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New method for data reduction in flash method

L. VOZÁR, J. GEMBAROVIČ and V. MAJERNÍK
Katedra fyziky, Pedagogická fakulta, Lomonosovova 1, Nitra CS-949 74, Czechoslovakia

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INTRODUCTION

THE PULSE 'flash' method [1] is actually the most popular method of measuring the thermal diffusivity of solids, especially at high temperatures. In this method, the front face of a small disc-shaped specimen is subjected to a very short burst of radiant energy coming from either a laser or a xenon flash lamp. The resulting temperature rise of the rear surface of the specimen is recorded and the value of the thermal diffusivity is computed from this temperature vs time data.

There exist several original methods for data reduction in the flash method. The first group includes a method in which the thermal diffusivity is calculated using one or a few characteristic experimental points [1, 2]. In the second group all the experimental points of temperature vs time data (in particular their rising part) are used for diffusivity determination. Such methods are based on fitting the experimental data by theoretical curve by means of a least square procedure [3–5]. In all the mentioned methods the precision of results depends on satisfying the conditions, which are assumed in the ideal theoretical model of the flash method [1] (heat pulse is uniform and instantaneous; sample is opaque, homogeneous, and thermally insulated; thermal properties are temperature independent).

In the real case heat transfer between the sample and its environment is usually unavoidable, especially for high temperature measurements or for materials with poor conductivity. Several original methods were proposed which take into account this effect. In refs. [6–9] the thermal diffusivity determined from the ideal condition model is corrected by multiplying with the appropriate numerical factor, depending on heat losses. Another way is used in methods based on the general mathematical model [10] obtained as a solution to a two-dimensional heat conduction equation with the heat losses from the whole sample surface. In those methods the thermal diffusivity is determined either by means of several particular points of the temperature vs time data [10, 11] or using the temporal moments of the defined temperature interval of the rising part of the experimental curve [10, 12]. An original way to eliminate the heat loss effect, described in ref. [13], is based on the knowledge, that rear surface temperature history is less perturbed as time is nearer to the time origin (time of flash). Thermal diffusivity is obtained by extrapolating the time evolution of experimentally gained values of 'apparent' thermal diffusivity to time zero.

In this paper the data reduction method is presented, which eliminates the effect of heat losses using the procedure of extrapolation, similar to that in ref. [13]. Apparent values of thermal diffusivity are calculated using the so-called 'logarithmic' method [5]. Results of testing and comparison with other existing methods are also given.

PRINCIPLE OF METHOD

The logarithmic method [5] for thermal diffusivity determination is based on the relation

$$\ln(t^{1/2}T) = \ln[2T_{\lim}(e^2/\pi\alpha)^{1/2}] - e^2/4\alpha t \tag{1}$$

where t is time, $T = T(e, t)$ the temperature of the rear face of the sample, e the sample thickness, α the thermal diffusivity, and $T_{\lim}$ the adiabatic limit temperature of the sample after the pulse. Equation (1) is an approximation of the formula, derived from the one-dimensional heat conduction equation using Laplace transformation and can be used over the time region in which the condition $T/T_{\lim} \leqslant 0.9$ is fulfilled.

In the ideal case the plot $\ln(t^{1/2}T)$ vs $1/t$ is a straight line, and the thermal diffusivity α is calculated by means of the slope K of this line using the formula

$$\alpha = -e^2/4K \tag{2}$$

which is independent of $T_{\lim}$.

The adiabatic limit temperature $T_{\lim}$ can be calculated through the point of intersection Q of the regression line with the axis of ordinates. According to equation (1) we have

$$T_{\lim} = (\pi\alpha)^{1/2}\exp(Q)/2e. \tag{3}$$

In the real case, when the heat transfer between the sample and its environment is non-zero, the experimental curve $\ln(t^{1/2}T)$ vs $1/t$ is distorted due to the effect of heat losses. Therefore, the slope K and the point of intersection Q of the regression line with the axis of ordinates became a function of the time point, around which the linear regression is used ($K = K(t)$ and $Q = Q(t)$). The apparent diffusivity $\alpha(t)$, and apparent limit temperature $T_{\lim}(t)$ can be calculated using equations (2) and (3), respectively.

In the method presented the values of thermal diffusivity and adiabatic limit temperature are specified by extrapolating time evolutions of the apparent diffusivity and apparent limit temperature, respectively, towards the initial time. From this point of view, our method corresponds to the procedure described in ref. [13]. However, in our algorithm the apparent diffusivity is independent of the apparent limit temperature and, consequently, the thermal diffusivity is independent of the adiabatic limit temperature. In addition, our method enables one to determine the value of the adiabatic limit temperature when using the analogical procedure as in the case of thermal diffusivity.

We see that the procedure presented transforms the problem of correction to the effect of heat losses to a mathematical problem of regression analysis.

In order to find the value of thermal diffusivity from the time evolution of the apparent diffusivity the polynomial regression of second order is used

$$\alpha(t) = \alpha_0 + \alpha_2 t^2 \tag{4}$$

NOMENCLATURE

e	sample thickness
K	slope of regression line
$K(t)$	apparent slope
Q	intersection of regression line with axis of ordinates
$Q(t)$	apparent intersection
R	sample radius
t	time
T	temperature
T_{lim}	adiabatic limit temperature
$T_{lim}(t)$	apparent limit temperature
T_{max}	maximal temperature rise.

Greek symbols

α	thermal diffusivity
$\alpha(t)$	apparent diffusivity
$\alpha_0, \alpha_2, \beta_0, \beta_1, \beta_2$	constants.

which approximates well the function $\alpha(t)$ for time intervals less than a quarter of the time of the temperature rise in the transient state after the pulse. For time intervals which exceed this one the higher term of the polynomial regression should be taken in equation (4).

For the time evolution of the apparent limit temperature we found the fitting formula

$$T_{lim}(t) = \beta_0 + \beta_1 \exp(-\beta_2 t). \tag{5}$$

The values of the constants α_0, α_2, β_0, β_1, and β_2 are calculated by the standard least square method. Finally, the thermal diffusivity is equal to α_0, and the adiabatic limit temperature $\beta_0 + \beta_1$.

The sensitivity of this method to the choice of the time range for computing of the apparent diffusivity and the apparent limit temperature can be decreased when using the weighted regression procedure. Every point $\alpha(t)$ (or $T_{lim}(t)$) can be taken into account with the weight, which corresponds to this uncertainty. The weight functions of the apparent diffusivity and the apparent limit temperature can be calculated by using the standard mathematical procedures for least square fitting.

Here we note that the determination of thermal diffusivity as a mean value of the apparent diffusivity is similar to the algorithm used in ref. [5].

VERIFICATION

The method presented was first tested on the set of theoretical temperature vs time curves, some of which are shown in Fig. 1. These data were obtained using the two-dimensional model of the flash method [10], in which the heat losses are governed by Biot numbers H_1, H_2, and H_3 related to the front, rear, and lateral faces of the disc sample with radius R.

The time evolution of the apparent diffusivity and the apparent limit temperature are shown in Figs. 2 and 3, respectively. Solid lines represent regression curves (equations (4) and (5), respectively). The numbers associated with the curves indicate the correspondence with curves shown in Fig. 1.

The results of our simulation (see Table 1) can be summarized as follows.

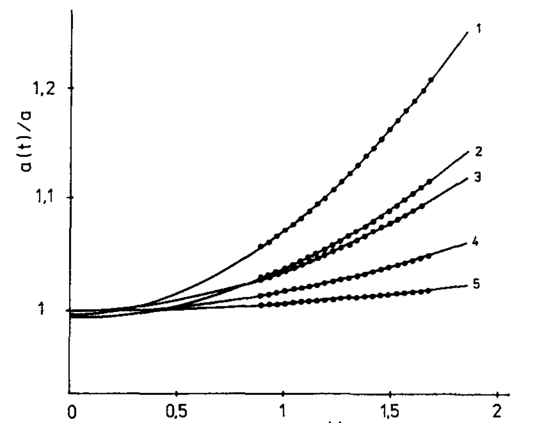

FIG. 2. Time evolution of apparent diffusivity $\alpha(t)$ and regression parabolas $\alpha_0 + \alpha_2 t^2$ for simulations Nos. 1–5.

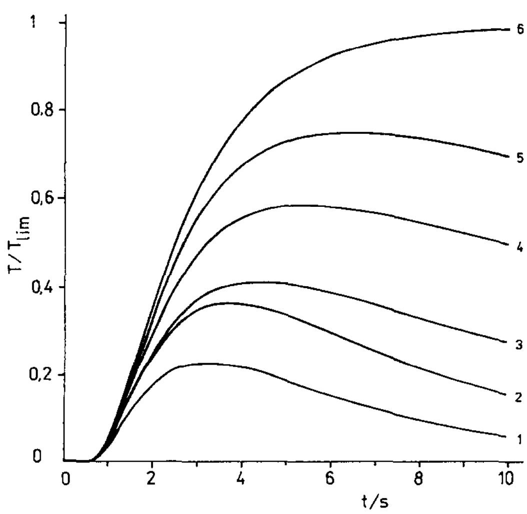

FIG. 1. Rear face temperature vs time evolution of samples with various heat losses (Nos. 1–5), and adiabatic sample (No. 6).

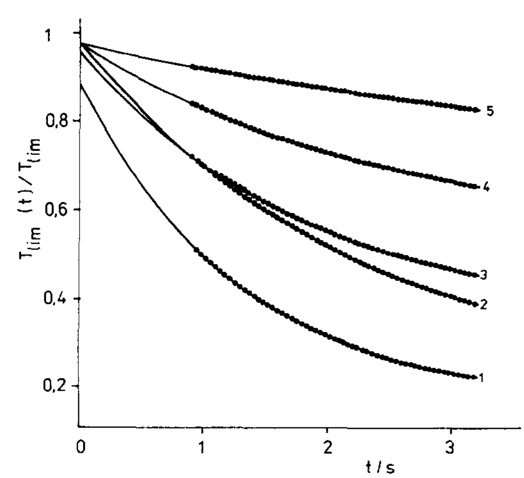

FIG. 3. Time evolution of apparent limit temperature $T_{lim}(t)$ and regression curves $\beta_0 + \beta_1 \exp(-\beta_2 t)$ for simulations Nos. 1–5.

Table 1. Results of simulation. The correct values of α and T_{lim} are equal to 1

Curve No.	H_1	H_2	H_3	R/e	α	α (%)	T_{lim}	T_{lim} (%)
1	2.1	2.1	2.1	1.5	0.997	−0.26	0.912	−8.8
2	1	1	1	1.1	0.993	−0.66	1.003	0.3
3	1.01	1.01	1.01	5	1.002	0.16	0.977	−2.3
4	0.51	0.51	0.01	2	1.001	0.08	0.993	−0.7
5	0.2	0.2	0.2	1.5	1.001	0.08	0.99	−1

Table 2. Experimental results and comparison with other methods (values are in 10^{-7} m^2 s^{-1})

Method	Ceramic	Plaster
Parker *et al.* [1]	8.256	1.988
Takahashi *et al.* [5]	7.361	1.568
Degiovanni *et al.* [11]:		
$\alpha_{1/3}$	6.751	1.429
$\alpha_{1/2}$	6.652	1.467
$\alpha_{2/3}$	6.606	1.502
Degiovanni et Laurent [12]	6.933	1.473
Balageas [13]	6.863	1.474
Present method	6.735	1.474

(1) In the range of $T_{lim}/T_{max} \leqslant 5$, where T_{max} is the maximal value of the temperature rise of the rear surface after the pulse (in tested interval $0.5 \leqslant R/e \leqslant 5$), the thermal diffusivity can be evaluated with precision better than 0.7%.

(2) In the range of $T_{lim}/T_{max} \leqslant 3$ the adiabatic limit temperature can be evaluated with precision better than 5%, and the relative error will not exceed 10% when $T_{lim}/T_{max} \leqslant 5$.

The second test of this data reduction method was performed on some real experimental data gained from two samples. The comparison of our results with the results determined by other methods is given in Table 2. This table shows that the precision of the values obtained by the present method is comparable with other special data reduction methods [11–13].

CONCLUSION

The main advantage of the present data reduction method consists of the fact that the thermal diffusivity is determined without the knowledge of T_{lim} (or T_{max}), and a reliable result is obtained even in the case when the heat losses from a sample are considerably high. This is why any section of the rising part of the temperature vs time curve can be used for the data reduction.

This method can also be applied to very noisy signals, provided that the perturbations have a Gaussian distribution.

The limitations of the use of our method arise from its sensitivity to the distortions of earlier parts of the experimental curve due to such effects as, e.g. finite pulse time effect, or inertia of temperature sensors. The uncertainty of the results increased when the low frequency noise occurred.

The method presented may have a large field of application in the measurements of low conductivity materials, especially at high temperatures.

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