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Flash method of measuring the thermal diffusivity. A review

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Abstract. It is more than forty years since Parker et al (1961 *J. Appl. Phys.* **32** 1679 – 1684), working for the US Navy Radiological Defense Laboratory, released their original paper introducing the flash technique. Since then this photothermal experimental method has been extended worldwide and it has become the most popular method for the measurement of the thermal diffusivity of solids. The simplicity and the efficiency of the measurement, the accuracy and the reliability of results, and possibilities of application under a wide range of experimental conditions and materials are the main advantages of the flash method. The fact that the flash method has received standard status in many countries acknowledges its universality.

We present an up-to-date summary of the theory and application of the flash method. We discuss the ideal adiabatic model and non-ideal models that account for the influence of the main disturbing phenomena — heat losses from the sample, finite heat pulse durations, and nonuniform heating effects. The paper focuses on the survey of data-reduction methods — algorithms for calculation of thermal diffusivity from the experimental data. It provides also references to several original papers with descriptions of the experimental apparatus. Attention is given to applications of the flash method for the measurement of advanced materials — semitransparent media, materials with significant dependence of their thermophysical properties on temperature, anisotropic materials, layered structures, thin films, and composites. The paper contains a short note about various experimental methods having their origin in the flash method.

1 Introduction

The concept of the laser flash method is rather simple. The front face of a small wall-shaped sample receives a pulse of radiant energy coming from a laser or a flash lamp. The thermal diffusivity value is computed from the resulting temperature response on the opposite (rear) face of the sample.

Parker et al (1961) are credited with the first analytical treatment as well as the first application of the flash method. Since then a lot of original contributions have appeared in the literature that led to a significant progress in the development of the method. Several review articles have summarised the current state of the art in theory and practice of the method (Righini and Cezairliyan 1973; Degiovanni 1977; Taylor 1979; Balageas 1989; Taylor and Maglić 1984; Maglić and Taylor 1992; Sheindlin et al 1998; Baba and Ono 2001; Vozár 2001).

2 Theory

2.1 *The ideal model*

The simple ideal analytical model of the flash method is based on the thermal behaviour of a homogeneous opaque thermally insulated infinite slab of thickness e uniformly subjected to a short heat pulse of radiant energy over its (front) surface. The model assumes that the sample is homogeneous and isotropic, and the thermophysical properties and the density ρ are uniform, constant, and invariant with temperature within the experimental conditions; the sample is thermally insulated; the heat pulse is uniformly distributed over the slab surface, and it is absorbed by a layer of material which is very thin in comparison to the thickness of the sample; and that the heat pulse is instantaneous, and its duration is negligible compared to the thermal response of the slab. The one-dimensional heat flow occurs across the slab under these assumptions, and the transient rear surface temperature $T(t)$ can be represented by the Fourier series (Parker et al 1961):

$$T(t) = T(e,\, t) = \frac{Q}{\rho c e}\left[1 + 2\sum_{n=1}^{\infty}(-1)^n \exp\left(-\frac{n^2\pi^2 a t}{e^2}\right)\right] , \tag{1}$$

where Q is the radiant energy per unit surface area, c the specific heat, and a the thermal diffusivity. The adiabatic-limit temperature $T_{\mathrm{lim}} = Q/\rho c e$ is the temperature the sample reaches in an infinite time.

Utilising the Laplace transformation technique, the evaluation of the transient rear face temperature rise can be written down in the form (Takahashi et al 1988):

$$T(t) = T_{\mathrm{lim}}\frac{2e}{(\pi a t)^{1/2}}\sum_{n=0}^{\infty}\exp\left[-\frac{(2n+1)^2 e^2}{4at}\right] . \tag{2}$$

This series has very good convergence at an early stage of time (for small values of at/e^2). It is thus complementary to the solution (1) that converges most rapidly at large values of time.

2.2 *Disturbing phenomena*

The precision of the flash method depends on maintaining experimental conditions required to satisfy the assumption formulated as the initial and boundary conditions of the analytical model. However, in a real experiment, heat transfer between the sample and its environment is usually unavoidable, especially in high-temperature measurements or in investigations of materials with poor thermal conductivity. The influence of non-uniformity and finite duration of the heat pulse may distort the experimental behaviour, especially in the case of measurements on thin samples and/or on materials with good thermal conductivity.

2.2.1 *Heat losses.* The heat transfer between the sample and its environment is mathematically well described for a disk-shaped sample of radius r_{s}. For the case of linearised boundary conditions for heat losses, the heat transfer between the sample and its environment can be analytically evaluated by Biot numbers related to each face of the sample ($Bi_0 = h_0 e/k$, $Bi_{\mathrm{e}} = h_{\mathrm{e}} e/k$, and $Bi_{\mathrm{r}} = h_{\mathrm{r}} r_{\mathrm{s}}/k$, with h_0, h_{e}, and h_{r} being heat transfer coefficients for the front, rear, and lateral faces, respectively). The transient temperature is

$$T(t) = T_{\mathrm{lim}}\sum_{n=1}^{\infty} A_n(Bi_0,\, Bi_{\mathrm{e}})\sum_{m=1}^{\infty} B_m(Bi_{\mathrm{r}})\exp\left[-\left(u_n^2 + w_m^2\frac{e^2}{r_{\mathrm{s}}^2}\right)\frac{at}{e^2}\right] , \tag{3}$$

where A_n, B_m, u_n, and w_m are appropriated terms (Watt 1966). The main difficulty in direct application of the model consists in the difficulty of quantitative evaluation of heat exchange between the sample and its environment that may have convective, conductive, as well as radiative characteristics.

2.2.2 *Finite heat pulse duration.* If the real heat pulse has the shape $\phi(t)$, and if $T_\delta(t)$ is a solution of the heat conduction equation that describes temperature rise vs time for an ideal, instantaneous heat pulse, then the rise of the rear-face temperature vs time can be derived with the formula

$$T(t) = \frac{\displaystyle\int_0^t \phi(t')T_\delta(t-t')\,\mathrm{d}t'}{\displaystyle\int_0^\infty \phi(t')\,\mathrm{d}t'} . \tag{4}$$

This theory is easy to introduce as an idea of a sequence of instantaneous pulse sources with appropriate energy applied in times $t = t'$ to which the origin of time is shifted (Watt 1966).

The shape function may be either a real one, found from an experiment, or any simplified approximation can be utilised (for a summary see Vozár 2001). The most common approximations for the heat pulse shape are: square (Cape and Lehman 1963; Watt 1966), sawtooth (Cape and Lehman 1963), triangular (Heckman 1973; Taylor and Clark 1974; Lechner and Hahne 1993), suitable for an adequate approximation of a laser pulse time distribution, trapezoidal (Dusza 1995/1996), exponential (Larson and Koyama 1966; Degiovanni 1987), that describes a xenon flash tube, and linear–exponential (Dusza 1995/1996).

2.2.3 *Nonuniform heating.* Unlike heat losses and finite pulse-time effects, which are significant in selective cases, nonuniform heating can occur in all flash diffusivity experiments. The problem of evaluation of this effect consists in the fact that nonuniformity of the heating may stem from a nonuniform laser-beam energy profile as well as nonuniform absorption of the radiation energy over the front face surface. The influence of the effect on thermal diffusivity estimation has been studied experimentally and also analytically, and particular results for certain nonuniformities have been reported (Watt 1966; Beedham and Dalrymple 1970; Schriempf 1972; McKay and Schriempf 1976; Fabri and Scafe 1992; Baba et al 1993; Yamane et al 1997). It has been experimentally proved that, when the heating is uniform over the central portion of the sample, good results for the thermal diffusivity can be obtained, while nonuniformity over the central portion can lead to substantial errors (Taylor 1975).

In general, the influence of nonuniform heating depends not only on the energy distribution, but also on sample geometry and the way the rear-face temperature is measured. In particular, the error may be neglected when the sample is thick enough ($e/2r_s \geqslant 1$) (Gembarovič 1984; Baba et al 1993). The nonuniform heating effect is most significant for $0.15 < e/2r_s < 0.3$, as demonstrated by Baba et al (1993). Unfortunately, this interval covers the most frequently used sample dimensions.

One very efficient way to overcome the nonuniform heating effect is based on the integration of the rear-face temperature. If the mean temperature over the whole surface is taken as the temperature of the rear face (Degiovanni et al 1985), the errors due to nonuniform heating may be neglected.

3 Data reduction

The known data-reduction methods (the algorithm for computing the thermal diffusivity from experimental data) in the flash method differ either in the analytical mathematical models used, or in the way the measured experimental rear-face temperature vs time data and theoretical curves are compared.

The conventional way to calculate the thermal diffusivity from the experimental data has been that proposed by Parker et al (1961). It is based on specifying the half-time $t_{0.5}$—the time in which the rear-face temperature rise reaches one half of its maximum value. The thermal diffusivity is then calculated from the expression

$$a = 0.1388 \frac{e^2}{t_{0.5}} \ . \tag{5}$$

The logarithmic data-reduction method is based on the first term of the approximate analytical expression (2) for the temperature rise vs time. Here, the thermal diffusivity is calculated from the formula

$$a = -\frac{e^2}{4K} \ , \tag{6}$$

where K is the slope of the $\ln(Tt^{1/2})$ vs reciprocal time $(1/t)$ dependence. The interesting feature of the method is that the thermal diffusivity estimation does not depend on the knowledge of the adiabatic-limit temperature T_{lim} (Takahashi et al 1988).

Algorithms based on fitting the experimental data with an ideal theoretical curve by means of a least-squares procedure utilise minimisation of the function

$$R(a,\ T_{\mathrm{lim}}) = \sum_{i=1}^{N} [T_i - T(t_i)]^2 \ , \tag{7}$$

where T_i are the experimental temperatures measured in times t_i, N is the number of points taken into account, and $T(t_i)$ is the analytical expression for the temperature rise vs time. As shown by Gembarovič et al (1990), the problem of finding the thermal diffusivity can be reduced to solving the equation

$$\sum_{i=1}^{N} T_i \theta_i(a) \sum_{i=1}^{N} \theta_i(a) \frac{\partial \theta_i(a)}{\partial a} - \sum_{i=1}^{N} T_i(a) \frac{\partial \theta_i(a)}{\partial a} - \sum_{i=1}^{N} \theta_i^2(a) = 0 \ , \tag{8}$$

where $\theta_i(a)$ is the theoretical dimensionless temperature rise in time t_i $[\theta_i(a) = T(t_i)/T_{\mathrm{lim}}]$. Use of other least-squares method algorithms has been described by Pawlowski and Fauchais (1986). Šrámková and Log (1995) discuss the application of χ^2 least-squares fitting.

The simplest data-reduction methods that take into account the effect of heat losses from the sample are the ratio methods. Here, the experimental data are compared with the theoretical rear-face temperature vs time curves with heat losses, for several particular points. The thermal diffusivity value calculated with equation (5) is corrected with the use of an appropriate numerical factor that depends (in a nonlinear way) on heat losses. In the procedure proposed by Clark and Taylor (1975) three corrected values of thermal diffusivities can be found from experimental temperature vs time data, giving the ratios of different fractional times $t_{0.8}/t_{0.4}$, $t_{0.8}/t_{0.2}$, and $t_{0.7}/t_{0.3}$, where t_x is the time corresponding to $T/T_{\max} = x$, and $T_{\max}$ is the maximal temperature rise. Degiovanni (1977) derived the set of formulas that give three thermal diffusivity values computed with the use of four different fractional times

$$a = \frac{e^2}{t_{5/6}} P \ , \tag{9}$$

with

$$P_{1/3} = 1.0315 \left(\frac{t_{1/3}}{t_{5/6}} \right)^2 - 1.8451 \frac{t_{1/3}}{t_{5/6}} + 0.8498 \ , \tag{10}$$

$$P_{1/2} = 0.6148 \left(\frac{t_{1/2}}{t_{5/6}} \right)^2 - 1.6382 \frac{t_{1/2}}{t_{5/6}} + 0.968 \ , \tag{11}$$

$$P_{2/3} = 7.1793 \left(\frac{t_{2/3}}{t_{5/6}} \right)^2 - 11.9554 \frac{t_{2/3}}{t_{5/6}} + 5.1365 \ . \tag{12}$$

The times $t_{1/3}$, $t_{1/2}$, $t_{2/3}$, and $t_{5/6}$ correspond to $T/T_{\max} = 1/3$, $1/2$, $2/3$, and $5/6$, respectively. The principle of these data-reduction procedures is in accordance with that suggested by ASTM.

The moment data-reduction method (Degiovanni 1985; Degiovanni and Laurent 1986) uses the temporal moments of the order 0 and -1 of the temperature from $t_{0.09}$ to $t_{0.81}$, corresponding to $T/T_{\max} = 0.09$ and 0.81, defined by

$$m_0 = \int_{t_{0.09}}^{t_{0.81}} \frac{T(e,\ t)}{T_{\max}} \,\mathrm{d}t \ , \tag{13}$$

and

$$m_{-1} = \int_{t_{0.09}}^{t_{0.81}} \frac{T(e,\,t)}{tT_{\max}}\,\mathrm{d}t \ . \tag{14}$$

The thermal diffusivity is calculated with the formula

$$a = \frac{e^2}{m_0} f(m_{-1}) \ , \tag{15}$$

where $f = f(m_{-1})$ is the polynomial expression

$$f = 0.08548 - 0.314(0.5486 - m_{-1}) + 0.5(0.5486 - m_{-1})^{2.63}, \qquad 0.44 > m_{-1} > 0.27, \tag{16}$$

$$f = -0.0819 + 0.305 m_{-1}\,, \qquad m_{-1} > 0.44 \ . \tag{17}$$

The data-reduction methods proposed by Balageas (1982) and Vozár et al (1991) are based on the knowledge that the rear-face temperature history is less perturbed by the heat-loss effect the nearer the time is to the origin (the time of the flash). The thermal diffusivity is obtained by extrapolating the time evolution of experimentally obtained values of the apparent thermal diffusivity to the time zero. In the first algorithm, the apparent diffusivities are computed with a formula similar to equation (5) where the numerical factor 0.1388 for $T/T_{\lim} = 0.5$ is replaced by the appropriate value corresponding to the other ratios $T(t)/T_{\lim}$. The second algorithm calculates the apparent diffusivities $a(t)$ by the logarithmic method [equation (6)]. The parabolic approximation

$$a(t) = a_0 + a_2 t^2 \tag{18}$$

describes the apparent diffusivity vs time evolution well in both cases.

The logarithmic data-reduction method can also be applied in the case of heat losses. One possibility follows from the theoretical knowledge obtained by the Laplace transformation technique (James 1980). The approach consists of the correction of the thermal diffusivity value a achieved with equation (6), by using the 'windscale logarithmic correction' (Shaw and Ellis 1998):

$$a_{\mathrm{corr}} = \frac{a}{1 + 0.14\ln(1 + 1.22Bi)} \ , \tag{19}$$

where Bi is the Biot number.

The other approach uses the more reliable approximation for the temperature rise vs time

$$\ln[\theta(t)t^{1/2}] = -\frac{K_1}{t} - K_2 t^2 + \ln\frac{K_3}{1 + K_4 t} \ , \tag{20}$$

where $\theta(t)$ is the dimensionless temperature rise in time t; $[\theta(t) = T(e,\,t)/T_{\lim}]$ and K_1, K_2, K_3, and K_4 are the governing parameters (Thermitus and Laurent 1997).

The approach described by Gembarovič and Taylor (1993) makes use of the Laplace transformation. The experimental data are first transformed into the Laplace space and then compared with the appropriate analytical solution. The data reduction may be in the form of the simple adiabatic model of the flash method; the theory that takes into account the heat losses and also in combination with respect to the shape and duration of the heat pulse (Gembarovič and Taylor 1994a). Similarly, the Fourier transformation may be successfully achieved in the data reduction. As reported by Gembarovič and Taylor (1994b, 1997), the thermal diffusivity estimation based on the discrete Fourier and cosine Fourier transformations does not depend on the knowledge of the temperature level before the flash application (the base line for the temperature rise calculation), and can also be applied in the case when the sample temperature is superimposed on an arbitrary linearly rising or falling signal.

Progress in computer technology makes it possible to calculate the thermal diffusivity by comparing experimental data and analytical curves computed on the basis of more sophisticated analytical models by a fitting technique. Various sequential estimations (Raynaud et al 1989) and least-squares fitting (Gounot and Battaglia 1994) techniques have been successfully applied. Nonlinear least-squares method algorithms described by Cezairliyan et al (1994) and Baba and Ono (2001) are based on theory that takes account of 'exact' heat exchange between the sample and the sample holder. The nonlinear χ^2 least-squares procedure (Šrámková and Log 1995) uses the Levenberg–Marquardt fitting method; the technique (Mourand et al 1998) makes it possible to estimate the thermal diffusivity map of a surface on the basis of thermal images from an infrared camera (Mourand and Batsale 2001). The nonlinear fitting algorithm proposed by Gembarovič et al (1990) can be used also in the case of the heat-loss model. Then the problem of finding the thermal difffusivity is reduced to solving the set of two algebraic equations

$$\sum_{j=1}^{N} T_j\theta_j(a,\,Bi)\sum_{j=1}^{N}\theta_j(a,\,Bi)\frac{\partial\theta_j(a,\,Bi)}{\partial a}-\sum_{j=1}^{N}T_j\frac{\partial\theta_j(a,\,Bi)}{\partial a}\sum_{j=1}^{N}\theta_j^2(a,\,Bi)=0\ , \tag{21}$$

$$\sum_{j=1}^{N} T_j\theta_j(a,\,Bi)\sum_{j=1}^{N}\theta_j(a,\,Bi)\frac{\partial\theta_j(a,\,Bi)}{\partial Bi}-\sum_{j=1}^{N}T_j\frac{\partial\theta_j(a,\,Bi)}{\partial Bi}\sum_{j=1}^{N}\theta_j^2(a,\,Bi)=0\ , \tag{22}$$

where $\theta_j(a,\,Bi)$ is the theoretical dimensionless temperature rise in time t_j (Vozár 2001).

A comparison of some of the data-reduction methods shows that procedures based on a least-squares fitting of the 'whole' temperature evolution are less sensitive to the distortion of the data caused by the main disturbing phenomena (Vozár and Gembarovič 1994).

As an alternative to the analytical approach, data reduction based on the numerical solution of the heat conduction equation with the appropriate initial and boundary conditions can be used. The numerical solution has the advantage of allowing greater consideration of more complex boundary conditions. This creates the possibility of analysing cases when an analytical solution does not exist or when it is too complicated (Schmitz et al 1999).

If the heat pulse duration is not negligible, it is necessary to take account of the shape and duration of the heat pulse in the data reduction. A very useful correction consists of taking as the time origin the effective irradiation time t_g (centre of the heat pulse gravity) defined as the ratio of temporal moments of the order 1 and 0 of the flux $\phi(t)$ by (Azumi and Takahashi 1981)

$$t_{\mathrm{g}}=\frac{\displaystyle\int t\phi(t)\,\mathrm{d}t}{\displaystyle\int \phi(t)\,\mathrm{d}t}\ . \tag{23}$$

This correction can be used for correcting experimental vs time data distorted by heat losses (Degiovanni 1987).

4 Experimental apparatus

Several apparatuses for the measurement of the thermal diffusivity of solids by the flash method have been built in scientific laboratories (Degiovanni et al 1979; Taylor 1980; Guanhu et al 1986; Mirkovich et al 1989; Log and Jackson 1991; Maglić and Taylor 1992; Hartman et al 1993; Cezairliyan et al 1994; Vozár 2001; Vozár and Hohenauer 2001a, 2001b; Demange 2002). Some of them are designed for measurements on molten materials (Taylor et al 1985, 1993; Maeda et al 1996), or are specially designed to operate under conditions imposed by the requirement to measure the thermal diffusivity of highly radioactive reactor-irradiated nuclear fuels (Sheindlin et al 1998). The devices described by Murabayashi et al (1970), Jian (1985), Giedd and Onn (1989); Vandersande et al (1989), Ronchi et al (1999), and Shinzato and Baba (2001) allow also measurement of the heat capacity. Commercial laser-flash measuring systems are produced by Netzsch Gerätebau GmbH, Anter Corp., Theta Industries, Holometrix, Ulvac Sinku-Riko Inc., Sopra SA, and others.

5 Extended applications

5.1 *Materials with significant dependence of thermophysical properties on temperature*

The analytical theory assumes that all the thermophysical properties (the thermal conductivity, the heat capacity, and the thermal diffusivity) as well as parameters describing the boundary conditions (the heat transfer coefficient) are independent of the temperature in the temperature range of the temperature increase during the experiment. This assumption may not be valid in the case of materials and experimental conditions with strong temperature dependence of the thermophysical properties, especially in the case of high temperature gradients across the sample.

Analytical calculations show that errors in thermal diffusivity estimation due to this influence are reduced when the diffusivity is related to the adiabatic-limit temperature T_{lim} the sample reaches under ideal adiabatic conditions (Soilihi and Degiovanni 1983; Degiovanni et al 1985; Ohta et al 2002).

5.2 *Semitransparent materials*

Particular difficulties occur when the measured material is transparent to electromagnetic waves at the working wavelength of the laser or when the sample is transparent at the wavelength of the infrared temperature detector that is used. The detector measures temperature rise that is influenced by direct radiation across the sample. There is a discussion how to interpret this effect. It can be viewed as a disturbing phenomenon that influences the measurement of thermal diffusivity—the property that describes the heat conduction in the body. The other approach is to take the radiation into account and consider thermal diffusivity as a property that consists of the sum of the radiation part as well as of the heat conduction part.

More about how to deal with problems in measurements on semitransparent materials (Araki 1990; André and Degiovanni 1995; Blumm et al 1997; Hofmann et al 1997; André and Degiovanni 1998; Mehling et al 1998; Lazard et al 2000), or those caused by combined radiative/conductive heat transfer in heterogeneous semitransparent materials (Hahn et al 1997), or how to deal with the partial heat pulse energy penetration (Tischler et al 1988; McMasters et al 1999) can be found in the literature.

5.3 *Anisotropic media*

The flash method with radial heat flow has been proposed as a method to measure simultaneously axial thermal diffusivity (across the sample) as well as radial thermal diffusivity (parallel to the front and rear surfaces) of an anisotropic material with cylindrical symmetry (Donaldson and Taylor 1975; Chu et al 1980). The method consists of irradiating the central part of sample front face—a circular area with a radius smaller than the sample radius. If the temperature response is monitored at the rear face at two different locations, both axial and radial thermal diffusivities are simultaneously deduced from the recorded experimental temperature vs time data (Donaldson and Taylor 1975; Chu et al 1980; Amazouz et al 1987; Wojtatowicz and Rozniakowski 1989; Lachi and Degiovanni 1991).

A generalisation of the flash technique for measurements on orthotropic materials with three mutually orthogonal thermal diffusivities for finite and semi-infinite solids has been worked out. Analytical (Graham et al 1999; Demange 2002) as well as numerical (Doss and Wright 2000) solutions for transient temperature distribution have been used in the data reduction.

5.4 *Layered structures*

The flash method is suitable for studying layered structures. The essential condition is that the material boundaries are flat and parallel to the sample front and rear surfaces. If there are no heat losses from the lateral surfaces, one-dimensional heat transfer occurs across the sample. By analysing the temperature rise vs time data the values of all thermophysical properties (thermal diffusivity of one layer, or the thermal contact resistance) can be computed. Sensitivity analyses indicate that only one property can be independently derived from recording of the temperature rise in a simple flash-method experiment (Koski 1985). A basic ideal theory for two-layered and three-layered composites was given by H J Lee (1975). The proposed data-reduction method is based on the half-rise point similar to the case of the original approach to homogeneous samples. T Y R Lee (1977) derived the theory for a composite formed from capacitive layers—layers whose material has a very high thermal diffusivity so that there is no thermal gradient across the layer. The models are suitable when analysing composites that consist of a combination of metal and a poor conductor. Practical aspects of estimation for layered composites are given by H J Lee and Taylor (1976a) and T Y R Lee et al (1978).

Measurements in the wider range of outer boundary conditions and materials (higher temperatures, poor conductive layers) require a model that takes account of heat losses from the front and rear faces. The quadrupole formalism of the Laplace transformation technique described by Degiovanni (1988) gives a tool for the solution of more sophisticated problems connected with complex layered materials (Maillet et al 1993). Another analytical formalism for studying the thermal behaviour of multilayered composites utilising the matrix form has been described by Araki et al (1992a). The theory can be applied to studying materials with a certain profile of thermophysical properties.

It is important to note that the determination of thermal diffusivity of a component (or the contact thermal resistance between two layers) in layered systems is a dependent measurement. An estimation of the thermal diffusivity of one layer or the thermal contact resistance requires, besides the knowledge of other properties (density, heat capacity, and thickness of components), the knowledge of the thermal diffusivity of the remaining layer(s). Errors in the measurement of the additional properties are propagated through the data reduction and result in the calculation inaccuracy of thermal diffusivity. These effects have been investigated in two-layered materials and special conditions for reliable determination of the thermal diffusivity have been given (Araki et al 1992b; Hohenauer and Vozár 2001; Vozár and Hohenauer 2001a). Araki et al (1992b) also discuss the concept of apparent thermal diffusivity estimated from the experimental data and mean thermal diffusivity which has physical meaning related to thermal resistance.

The concept and analytical theory of measurement on layered composites may be applied when measuring the thermal diffusivity of liquids or melts. Such materials have to be put into a suitable container, or the liquid sample is simply sandwiched between thin solid slabs. Then the samples are treated as three-layered structures where the first and the third are layers with known thermal properties that form the container (Schriempf 1972; Tada et al 1978; Araki et al 1981; Gobbé et al 1989; Ohta et al 1990). A semi-infinite media arrangement, based on measuring the temperature of a metal disk placed on the top of the liquid, has been examined by Fang and Taylor (1987). Similarly, a layer made of transparent material may be utilised (Wei and He 1989).

5.5 *Thin films*

The laser flash method has been employed for measurements on very thin materials (thin films). When such a material is investigated in the transverse direction, some effects, which may be ignored for thick samples, may become important because of the limitation of the measuring system. Heating and sensing speed bring about experimental restrictions. The phenomena to be kept in mind are the finite heat-pulse-duration effect, the inertia, and the nonlinearity of the temperature detector, the response time of the measuring system, and the finite absorption depth effect (Tang et al 1995; Tang and Araki 2000) limit the sample thickness. With a special arrangement, as for example in the thermoreflectance technique (Taketoshi et al 1999, 2001), the flash method can be successfully applied to estimate submicrometer thin films.

Special methods for the measurement of the in-plane thermal diffusivity on thin materials having large length to thickness ratio have been proposed. They are based on heating of the sample at one end by a pulse (Hadisaroyo et al 1992), periodic heat flow (Gu et al 1993; Stanimirović et al 1998) and step heating (Nabi et al 2000). The temperature evolution monitored at the opposite end of the sample is used for thermal diffusivity estimation.

5.6 *Composites*

The thermal diffusivity measurements on various kinds of composites (fine weave, dispersed, fibre-reinforced, etc) are mostly performed under the assumption that the composite material behaves as a homogeneous medium. This assumption may be acceptable if the scale of the microstructure is far smaller than the size of the sample, and this is obviously true for sufficiently thick samples (Kerrisk 1971, 1972; Lee and Taylor 1976b, 1978).

The equivalent homogeneous-medium assumption and the concept of the diffusivity of composite materials have to be discussed for each specific material. In the case of longitudinal heat flow through composites with fibre reinforcements (directionally reinforced composites) and where the fibre length is comparable with the sample thickness, serious problems may occur. These problems have been analysed by various authors (Taylor 1983; Balageas 1984; Luc and Balageas 1984; Balageas and Luc 1986; Taylor and Kelsic 1986), and it has been shown that such homogeneous-medium assumptions may lead to poor results, such as diffusivities dependent on time and sample thickness. Optimally, sample thickness has to be much larger than fibre diameter, the fibre volume fraction should be as large as possible, and fibre and the matrix should be in perfect thermal contact, ie interfacial thermal conductance should be large.

6 Extensions of the flash method

A review of various photothermal techniques of measuring thermal diffusivity as well as some examples of experiments can be found elsewhere (Lepoutre 1987; Park et al 1995). One of these is photothermal radiometry (or the front-face flash method) where the plane surface is uniformly irradiated by a laser pulse and the resulting temperature rise is measured on the same (front) face. More about the technique can be found in the paper by Leung and Tam (1984) and in the review article by Balageas (1989). The analytical basis of another experiment arrangement is given by Schimmel (1991). Uniform flat radiative heating approach may also be used for thermal conductivity estimation as proposed by Černý and Toman (1995, 1997). The method utilises the results of temperature field analysis based on the solution of the inverse problem of heat conduction.

To overcome large thermal gradients in the sample that limit general use of the laser flash method, the flash method with extended pulse and the step heating method have been proposed. These are based on simultaneous reduction of the intensity of the energy source and increase of the exposure time (Donaldson and Faubion 1978; Kobayasi and Ohmori 1983), or on substituting step (continuous) heating for pulse irradiation (Bittle and Taylor 1984, 1985; Vozár and Šrámková 1997). The practical advantage of using the flash method with extended pulse or the step heating method over the laser flash method with instantaneous pulse is to be balanced with the negative aspects of the sensitivity and optimal experimental design analysis—reducing the intensity of the energy source and increasing the exposure time decreases the sensitivity of thermal diffusivity estimation (Vozár and Groboth 1997).

In the flash method with repeated pulses, the heat pulse energy is split among several laser pulses consecutively applied to the sample front face (Vozár and Hohenauer 2002). As has been demonstrated, a 'one-pulse' flash method apparatus can easily be modified to a flash method apparatus that utilises the several pulse principle (Vozár and Hohenauer 2001b). Experimental results show that a level of measurement accuracy and reproducibility comparable to the standard flash method can be achieved.

7 Conclusion

The numerous scientific papers dealing with applications and further developments of the flash method, especially those that have appeared in the recent years, testify to the quality of basic principles of the method. Thanks to all contributors from the academic, industrial, and business world the flash method has become an efficient and reliable experimental method of measuring the thermal diffusivity.

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