INVESTIGATION OF HEAT TRANSPORT IN CALCIUM SILICATE BOARDS BY PULSE TRANSIENT METHOD

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Abstract

The building industry is using modern materials that are usually extremely porous to improve the thermal insulation properties. The performance of these materials depends on their thermophysical properties. This paper discusses the heat transport properties in Calcium-Silicate boards reinforced by cellulose fibers measured by pulse transient method.

Thermophysical data were measured at various thickness of the specimen. Analysis of influence of the effects of contact area for little thickness and heat losses from the sample surface for large thickness is shown. Data stability interval was found for a MIDDLE range of specimen thickness. Correction procedure is used for heat loss effects from the specimen surface.

Thermophysical properties of mentioned material was measured in air and vacuum atmosphere. Influence of the environmental atmosphere on heat transport in porous systems is observed and discussed.

Key words: transient methods, thermal diffusivity, specific heat, thermal conductivity, heat losses, PMMA,

1 Introduction

Measurement of thermophysical properties (specific heat, thermal diffusivity and thermal conductivity) of building materials shows that some effects influence the process of heat transport. The knowledge of these effects is important for the building construction in real conditions. The heat transport in porous materials is influenced by transport properties of skeleton and by environmental atmosphere that fills up the pores. The moisture content in the pores strongly influences the heat transport. In addition the atmosphere and various moisture content in the material pores change thermodynamic equilibrium state of the material.

Previous investigation of thermophysical properties by Pulse Transient method [1] showed various effects that depend on specimen thickness of PMMA [2]. Effects of different atmosphere were observed on autoclaved aerated concrete, POROFEN [3, 4, 5]. Depending on paternal shape of the heat source and the specimen geometry the plateau of the values of thermophysical parameters near the recommended one was found. In all cases the measurements were made on several sets of specimen of different geometry.

When the thickness was outside the range of plateau, all tests shown data deviations from the recommended one for increasing thickness of specimen [2, 3, 4, 5].

We assume that effects of non-ideal heat source and contact roughness cause the data shift at lower specimen thickness. The effects of contact resistance are neglected when conductive paste is applied to improve heat transport through contact. In the case of porous material this is not available because the conductive paste could penetrate into the material pores. Thus the contact resistance is greater than for compact materials.

The constriction effect caused by non-ideal paternal shape of the heat source in connection with specimen surface roughness generates not perfect planar temperature field [6]. The heat flux penetrating the specimen is homogenized at some distance from the heat source and measured thermophsical parameters at small thickness of the specimen are shifted. Therefore the specimen thickness at the transient experiments has to be chosen according the rule that the specimen volume penetrated by deformed temperature field should be negligible in comparison with the volume penetrated by the non-deformed temperature field [7]. Similar effect for small thickness of PMMA was observed on thermal conductivity measured by guarded hot plate method [5].

In this paper we are discussing mainly the effects caused by heat losses from the free specimen surface. Heat loss effect is active at larger specimen thickness. The penetrated temperature field in the specimen is deformed by the heat flux from the free specimen surface. Effect of heat loss at the larger specimen thickness is discussed. The aim was to find optimal geometry, e.g. the thickness range with stabile and reliable data.

2 Theory

2.1 Ideal model

The principle of the Pulse Transient Method and specimen arrangement are shown in Figure 1. Standard specimen set consists of three pieces of investigated material. The heat pulse is generated by passing of the electrical current through the plane electrical resistor made of a copper or nickel foil of 20 microns thick. The temperature response is measured by a thermocouple. The thermophysical parameters are calculated from the parameters of the temperature response to the heat pulse. The temperature increase of transient record depends on the material. Typical temperature increases are between 0.5 K and 2 K. Theoretical model for this technique was described in [1], and the approximate solution valid for the maximum of the temperature response gives simple formulas for the calculation of thermophysical parameters. The thermal diffusivity is given by

$$a = h^2 / 2t_m \tag{1}$$

the specific heat by

$$c = \frac{Q}{\sqrt{2\pi e}\rho h T_m} \tag{2}$$

and the thermal conductivity by

$$\lambda = a\rho\, c \tag{3}$$

where, $Q = RI^2 t_o$, R is the electrical resistance of the heat source, ρ is density and other parameters are given in Fig. 1.

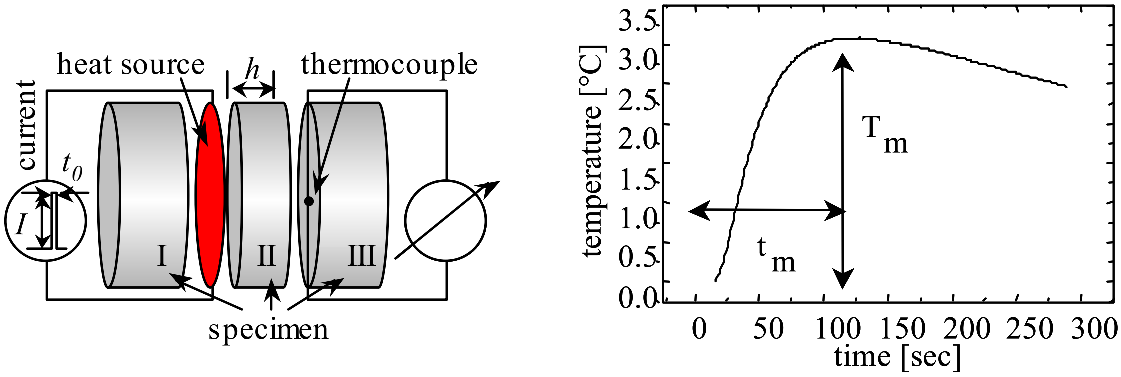

Figure 1. Principle of the Pulse Transient Method and an example of the temperature response.

2.2 Modified model

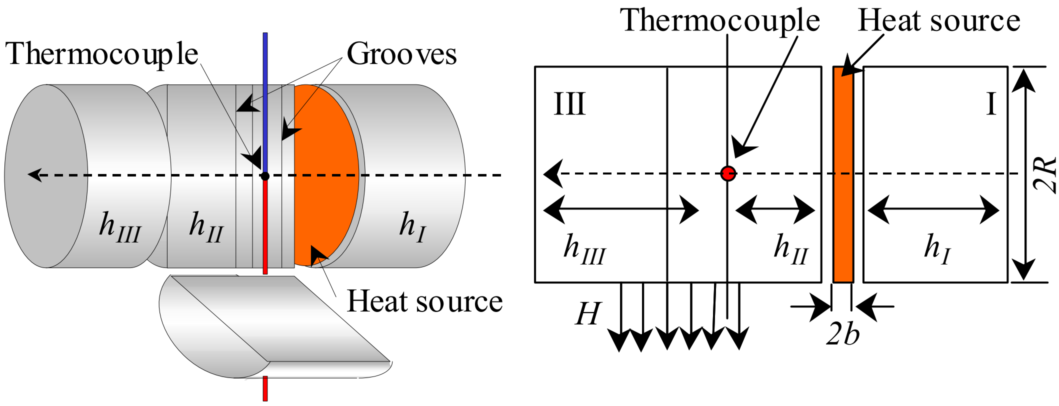

Figure 2. Modified specimen set for measurements using various thickness of the specimen (left) should have cylindrical or brick shape. Model for heat losses from the specimen free surface is on the right. Thermocouple should be placed into a grooves made at different distances h_{II} from the heat source.

Usually, at routine measurements by pulse transient technique [1] an ideal model for the calculations of thermophysical parameters (specific heat, thermal diffusivity and thermal conductivity) is used that doesn't take into account any effect. One can use more complicated - modified model involving various effects on the account of complicated temperature function and time consuming calculations.

The ideal model of pulse transient method that assumes infinite specimen was modified to include effect of heat losses from the free specimen surface [1]. This model takes into account the finite geometry of the specimen (Fig.2).

Then, the calculated values of thermal diffusivity and specific heat should be corrected using correction factors. [1].

$$a = a^* f_a \tag{4}$$

$$c = c^* / f_c \tag{5}$$

where a* and c* are values calculated according (1) and (2), respectively. f_a and f_c are transcendental equations

$$f_a = 1 + \frac{\sum_{n=1}^{\infty} \left(\alpha_n^2 h^2 / f_a\right) \frac{\alpha_n J_1(\alpha_n R)}{\left(s^2 + \alpha_n^2\right) J_0^2(\alpha_n R)} \exp\left(-\alpha_n^2 h^2 / 2 f_a\right)}{\sum_{n=1}^{\infty} \frac{J_1(\alpha_n R)}{\left(s^2 + \alpha_n^2\right) J_0^2(\alpha_n R)} \exp\left(-\alpha_n^2 h^2 / 2 f_a\right)}, \tag{6}$$

$$f_c = \sqrt{f_a \exp(1 - f_a)} \sum_{n=1}^{\infty} \frac{\alpha_n J_1(\alpha_n R)}{R\left(s^2 + \alpha_n^2\right) J_0^2(\alpha_n R)} \exp\left(-\alpha_n^2 h^2 / 2 f_a\right) \tag{7}$$

Here the $J_0(x)$ and $J_2(x)$ are the Bessel functions, $s=H/\lambda$, H is heat loss from the specimen surface, λ is thermal conductivity, f_a and f_c are correction factors for thermal diffusivity and specific heat respectively. R denotes radius of the specimen. α_n are roots of equation

$$\alpha_n J_1(\alpha_n R) - s J_0(\alpha_n R) = 0 \tag{8}$$

3 Experiment

For application of the material in construction the investigated thermophysical parameters should be measured as close as possible to real working conditions. Thus the method used should allows to simulate the change of working temperatures under various atmospheres (contribution of the gas and moisture in pores to the heat transport) and possibility to suppress influence of heat loss effects at larger specimen thickness (esp. for non-homogeneous materials). All these attributes fulfill the instrument RTB1.01 based on Pulse Transient method that gives all 3 thermophysical parameters within single measurement: specific heat, thermal diffusivity, thermal conductivity

Investigated material – the calcium silicate boards reinforced by cellulose fibers had the total porosity 0.9 m^3m^{-3} and the density 280 kg m^{-3}. A modified specimen set of Calcium-Silicate board in the shape of brick has the base dimension 150x150 mm. The thickness of one part of measured bricks was 38 mm. A middle part was cut into two pieces in longitudinal direction and a series of grooves corresponding to various thickness of specimen was made in radial direction. The grooves corresponding various thickness of material were arranged at the distances from the heat source in the range from 5 to 38 mm. The thermocouple was placed into these grooves. Changing the distance (the groove) from the heat source we measured thermophysical parameters for various thickness of specimen. This design of the specimen guarantees, that measurements were made on the same piece of the material for all thickness.

We assume that the modified specimen set doesn't influence the physical model, as the heat is transported in axial direction. In this way we avoid the troubles with the possible contact effects between the second and third part of the specimen set (Fig.1.). The previous tests made on specimen sets shown in fig.1 shown that just usual statistical difference between measurements on standard and modified specimen sets was found [2].

The pulse width of 5-120 s, the heat pulse energy of 5000-40000 Jm^{-2} was used. The temperature response T_m in the range of 0.5 up to 2°C was obtained. The heat pulse was generated by the heat source having the thickness of 0.25 mm, the electrical resistance 11 Ω, the metallic strips width 2.5 mm and the spaces between strips 1.5 mm.

4. Results

The experimental results are plotted on fig 3, 4 and 5. Figure 3 shows investigation of relaxation effects when changing the atmosphere (air-vacuum-air) for the specimen thickness 15 mm. The values of specific heat are changing in time when atmosphere from porous specimen was evacuated. Material was relaxed after 42 hours. The transport parameters are changing rapidly due to environmental atmosphere. As it was presumed, the measured thermophysical parameters are dependent on atmosphere that fills the pores. Figure 5 illustrates the difference of thermophysical parameters measured in different atmospheres for the specimen thickness 15, 20 and 30 mm. Subsequent aeration of the system caused the difference in thermophysical parameters comparing an initial state before evacuation (Figure 3). This difference was removed by reassembling of the specimen set providing that individual parts of the specimen set were exposed one hour on air atmosphere. After reassembling of the specimen set the measured thermophysical parameters were of nearly the original values as before the evacuation. The exception is the higher value of specific heat. In this case at aeration the penetrated moisture to the pores invoke mechanical stresses in the material structure.

This effect should be explained by the shrinkage strain effect during decreasing humidity that was observed earlier on the same specimens of calcium silicate boards [8].

The effects of constriction and contact resistance for small thickness as well as heat losses for large thickness of the specimen are shown in fig. 4. The contact effects influence measured values of thermophysical parameters for the thickness of the specimens up to 15 mm.

The effect of heat losses is evident for specimen thickness larger than 25 mm. There is a clear region of stabile values for the thickness of the specimen from 15 up to 23 mm. Averaged data calculated from this interval are drawn as lines in fig.4.

Effect of heat losses from the free specimen surface is increasing with the increasing thickness of the specimen. The correction procedure was applied for values of the heat loss coefficient H from 0.01 up to 5 $Wm^{-1}K^{-1}$. The value of H 0.1, 1, and 5 $Wm^{-1}K^{-1}$ change correction very moderately or gives practically the same results. The correction was calculated by equations 4 and 5 [1]. The measured and corrected data are shown in Fig.4. The calculations were performed for various values of heat loss coefficient H. The heat loss coefficient $H=5\ Wm^{-1}K^{-1}$ matches best to equalize the corrected data with the intercompared one. $H=5\ Wm^{-1}K^{-1}$ is physically acceptable value. Corrected values are marked as circles in the figure 4 and one can see that this procedure can prolong the data stability interval comparing the data evaluated from experiment by standard procedure (equations 1, 2 and 3).

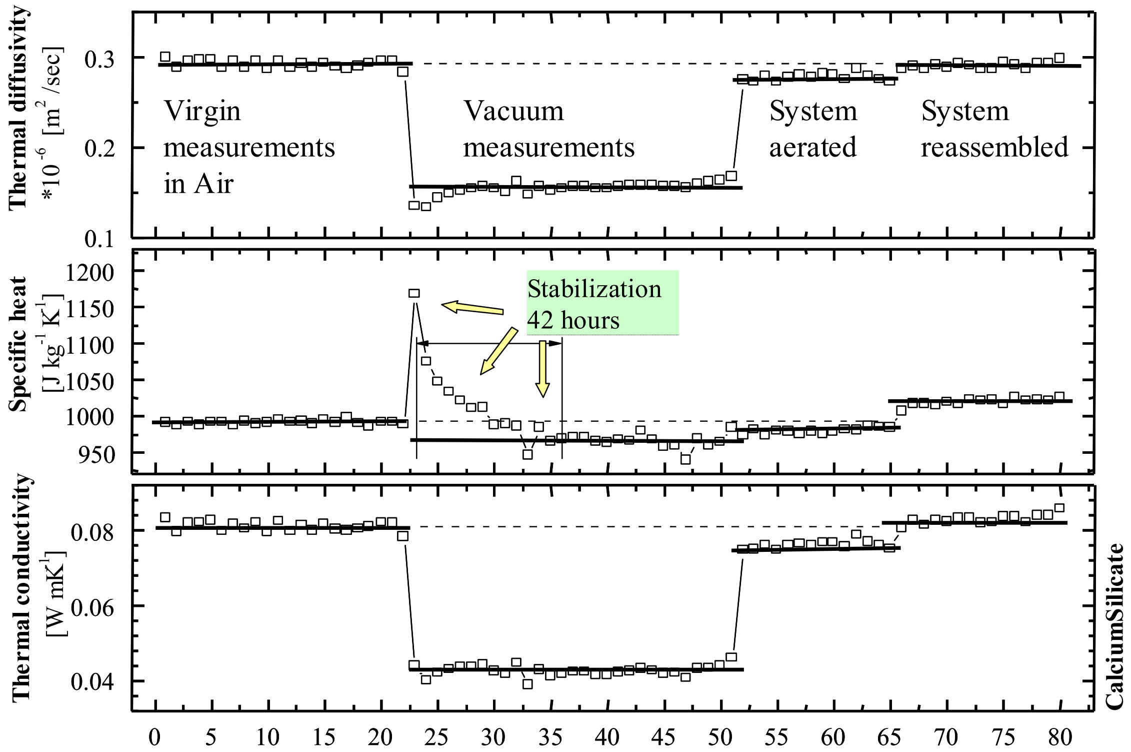

Figure 3 Investigation of stability at the change of atmosphere (air-vacuum-air). Relaxation of material within 42 hours was observed. Nearly original values were obtained after reassembling of the specimen set.

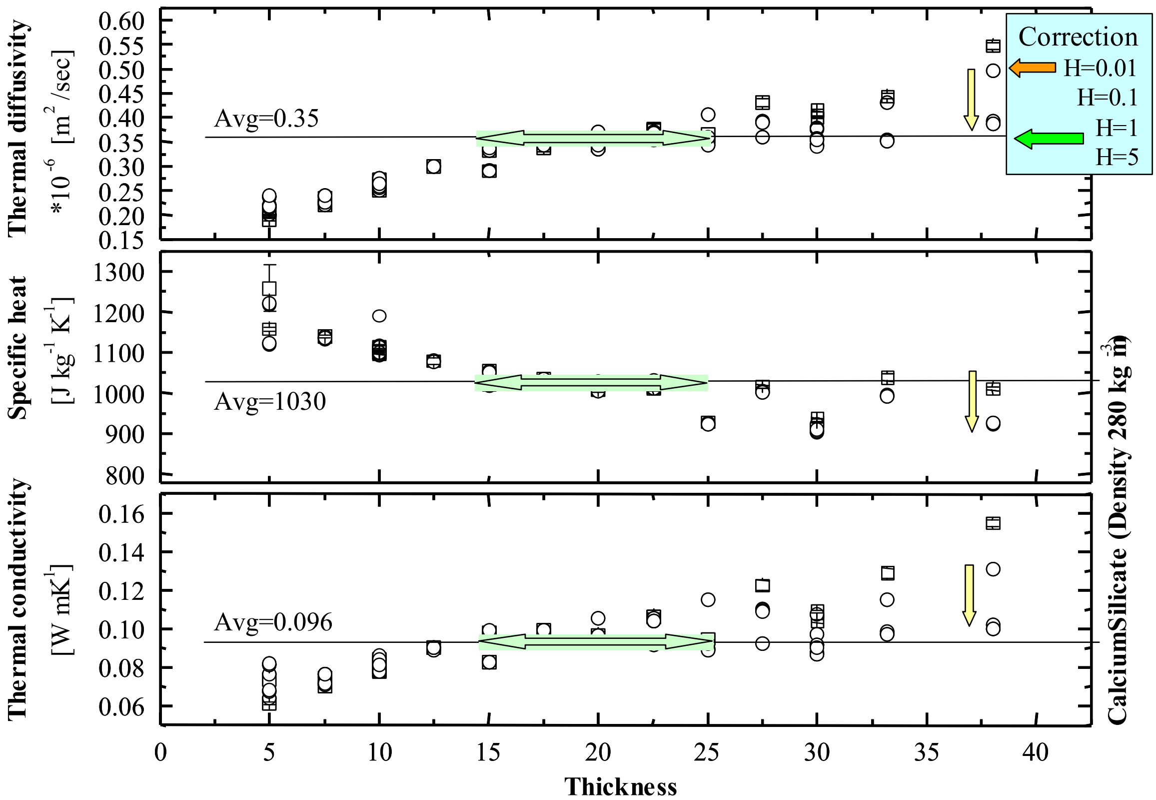

Figure 4. Thermophysical data plotted at various thickness of the specimen. Data are influenced by shrinkage effect at small thickness and by heat losses at large thickness.

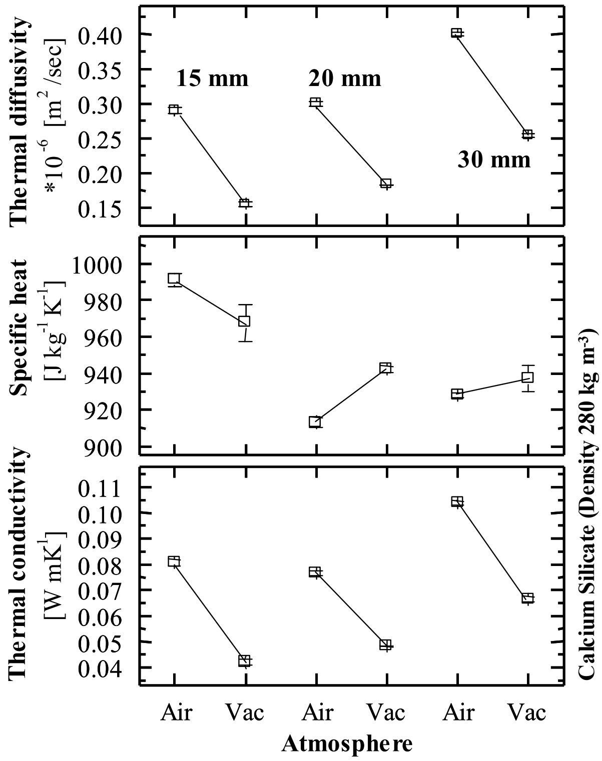

Figure 5. Effect of different atmosphere in pores measured at various thicknesses.

5 Conclusion

The thermophysical properties of porous material - Calcium-Silicate boards reinforced by cellulose fibers were investigated by pulse transient method.

Thickness optimization procedure was used to find the optimal range of thickness where data stability interval exists, e.g. the disturbing effects like heat losses from specimen free surface, constriction and contact effects are suppressed. The analysis of these effects was discussed. Analysis shows clear plateau with reliable thermophysical data at the range of specimen thickness between 15 and 23 mm.

It was shown that the data shift of thermophysical parameters for bigger thickness of the specimen is possible to explain within a theory of heat losses from the specimen free surface. Applied correction procedure can prolong the data stability interval.

Influence of the surrounding atmosphere on the measured data was found (clearly mechanism of the heat transport in the system of porous material is influenced by gas and humidity in pores as well as by radiation).

The simple ideal model can be used for reliable data determination providing that the experimental setup is designed within presented analysis.

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