

They also ignored the thermal convection between the solid wall and the filled gas, due to the low pressure of air at normal temperature, but they considered the effect of thermal radiation inside pores.

The equation of the thermal conductivity accounting for the radiation transfer between internal channel surfaces of the panel is indicated by the same authors [6] as follows:

$$\lambda_e = 4 l, \sigma (T_1 + T_2) \left[ T_1^2 + T_2^2 \right] / 3 \phi$$

where, $l_c$ is the thickness of the core material, $\phi$ is the attenuation coefficient for porous media ($\phi = 445 \text{m}^{-1}$), $\sigma$ is Boltzmann constant ($\sigma = 5.6697 \times 10^{-8} \text{W/m}^2\text{K}^4$).

Jelle et al. [2] applied Stefan-Boltzmann equation to find the total radiation heat flux through a material with $n$ air gaps in series with infinite parallel surfaces of equal emissivity, which may be approximated as $n$ pores along a given horizontal line in the material. Accordingly, the radiation thermal conductivity $\lambda_r$ in the nano insulation materials’ pores may be approximately calculated by:

$$\lambda_r = \frac{\sigma \delta \left( T_1^4 - T_2^4 \right)}{\left( \frac{2}{\varepsilon} - 1 \right) \left( T_1 - T_2 \right)}$$

where, $\delta$ is the pore diameter, $\varepsilon$ is the emissivity of inner pore walls. The emissivity of polystyrene is 0.9.

The number of horizontal orifices, $n$ from Eq. (1) is related with the distance between the centers of the orifices, $x$ by the following equation:

$$n = \left( \frac{L}{x} - 1 \right)^2 \text{, for } D < x$$

In the case of a rectangular panel ($L \neq l$), the general equation becomes:

$$n = \frac{(L-x)(l-x)}{x^2}$$

The number of orifices can be increased if the distance between their centers is decreased. If the orifices are inclined, the angle of inclination, $\alpha$ depends on the thickness of the panel, $g$ and
the distance between centers, $x$, as shown in figure 3.

![Figure 3. Dimensional quantities of the inclined orifices.](image)

The following equations describe the relation between the dimensional quantities:

\[ x = y + z \]  \hspace{1cm} (7)

and

\[ y = g \cdot \tan \alpha \]  \hspace{1cm} (8)

Therefore:

\[ x \geq g \cdot \tan \alpha \]  \hspace{1cm} (9)

or, if selecting $x$, the angle can be found from:

\[ \tan \alpha \leq \frac{x}{g} \]  \hspace{1cm} (10)

The number of air channels decreases if they are inclined.

3. Results and discussion

It can be observed from Eq. (1) that the effective thermal conductivity depends on the variables $\lambda_s$, $n$ or $x$ and $D$. It does not depend on the panel thickness. Their influence on the effective thermal conductivity can be observed in figures 4-6 for the range of values $\lambda_s$: 0.03-0.3 W/mK, $n$: 100-10000, $D$: 0.005-0.01 m.

Figures 4-6 indicate that the increase in the number of orifices and the increase in their diameter determine the decrease of the thermal conductivity. Also, an increase of the thermal conductivity of the base material increases the effective thermal conductivity. Therefore, the higher the thermal conductivity of the solid, the more significant is the presence of the orifices, reducing thus the effective thermal conductivity of the panel.

The thermal conductivity of radiation of the XPS panel subjected to the temperature conditions indicated in table 1 was calculated using Eq. (3) and the following values were obtained: $4.4 \times 10^4$, $4.88 \times 10^4$ and $5.54 \times 10^4$ W/mK.
Figure 4. Variation of effective thermal conductivity of the perforated panel as function of thermal conductivity of the solid for average values $L=0.6$ m, $D_{av}=0.0075$ m, $n_{av}=5050$.

Figure 5. Variation of effective thermal conductivity of the perforated panel as function of the orifices’ diameter for average values $L=0.6$ m, $\lambda_s_{av}=0.165$ W/mK, $n_{av}=5050$.

Figure 6. Variation of effective thermal conductivity of the perforated panel as function of the number of orifices for average values $L=0.6$ m, $\lambda_s_{av}=0.165$ W/mK, $D_{av}=0.0075$ m.

The experimental results of the thermal conductivity of simple XPS, perforated XPS with horizontal and inclined air channels and the calculated results (Eq. 1) of the thermal conductivity are indicated in figure 7. For $L = l = 0.6$ m and $x = 20$ mm, $n$ becomes 841 (Eq. 5). The number of orifices reduces to 361 (maximum) if they are inclined at 45°, because the distance $x$ becomes in this case equal to 30 mm (minimum), (Eq. 9). Considering the orifices, the porosity increases by 0.7% in the first case and by 0.45% in the second case.

For the first temperature regime only the calculated thermal conductivity is lower than the thermal conductivity of the simple XPS panel. Some condense may be present in the air channels because of the negative temperature of the cold plate of the experimental device, improving thus the heat conduction. For the second temperature regime, the thermal conductivity of the perforated XPS panels slightly decreased as compared to the simple XPS panel. The decrease was higher for the XPS panel with inclined air channels (0.84%). The calculated thermal conductivity also decreased due to the presence of the air channels. For the third temperature regime the thermal conductivity of the perforated XPS panels decreased as well. The decrease was again higher for the XPS panels with inclined air channels (0.4%).
Figure 7. Experimental results of the thermal conductivity of simple XPS, perforated XPS with horizontal and inclined air channels and calculated results of thermal conductivity.

The differences between the thermal conductivity of simple XPS and perforated XPS panels are small, but the latter can be improved by increasing the number of orifices and lowering the air channels diameter (nano scale channels). The mean free path of the air molecules should be larger than the pore diameter, thus hindering collisions between molecules and decreasing thermal conductivity.

The experimental values include the effect of the radiation heat transfer inside air channels (Eq. (3) or Eq. (4)). If neglecting this component, a further reduction of the thermal conductivity may be achieved (figure 8).

Figure 8. Experimental results of the thermal conductivity of simple XPS, perforated XPS with horizontal and inclined air channels and calculated results of thermal conductivity without radiation heat transfer effect.

In this case, the thermal conductivity of the XPS panels with inclined orifices decreases by 1.2%, 2.2% and 1.8%, respectively for the three temperature regimes.

The radiation thermal conductivity depends on the dimensions of the pores or panel and emissivity of the base material. Lowering dimensions and using a base material with low emissivity would decrease the radiation thermal conductivity.

Also, a base material with high thermal conductivity is influenced by the presence of air channels inside the panel, decreasing significantly its thermal conductivity (figure 4).

Finally, there was an increase in thermal conductivity with the increase in the average temperature of the panels in all studied cases.
4. Conclusions
A new design of existing building materials by generating air channels inside was reported in the paper. XPS panels were horizontally perforated and at an angle of 45°. The presence of air channels reduced the thermal conductivity in both cases, but the reduction was more significant at the panels with inclined channels.

An optimized design would assume the reduction of the channel diameter and the increase in the number of channels. A base material with low emissivity may also reduce the thermal conductivity.

Perforated panels can be included in a multilayer insulation structure.

5. References
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