Development of a New Model for the Pulse Transient Technique

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Abstract. *The problems connected with deficiency in a large amount of testing material cause some problems in data evaluation as an ideal model usually assumes infinitively large specimen. The finite geometry of the specimen cause additional effects that harm the efficiency of the measurement evaluation. In this paper a new model was introduced that includes the effect of heat capacity of the heat source and completes the series of models introduced previously for the effects of heat losses from the sample surface.*

Keywords: pulse transient method, thermal conductivity, thermal diffusivity, specific heat

1. Introduction

Ideal model with infinite specimen geometry is used to keep a low number of unknown parameters but sometimes do not satisfy the real experiment. A detailed study has to be performed to find experimental circumstances when disturbing effects influence ideal model [1, 2]. Then, a modified model for the real experiment has to be used to take into account additional disturbing effects characterized by corresponding, and usually unknown parameters [3, 4]. In the past we introduced a difference in models based on ideal case when assuming non-infinite specimen geometry and the real pulse duration. New models assume real sample radius, heat capacity of the heat source and heat loss effect from the free sample surface. There were several papers published that covered the problems of the specimen geometry optimization on accuracy of the measurement. Ideal model assumes the infinitively large specimen as well as infinitively thin heat source having neglected heat capacity. Some effects were observed through measurements for thin thicknesses of the investigated material. These additional effects are influencing the measurement and thus the estimated parameters were covered by additional error [1, 2, 3].

For the lower and higher thicknesses the measured values of the thermophysical parameters e.g. specific heat, thermal diffusivity and thermal conductivity, were apparent, e.g. overestimated or underestimated. Analysis of this experiment show that heat losses from the sample surface lowered the measured temperature response and this effect rises with increasing material thickness. In case of lower thicknesses it was found influence of heat capacity of the heat source. Models that include the heat transfer coefficient from the sample surface to the surrounding were published previously [3, 4].

This paper concentrates on the effect caused by heat capacity of the heat source observed on the measurements at lower material thicknesses. In this case the evaluated parameters were below the recommended ones. This effect was caused by inadequate ratio between the heat capacity of the heat source and the measured material [5]. This was the main reason to introduce next parameter - a heat source capacity in a physical model.

2. Experimental method

The principle of the method is to record the temperature transient response to the heat pulse generated by a plane heat source and to calculate the thermophysical parameters from the characteristic features of the measured curve of the temperature response (Fig. 1. right). Transient temperature response measured at the distance *h* from the heat source is calculated according temperature function *T(h,t)* providing that the ideal model (Eq. 1.) is valid [1, 2]. The ideal model assumes that a planar temperature flow is not deformed as it penetrates into the depth of the specimen bulk (white-dotted area in the Fig. 1). The problem is that the temperature isotherms are not planar over the cross section of the specimen but they are deformed at the edges by the heat losses from the sample surface for large distances.

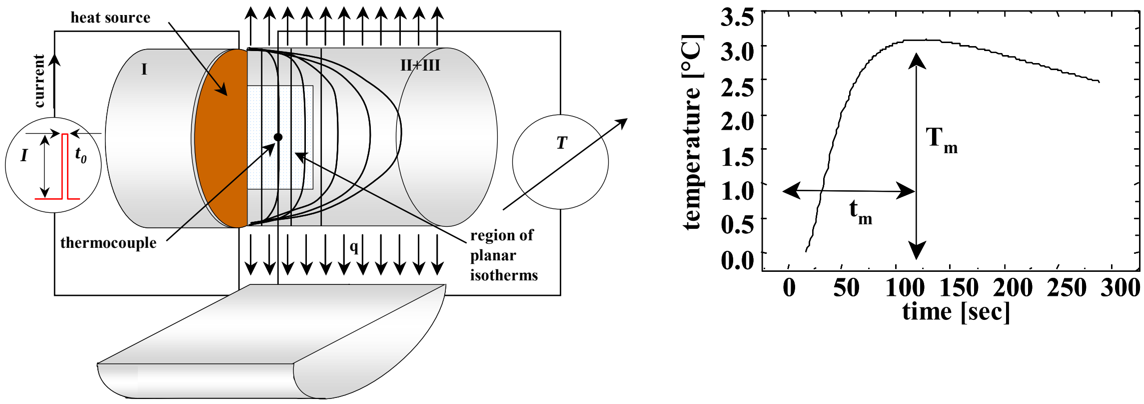

Fig. 1. The principle of the pulse transient method. Specimen set is drawn with heat flow paths when drawn isotherms are influence by heat loss effect (left). An example of the temperature response is on the right.

Model

In previous experiments a correction to the ideal model considering the real pulse width was applied to ideal model. The model is characterized by [1]

$$T(h,t)=\frac{2\cdot Q}{c\rho\sqrt{\kappa}}\left[\sqrt{t}\cdot i\Phi^{*}\left(\frac{h}{2\sqrt{\kappa t}}\right)-\sqrt{t-t_0}\cdot i\Phi^{*}\left(\frac{h}{2\sqrt{\kappa\left(t-t_0\right)}}\right)\right] \tag{1}$$

where $i\Phi^{*}=\frac{e^{-x^2}}{\sqrt{\pi}}-x\cdot erfc(x)$. Here Q means heat flow density at source, c is specific heat, κ is thermal diffusivity, ρ is density and t is time. Equation 1 should be used for data evaluation by fitting procedure.

One point evaluation procedure

At the standard experiment due to fast calculations we use simple relations for the evaluation of thermal diffusivity, specific heat and thermal conductivity. These relations were derived for the maximum of temperature response on Fig.1. (one-point evaluation procedure). The thermal diffusivity is calculated according to the equation

$$\kappa=h^2\cdot f_\kappa/2t_m \tag{2}$$

and the specific heat

$$c=Q\cdot f_c/\sqrt{2\pi e}\rho h T_m \tag{3}$$

where f_κ and f_c are correction factors [5] and ρ is the density of material. Maximum temperature of transient response is T_m at time t_m (Fig. 1.) Thermal conductivity is given by

$$\lambda = a\rho\ c = h\cdot Q\cdot f_\kappa \cdot f_c / 2\sqrt{2\pi e}\ t_m T_m \tag{4}$$

Real model assuming heat capacity of the heat source

A previous explanation of a heat capacity effect was solved in a new model by defining the initial and boundary conditions for the basic heat transport equation. Specimen set is arranged symmetrically in a form of planar boards inserted in between the heat exchangers having infinite large heat capacity stabilized at certain temperature. The thermal contact with the specimen is ideal (thermal contact resistance is zero). The heat source having non-zero heat capacity as well as perfect thermal contact with specimen is placed in between specimen boards. The solution of the heat equation is a temperature function in the form

$$T(t,x) = T_0 \left\{ \left(1 - \frac{x}{L}\right) + 2a\sum_{\upsilon} e^{-\frac{kt}{L^2}\upsilon^2} \times \frac{\upsilon \sin(\upsilon \frac{x}{L}) - a\cos(\upsilon \frac{x}{L})}{\upsilon^2[\upsilon^2 + a(a+1)]} \right\}. \tag{5}$$

where $T_0 = \frac{qL}{\lambda}$, $a = \frac{\lambda L}{C\kappa}$; T is temperature increase, t is time, x Cartesian coordinate, L thickness of sample, q heat flow density at source, λ thermal conductivity, κ thermal diffusivity, C. heat capacity per unit area of source, v is a root of the equation $a\cos\upsilon - \upsilon\sin\upsilon = 0$ and k is the Stefan-Boltzmann constant. The relation (5) characterizes the step-wise measuring regime. After the duration of the heat pulse t_0, the temperature is expressed by the relation

$$T^*(t,x) = T(t,x) - T(t - t_o, x) \tag{6}$$

where $T(t,x)$ and $T(t-t_0,x)$ are given by the relation (5). The relation (6) characterizes the pulse transient regime.

3. Experiment and results

The specimen dimensions of calcium silicate reinforced by cellulose fibers were 150x150 mm in cross section and 40 mm in thickness (all 3 parts of the specimen set). The middle part was cut on two halves. The thermocouple was placed at different position from the heat source, to measure the thermophysical parameters for a range of thicknesses. The experimental details were described in [2, 4]. The theoretical temperature responses were calculated using thermophysical parameters evaluated by three different procedures – one point evaluation (Eq. 2 and 3.), fit of the data using Eq. 6. for the thicknesses up to 17 mm, and model described in [4] that account heat losses from the sample surface for the thicknesses bigger than 17 mm.

In the past the use of the ideal model (Eq. 1) and the one point evaluation procedure led to a problem with the heat capacity that was avoided by optimization of specimen geometry [2]. In practice this limit resulted in limits of the specimen thickness between 17 – 25mm for a class of porous building construction materials. Fig. 2 shows an illustration of this effect measured on a calcium silicate board reinforced by cellulose fibers (square points).

4. Conclusions

The new model assuming heat capacity of the heat source completes the series of models introduced previously for the effects of heat losses from the sample surface. In this case the values of thermophysical parameters were shifted towards the recommended one at lower thicknesses of the material and extended the range of data validity for a broader range of thicknesses. The statistical difference of data within ±5% is marked in Fig 2. for all parameters. The temperature responses theoretically calculated from the parameters obtained by fitting procedure are in good coincidence with the experimental one (Fig. 1.). The one point evaluation procedure that uses the ideal model is available only in the case when optimized specimen geometry is used [2].

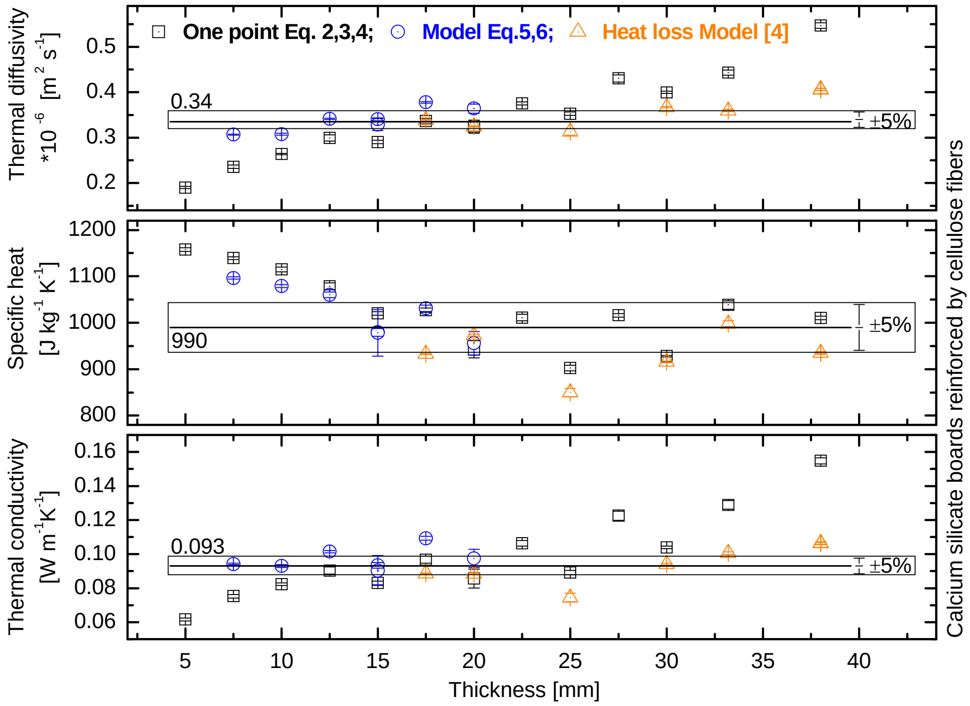

Fig. 2. Thermophysical parameters of calcium silicate boards reinforced by cellulose fibres. Values of one point procedure are compared with real models assuming heat capacity of the source (circles) as well as with model assuming real sample geometry and accounting heat losses from the sample surface [4].

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