Study of behaviour of thermal insulation materials under extremely low pressure

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Abstract. In most thermal insulation materials, reduced internal pressure improves thermal insulation properties. It reduces heat transport by convection as well as heat conduction in gases in the material's pore structure. The dependence of thermal conductivity on pressure is individual to every type of insulation with open porosity. In general, a material with fine porosity is not very sensitive to pressure change within the range of very low pressure to vacuum. On the other hand, materials with a larger number of bigger pores are more sensitive to changing pressure. Any pressure change between atmosphere pressure and vacuum causes a change in thermal conductivity. The paper presents the results of an investigation into the behaviour of alternative fibrous insulations usable in the production of vacuum insulation panels at low pressure.

1 Introduction

Vacuum insulation boards/panels (VIP) that are formed of core material and gas-barrier envelope represent a very promising thermal insulation of the future in the building industry, which can significantly contribute to reducing the energy performance of buildings. Their thermal insulation properties are significantly better compared to conventional insulating materials commonly used, exhibiting up to 10 times higher thermal resistance. Although the beginning of these materials is recorded in the first half of the 20th century, their first use in construction is known only in 1999 in the USA [1]. Currently, these materials are still used most in the freezing and refrigeration industry, about 60% of production. Other major uses of VIP are packaging and shipping boxes. About 10% of VIP production is used in the construction industry as thermal insulation materials [2]. One of the factors that result in lower utilization of VIPs in the construction industry is the durability of these materials and the high work demands for their application. The objective of many research groups around the world is to develop VIP and study their behaviour depending on pressure. Core materials play an essential role in the case of excellent thermal insulation properties. Today, in particular, inorganic materials based on aerogel or microsilica, powdered perlite and various types of glass-fibre materials are widely used as core materials. The paper deals with the results of the study of the behaviour of alternative

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fibrous insulators usable as core materials in vacuum insulation panels under reduced pressure.

2 Study of heat transfer of VIP

Total effective thermal conductivity λ_{eff} VIP is given by the sum of thermal conductivity of solid matrix of core insulator λ_s , thermal conductivity of gas convection λ_g , thermal conductivity by radiation λ_r and thermal conductivity given by envelope (thermal bridge effect) λ_{tb} . The solid conduction λ_s depends on the structure and material properties of the core.

$$\lambda_{eff} = \lambda_s + \lambda_g + \lambda_r + \lambda_{tb} \text{ [mW/(m.K)]} \quad (1)$$

There λ_s and λ_r are not depend on gas pressure and it is the lowest thermal conductivity of core insulation λ_0 :

$$\lambda_0 = \lambda_s + \lambda_r \text{ [mW/(m.K)]} \quad (2)$$

The gaseous conduction λ_g by residual gases depends on the gas pressure which increases with time by infusion of atmospheric gases and outgassing of the inner material. [5]

3 Dependence of thermal conductivity on the pressure

Typical for each type of insulation material is dependence of thermal conductivity on the pressure. Depending on the pore size, the insulator sensitivity to the change in pressure also varies. This characteristic is described by the parameter $p_{1/2}$ pressure at which the gas thermal conductivity reaches the value of one half of $\lambda_g = 25.5 \text{ mW/(m.K)}$ in the case of air. $p_{1/2}$ depends on the mean pore size of the material δ , the diameter of the gas molecules d_g , the temperature T , the gas type constant β depending on the gas type and the Boltzman constant k_B [5], see below equation (3).

$$p_{1/2-g} = \frac{T}{\delta} \cdot \frac{2 \cdot \beta \cdot k_B}{\sqrt{2} \cdot \pi \cdot d_g^2} \quad (3)$$

It is generally known that the core material must be porous for easy vacuuming, ideally have open porosity, exhibit long-term structural stability, and have minimal negative impact on thermal transport by conduction. It has been proven that the smaller the pores (with very high total open porosity), the better the thermal insulation properties of the final vacuum insulation panels are achieved [6]. Reducing internal pressure leads to improved thermal insulation properties for most thermal insulation. The cause is a gradual reduction in heat transfer due to flow in the porous structure of the insulator and a reduction in heat transfer through the gas phase contained in the pores of the insulator. For each type of insulator with open porous structure, the dependence of thermal conductivity on pressure is individual. It is well known that a material with a finer porous structure is less susceptible to pressure variation in the very low pressure area to vacuum. On the contrary, materials with a larger pore ratio are more sensitive to pressure change and a change in pressure practically throughout the pressure range from atmospheric pressure to vacuum will also cause a change in their thermal conductivity.

4 Experimental works

In the framework of experimental works at the Faculty of Civil engineering of the Brno University of Technology, the development of core insulators for vacuum insulation panels using secondary raw materials was carried out. As a suitable raw material, new types of fibres based on flax and cotton were selected. These were dusts from the filters of the production line for textile tearing - see Figure 1.

Fig. 1: Photography of cotton (left) and flax (right) fibres

Both macroscopic and microscopic analyses were performed on the fibres, wherein the following has been found:

- Both fibre types contain a larger proportion of significantly fine fibres.
- The cotton sample is homogeneous; coarse samples of hemp shives are also included in the flax sample (this can be seen from the larger standard deviation in the case of flax fibre thickness (see Table 1).
- The length of the fibres is lower in both cases, but the predominant proportion of fibres in the samples has a length 10-20 mm.

The microscopic analysis confirmed the assumptions of macroscopic analysis and the length and thickness of both types of fibres were determined. The results are shown in Table 1.

Table 1. Properties of tested fibers

Type of fibre	Average fibre thickness [μm]	Standard deviation of thickness [μm]	Average fibre length [cm]	Standard deviation of length [cm]
Cotton	12.49	3.45	1.6	0.10
Flax	19.03	11.66	1.2	0.05

As can be seen from the values found, the thickness of both types of fibres is very low. Especially in the case of flax, the thickness is considerably smaller than that of conventional technical flax fibres (where the thickness can be up to 10 times higher). Thus, both types of fibres are potentially interesting from the point of view of producing insulators, which are suitable for VIP. For the production of test samples, polyester bicomponent fibres with a thickness of 2.2 dTex were used in the addition of 15% to the raw fibres. Test samples were made under laboratory conditions. The raw fibres were homogenized and mixed with bicomponent fibres. Thereafter, samples were pressed from

the fibres at 150 °C. The objective was to achieve the highest possible bulk density for the samples. The samples were always made by pressing to a thickness of 10 mm. After production, there was a subsequent expansion (relaxation) in the samples, which was, as can be seen from the results given in Tab. 2, significantly higher in the case of cotton.

Table 2. Properties of core insulators (according to EN 823, EN 12085, EN 1602)

Sample	Thickness [mm]	Density [kg/m ³]	Square weight [kg/m ²]
Cotton	15.60	119	1.86
Flax	10.46	178	1.85

The dependency of thermal conductivity to pressure at a thermal gradient of 10 °C was determined on samples of core insulators according to EN 12667 and ISO 8301 (by equipment Lasercomp FOX 200 Vacuum). The thermal conductivity was determined at normal pressure ($p = 1013.25$ mbar) and then under vacuum at 0,05 mbar, 0,5 mbar, 1 mbar, 10 mbar.

Table 3: Dependence of thermal conductivity on pressure of samples based on cotton

Pressure [mbar]	Thickness of samples [mm]	Thermal conductivity [mW/(m·K)]
0.05	15.062	5.146
0.5	14.389	7.306
1	14.446	14.300
10	14.364	30.047
Normal pressure	14.776	41.903

Table 4: Dependence of thermal conductivity on pressure of samples based on flax

Pressure [mbar]	Thickness of samples [mm]	Thermal conductivity [mW/(m·K)]
0.05	10.300	4.451
0.5	9.919	9.138
1	9.893	12.467
10	9.874	28.703
Normal pressure	9.614	43.423

5 Evaluation of results

Dependencies were compiled from the measured values (see Figs. 2 and 3) and the results were evaluated and the measured values were compared with the commercial insulators used for VIP production (see below).

Fig. 2. Dependence of thermal conductivity on pressure of samples based on cotton

Fig. 3: Dependence of thermal conductivity on pressure of samples based on flax

According to [5] pressure $p_{1/2}$ [mBar] was evaluated (as pressure when the initial thermal conductivity increases by 12.75 mW/(m.K)). The calculated values are shown in the following table.

Table 5. Properties of core insulators

Sample	Thermal conductivity λ_0 [mW/(m.K)]	Pressure $p_{1/2}$ [mBar]
Cotton	5.146	2,47
Flax	4.451	2,81

As can be seen from the results, the vacuum thermal conductivity values (λ_0) are relatively low, comparable to SiO₂ based insulators, but do not reach extremely low values comparable to, for example, mulled wool (for fiber based core insulator is $p_{1/2}$ typical between 3 mBar and 7 mBar [5]). Regarding the determined values of pressures $p_{1/2}$, it was found that the pressures are relatively low, therefore these insulators are not suitable for classical building applications and the use of films with classical aluminum foil would be necessary for their use.

6 Conclusion

Research work has shown that flax-based and cotton-based fibers (textile line filtering dust) can be an interesting and potentially beneficial secondary raw material useful for the production of insulators that can be used for VIP production. It has been found that the fiber processing of the flax is fiberized and the fibers trapped in the filters are only about 19 microns thick, which is considerably less than the thickness of conventional hemp fibers (typically 100-200 microns) [7].

The experimentally produced insulators exhibit, under normal thermal conductivity conditions, 41.9 - 43.4 mW/(m.K), which is a relatively high value compared to conventional like mineral wool or polystyrol (mainly due to the high bulk density of insulators), thermal conductivity of about 10x, which is a very good result, and insulators are therefore useful for VIP production. However, in view of their long-term properties, it is also necessary to evaluate the change in thermal conductivity depending on the pressure change within the VIP. The properties of the newly developed insulators are comparable to those of glass wool. For use in building construction, cotton and linen fibers would need to be combined with SiO₂.

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