The Heat Loss Effect at the Measurements by Transient Pulse Method

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Abstract. *In this paper we bring the new physical approach to a solution of deficiency in a large amount of testing material. It is a real problem of finite geometry of the specimen that additional effects harm the efficiency of standard way of the measurement evaluation. Three different models used for data evaluation are discussed in this paper. As a model material a PMMA specimen was used. There are discussed two approaches how to avoid the problem of heat loss effect in real experiment. The ideal one that assumes infinite geometry in a model and the limited time of recorded data used for parameters evaluation as the temperatures recorded at short times are not influenced by heat loss effect. The new model introduces next parameter - a heat transfer coefficient that represents heat loss effect from the free sample surface. Thermophysical data are given also numerically and agree with recommended data within 6% for all discussed models.*

Keywords: pulse transient method, thermophysical properties, heat loss effect

1. Introduction

A modern technology demands brings together principles of rapid development of materials and their testing methods. Thermal properties of materials are one of basic criteria how to recognize between good and bad in a new offer on a market. Thus the new testing procedures are required in this area also. The class of transient techniques has been developed that should satisfy all the testing requirements of new technology [1, 2, 3, 4, 5]. The use of any technique is conditioned by good knowledge of basic model and the effects influencing the resulted data. In this paper we show the methodology of evaluation procedures and testing of physical models. Three procedures of data evaluation based on two physical models were used. The models were tested on data measured on PMMA specimen. The heat loss effect is discussed and shown using the model with infinite geometry and a model assuming real sample radius and heat losses from it's free surface.

2. Theory

Ideal model with infinite specimen geometry is used to keep 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. Then, the modified model has to be used that take into account additional disturbing effects characterized by corresponding, and usually unknown parameters [6, 7, 8, 9]. In the following we introduce a difference in models based on ideal case when assuming infinite specimen geometry and the real pulse duration and a new model with real sample radius and heat loss effect from the free sample surface. The principle of the method is to record the temperature transient response to the heat pulse generated by plane heat source and to calculate the thermophysical parameters from the characteristic features of measured curve (Fig. 1). Transient temperature response measured at the distance h from the heat source is calculated according temperature function $T(h,t)$ providing that ideal model (Eq. 1.) is valid [1]. In an ideal model we assume that a planar temperature wave is not deformed as it penetrates into the deep 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 and are deformed at the edges by the heat losses from the sample surface for large distances.

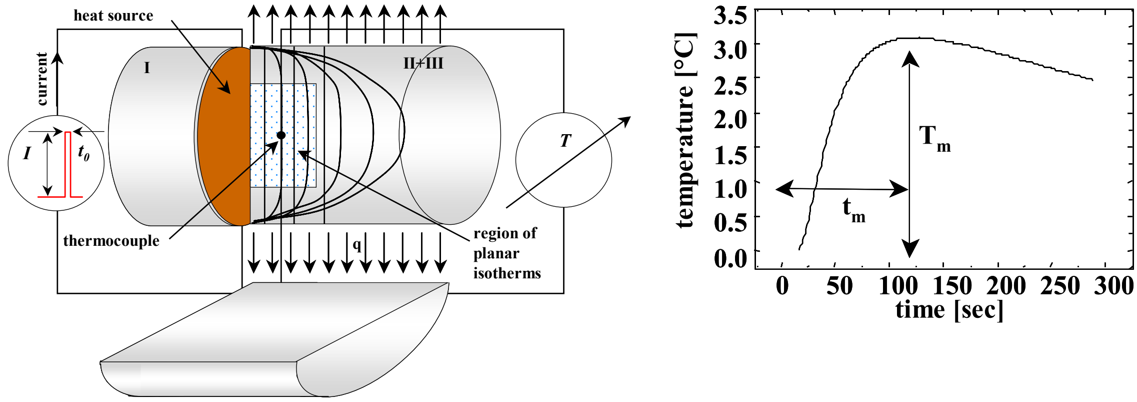

Figure 1. The principle of the pulse transient method and the heat loss effect model with drawn isotherms (left). The example of the temperature response for PMMA is on the right.

Ideal model

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

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

where

$$i\Phi^{*} = \frac{e^{-x^2}}{\sqrt{\pi}} - x\cdot erfc(x) \qquad (2)$$

Here Q means total pulse heat energy, c is specific heat, a is thermal diffusivity and t is time. Equation 1 should be used for data evaluation by fitting procedure.

One point evaluation model

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

$$a = h^2/2t_m \cdot f_a \qquad (3)$$

and specific heat

$$c = Q/\sqrt{2\pi e}\rho h T_m \cdot f_c \qquad (4)$$

where f_a and f_c are correction factors and ρ is the density of material. T_m is maximum of temperature transient response at time t_m (Fig. 1.)

$$f_a = (t_m/t_0 - 1)\cdot \ln\left(\frac{t_m/t_0}{t_m/t_0 - 1}\right) \qquad (5)$$

$$f_c = 2\cdot \exp(1/2)\sqrt{\pi f_a}\cdot t_m/t_0\left\{1/\sqrt{\pi}\left[\exp(-f_a/2) - \sqrt{(t_m/t_0-1)/t_m}\exp(t_m/t_0\, f_a/2(t_m/t_0-1))\right] - \right.$$
$$\left. - \sqrt{f_a/2}\left[\Phi^{*}\left(\sqrt{f_a/2}\right) - ercf\left(\sqrt{t_m/t_0\, f_a/2(t_m/t_0-1)}\right)\right]\right\} \qquad (6)$$

Thermal conductivity is given by

$$\lambda = h^2 Q / 2t_m \sqrt{2\pi e} h T_m \tag{7}$$

Real model

A previous explanation of a heat loss effect was solved in a new model by defining the initial and boundary conditions for basic heat transport equation. The heat losses were taken into account at real radius of the specimen and heat source R at infinite length l. The model parameters are of the same meaning like in an ideal model. The heat loss from the specimen surface is considered by heat transfer coefficient α. The temperature function of the heat equation according to [10] has a form

$$T(t,x,r) = \beta \frac{q}{\lambda} R \sum_{i=1}^{\infty} \frac{J_0\left(\xi_i \frac{r}{R}\right)}{\xi_i\left(\xi_i^2 + \beta^2\right) J_0(\xi_i)} \left[e^{-\xi_i \frac{x}{R}} \Phi^*\left(\frac{x}{2\sqrt{kt}} - \xi_i \frac{\sqrt{kt}}{R}\right) - e^{\xi_i \frac{x}{R}} \Phi^*\left(\frac{x}{2\sqrt{kt}} + \xi_i \frac{\sqrt{kt}}{R}\right)\right] \tag{8}$$

where $\beta = \frac{\alpha R}{\lambda}$; $\{\xi_i\}$ are the roots of the equation $\beta J_o(\xi) - \xi J_1(\xi) = 0$, q – is the heat output power of the heat source and $\Phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$, $\Phi^*(x) = 1 - \Phi(x)$.

The relation (8) characterizes the step-wise measuring regime. For the duration of the heat pulse t_0, the temperature for $t > t_0$ is expressed by the relation

$$T^*(t,x,r) = T(t,x,r) - T(t - t_o, x, r) \tag{9}$$

where $T(t,x,r)$ and $T(t - t_0, x, r)$ are given by the relation (8). The relation (9) characterizes the pulse transient regime.

3. Results

In the past using ideal model (Eq. 1), and one point evaluation procedure the problem with the heat loss effect was avoided by optimized geometry and limited time for data evaluation by fitting procedure [9]. In practice this limited time region was named as a “time window for data evaluation” and was already taken from a region of temperatures recorded at lower times, e.g. the times when temperatures did not reached the maximum of the temperature response. For the calculation of theoretical response the evaluated parameters were used for the calculation of theoretical response. With an increasing time the increase of temperature difference between the theoretically calculated temperature response and really measured data was observed. These differences satisfy to effect of the heat loss from the sample surface. Figure 2 shows an illustration of this effect measured on PMMA specimen. The specimen diameter was 30 mm and the length of three parts was 30, 14 and 20 mm. The experimental details were described in [9]. 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 for small times up to 200 s. using Eq. 1 and the fit of all data using Eq. 9. The difference in shape of a theoretically calculated temperature responses using equation 1 and 2 is evident. In the case of real sample radius the values of the temperature response theoretically calculated fits the experimentaly measured one.

4. Conclusions

The new model assuming real sample radius and heat loss effect from the sample surface fits the real experiment and operates automatically. The fitting procedure based on model assuming infinite sample geometry should be used just in a time window of the initial onset of the temperature response. This procedure requires to sets manually the time window for evaluation by fitting procedure and thus it is not so objective. The one point evaluation procedure that use ideal model is available only under the condition when optimized specimen geometry is used [9].

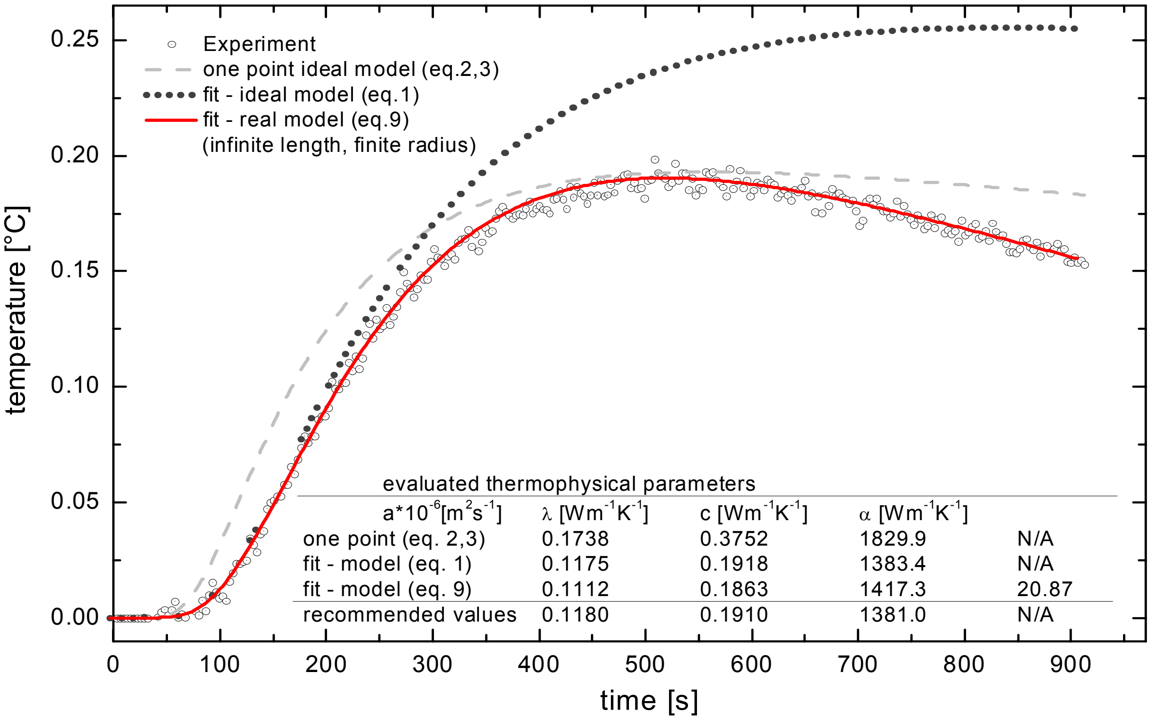

Figure 2. Temperature response measured for the sample thickness of 14.2 mm compared with theoretically calculated one according ideal model (Eq. 1) and real model (Eq. 9).

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