

Developments in the Data Evaluation of the EDPS Technique to Determine Thermal Properties of Solids

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Abstract:- Developments to the data evaluation procedures of the Extended Dynamic Plane Source (EDPS) Technique have been introduced. This technique has been used for simultaneous measurements of the thermal conductivity, diffusivity and the specific heat. The theoretical principle and the experimental arrangement of the technique are highlighted. The technique has the potential to determine these three parameters from a single transient recording of the temperature increase. Within the total time of this transient recording, and by using the difference analysis model, it is possible to select a correct “optimal” time sub-interval for the evaluation procedures. The difference analysis model is based on a mathematical procedures that provides the selection of the optimal time interval within the total measuring time and thus to obtain more accurate and reliable results. The selected time interval is defined as $(t_B, t_B + t_S)$. The beginning and the size of the interval are represented by t_B and t_S , respectively. The procedures consider t_B as the varying variable within the selected t_S values. The results are plotted versus t_B and the optimal time interval is the interval within which the fitting is not sensitive to the interval size that cause a plateau in the plot.

Measurements on (**P**olymethl**m**ethacrylate) PMMA has been performed and analysed based on the difference analysis model. The estimated uncertainties in measurement were 3.6% for thermal conductivity and 2.7% for thermal diffusivity. The results were compared with those obtained from the sensitivity coefficients (parameter estimation) model.

Key-Words: Difference Analysis; Dynamic Plane Source Technique; Thermal Conductivity; Thermal Diffusivity; (**P**olymethl**m**ethacrylate) PMMA.

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1 INTRODUCTION

The transient dynamic techniques [1-7] are a class of techniques for measuring the

thermal properties of materials. The principle of these techniques is simple. The sample is initially kept at thermal equilibrium, and then a small disturbance is

applied to the sample in a form of a short heating pulse.

The most simple transient techniques are the hot-wire and the hot-strip. Each uses a line heat source (wire or strip) that is embedded in the specimen initially kept at uniform temperature. Using these techniques, it is possible to measure both the heat input and the temperature changes, from which the thermal conductivity λ or both (only in hot strip case) λ and thermal diffusivity a are simultaneously determined. The transient plane-source (TPS) technique is originally based on hot-strip technique and characterized by the transient temperature rise of a plane heat source/sensor "resistive element" at constant energy input [1,8].

Measurements are simply performed by recording the voltage (resistance/temperature) variations across the sensor during the passage of a heating current in a form of a constant electrical pulse. The theory of the TPS method is based on a three-dimensional heat flow inside the sample, which can be regarded as an infinite medium, if the time of the transient recording is ended before the thermal wave reaches the boundaries of the sample.

In the dynamic plane source (DPS) technique [9-10] we have used the TPS-element as a plane source [PS] placed inside the medium. The heat is supplied in such a way so that its experimental arrangement resembles a one-dimensional heat flow.

The main features distinguishing DPS from the TPS can be summarized as:

(i) DPS is arranged for a one-dimensional heat flow into a finite sample which is in a contact with relatively poor heat conductor to approach the adiabatic conditions for samples with $\lambda \geq 2$ W/mK.

(ii) DPS also works in the time region where the sample is treated as a finite medium and is not restricted only to the time region where the sample is regarded as infinite medium.

(iii) DPS has the potential to give λ , a , and ρC_p from a single measurement even if the

experimental arrangement resembles a one-dimensional heat flow.

2 EXPERIMENT

There are several factors that affect the reliability of a specific technique to measure thermal properties. Some of these factors are the required accuracy, the speed of operation, the physical nature of material, the geometry of the available sample and the performance under various environmental conditions. However, in most techniques the main concern is to obtain a controlled heat flow in a prescribed direction, so that the actual boundary conditions in the experiment agree with those assumed in the theory. The extended dynamic plane source (EDPS) technique is a modified version of DPS which is also based on a one-dimensional heat flow into a finite sample. For samples with $\lambda \leq 2$ W/mK, the sample must be in contact with very good heat sink such as copper to approach the steady state conditions in relatively short time. The configuration of the experiment is shown in Fig. 1. The plane heat source/sensor [PS disc], which simultaneously serves as the heat source and thermometer, is made of a nickel 10 μm film covered from both sides with a thin layer made of kapton. The kapton layer serves as an insulating layer that supports the heater in the element. Two identical sample pieces of cylindrical shape are used to provide symmetry to the heat flow through the samples and into a heat sink (high thermal conducting material), copper in this case.

In this arrangement, we fulfil the isothermal boundary conditions required by experimental setup. In other words, by using a good heat sink, the technique will have the potential to determine the thermal properties of low thermally conducting materials. The presence of the heat sink on the rare surface of the samples, in addition to its role as a mechanical support, it makes the heat conduction process through the sample approaches the steady-state condition in a short time. Thus, the data

evaluation procedures become particularly simple for low thermal conductivity samples with $\lambda \leq 2$ W/mK. The heat, in a form of a step-wise function, is produced by the passage of an electrical current pulse through the source/sensor.

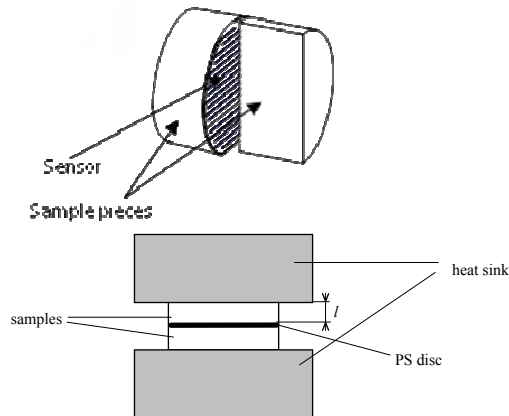


Fig. 1a Schematic drawing of the sample pieces and experimental Setup

The voltage (resistance/temperature) variations across the sensor were monitored using Keithley 2001 DMM with an accuracy of $13 \mu\text{V}$. A schematic drawing of the electric circuit is shown in Fig. 1b. The electric current and the voltage across the sensor (PS) are measured using a standard resistor R, and a multichannel PC plug-in card PCL 711 (Advantech) for data acquisition.

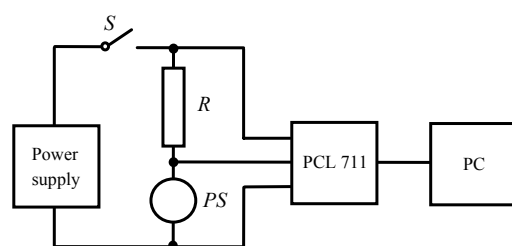


Fig. 1b Schematic drawing of the electrical circuit used to perform the measurements.

According to Fig. 1a, a sample of length $2l$ occupies the region $-l < x < l$, with the heater is placed in the plane $x = 0$. At the planes $x = -l$ and $x = l$ the sample is in

contact with high conducting material (copper), here with thermal coefficients λ_{cu} and a_{cu} . The temperature developments are governed by the solution to the following partial differential equations:

$$\frac{\partial^2 T}{\partial x^2} - \frac{1}{a} \frac{\partial T}{\partial t} = 0 \quad 0 < x < l$$

$$\frac{\partial^2 T_{Cu}}{\partial x^2} - \frac{1}{a_{Cu}} \frac{\partial T_{Cu}}{\partial t} = 0 \quad l < x < \infty$$

The initial and boundary conditions for one side are given by

$$T = T_{Cu} = 0 \quad 0 < x < \infty \quad \text{at} \quad t \leq 0$$

$$-\lambda \frac{\partial T}{\partial x} = \frac{1}{2} q \quad x = 0 \quad \text{at} \quad t > 0$$

$$\lambda_{Cu} \frac{\partial T_{Cu}}{\partial x} = \lambda \frac{\partial T}{\partial x} \quad x = l \quad \text{at} \quad t > 0$$

$$T_{Cu}(t) = T(t) \quad x = l \quad \text{at} \quad t > 0$$

$$T_{Cu}(t) \rightarrow 0 \quad x \rightarrow \infty \quad \text{at} \quad t > 0$$

Where, q is the total output power per unit area dissipated by the heater.

In order to establish the theoretical basis of the solution we will proceed starting with the ideal conditions as follows:

- (i) The heater has a negligible thickness and mass and is in perfect thermal contact with the sample.
- (ii) There is no thermal resistance between the sample and the heat sink
- (iii) There are no heat losses from the lateral surfaces of the sample.

Later we will discuss how close the actual experimental arrangement fits these ideal conditions and how to detect and eliminate the errors due to the influence of these non-ideal conditions.

According to ref. [10], the temperature response function at $x = 0$, is given by :

$$\Delta T(t) = \frac{ql}{\lambda\sqrt{\pi}} F(\Theta, t) \quad (1)$$

Where

$$F(\Theta, t) = \sqrt{\frac{t}{\Theta}} \left(1 + 2\sqrt{\pi} \sum_{n=1}^{\infty} \beta^n \operatorname{ierfc} \left(n \sqrt{\frac{\Theta}{t}} \right) \right) \quad (2)$$

As it was mentioned above, q is the heat current density, and Θ is the characteristic time of the sample which is defined in terms of the sample thickness and the thermal diffusivity as:

$$\Theta = l^2/a \quad (3)$$

The coefficient

$$\beta = \left[\frac{\lambda}{\sqrt{a}} - \frac{\lambda_{cu}}{\sqrt{a_{cu}}} \right] / \left[\frac{\lambda}{\sqrt{a}} + \frac{\lambda_{cu}}{\sqrt{a_{cu}}} \right]$$

is associated with the effect of the heat sink which is made of two copper cylinders, in our case. $\beta = -1$ for perfect heat sink, and ierfc is the error function integral [11].

$$\operatorname{ierfc}(z) = \frac{1}{\sqrt{\pi}} e^{-z^2} - \frac{2z}{\sqrt{\pi}} \int_z^{\infty} e^{-\eta^2} d\eta$$

Figure 2 shows a typical temperature response function as a solution to the partial differential equations using the boundary and initial conditions that corresponds to the isothermal experimental arrangement.

3 Evaluation Procedures

3.1 Standard model

The principle of the evaluation procedures is based on fitting the theoretical temperature function to the experimental points. The standard fitting procedure (standard model) is based on a linear regression using least square fitting [9-10]. According to Eq. (1), the plot of experimental points T_i versus the calculated $F(\Theta, t_i)$ should be a straight line if Θ has its proper value. This equation predicts a zero intercept but real measurements showed a nonzero value T_0 referred to an additional increase in the temperature due to design defects of the heater/sensor. The proper value of Θ can be found by using an iterative procedure to vary the characteristic time Θ until the correlation coefficient

calculated from T_i and $F(\Theta, t_i)$ reaches its maximum. The slope of this straight line gives the thermal conductivity λ , and the proper iterated Θ value is used in Eq.(3) to get the thermal diffusivity a .

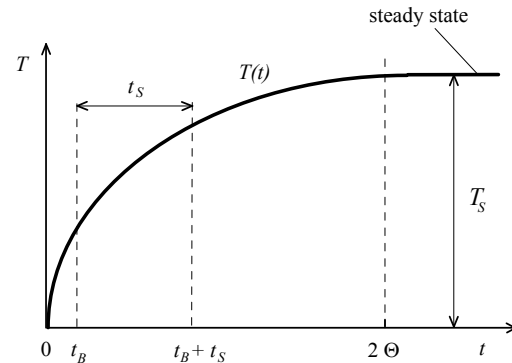


Fig. 2 A typical temperature response function vs. time.

3.2 Difference analysis model

As mentioned in the previous section, in principle, there are two parameters whose values should be determined. Namely; the thermal conductivity λ and thermal diffusivity a . However, due to the influence of the heater geometry, insulation layers, and contact resistance, a third parameter T_0 related to the baseline of the temperature response could be added to Eq. (2) so that the temperature response function becomes:

$$\Delta T(t) = \frac{q}{\lambda} \sqrt{\frac{ta}{\pi}} \left(1 + 2\sqrt{\pi} \sum_{n=1}^{\infty} \beta^n \operatorname{ierfc} \left(\frac{nl}{\sqrt{at}} \right) \right) + T_0 \quad (4)$$

The difference analysis model uses the evaluation procedures to select the optimum time interval for fitting the theoretical temperature function. It fits Eq.(4) to the points in the time interval $(t_B, t_B + t_S)$, where t_B and t_S are representing the beginning and the size of the interval, respectively, as shown in Fig. 2. If t_B is successively increased while t_S is kept constant, a series of parameter values is obtained. If the time interval $(t_B, t_B + t_S)$ is not suitable for determining a and λ , the results of fitting are unreliable and it will

show considerable scatter with large deviations from the expected results.

In order to verify this model we construct a mathematical model of the experiment. In the first stage, the points were computed using Eq. (4) and simulating the measurement on polymethylmetacrylate (PMMA), the following values were used: $l = 0.003$ m, $q = 1000$ W·m⁻², $\lambda = 0.19$ W·m⁻¹·K⁻¹, $a = 0.12 \times 10^{-6}$ m²·s⁻¹, $T_0 = 0.2$ K, and $\beta = -0.954$. The sampling rate was one reading per second, and the number of sampling points $n = 300$. In the second stage, noise was added by rounding the temperature coordinate of the points to seven digits. Then the points were re-computed by difference analysis with the smallest possible time interval. If we have three unknown parameters in Eq. (4), we need at least three points for evaluation. In this situation - instead of the standard fitting procedures- we solve a system of three equations according to the following formula:

$$R_x = \left| \frac{x - x_0}{x_0} \right| \quad (5)$$

Where x_0 is the simulated value used originally in the model and x is the value calculated using difference analysis. If the time interval is not suitable for estimation of parameters a and λ , the results are unreliable and relative differences are far from zero.

To investigate the effect of the interval size within the difference analysis model we have tested the simulation using two different values of interval size: namely (a) $t_s = 10$ s and (b) $t_s = 25$ s, respectively. The results are depicted in Fig. 3. When we used a small window $t_s = 10$ s, the curves are rather scattered and deviated from the original value -presented by the straight horizontal line- used in the model. see Fig. 3(a).

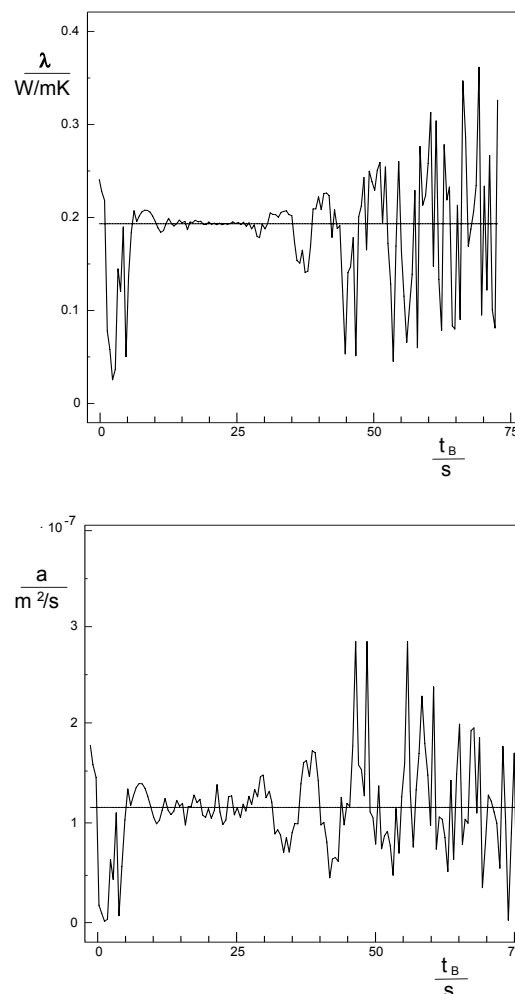


Fig. 3(a) Results of the simulations using difference analysis model. Thermal conductivity λ and diffusivity a as a function of the time window $(t_B, t_B + t_s)$, for $t_s = 10$ s

However, figure 3(b) shows the case of a larger window $t_s = 25$ s, the fitted values of λ and a are nearly identical to the values used originally in the model up to $t_B = 50$ s. It is very obvious from these figures that the results are influenced by the size of the window.

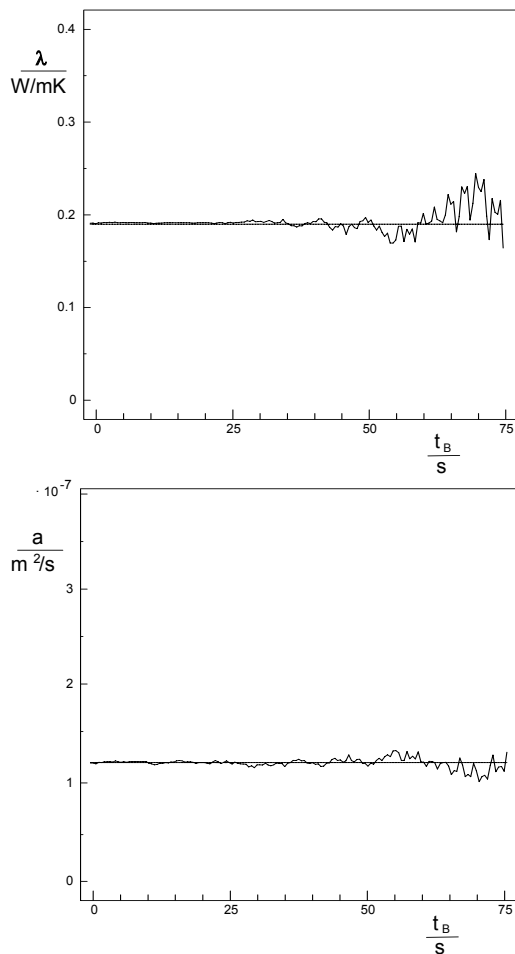


Fig. 3(b) Results of the simulations using difference analysis modeling. Thermal conductivity λ and diffusivity a as a function of the time window $(t_B, t_B + t_S)$, for $t_S = 25$ s

4 RESULTS & DISCUSSION

The standard and difference analysis are evaluation models to seek an optimal time interval, in which the fitting procedures give results with minimum errors.

The standard model is based on estimating the parameters using least-squares fitting when t_B is constant while t_S is successively increased and the results are plotted versus t_S . In the standard analysis a number of points is used in the fitting procedure and can be defined as the interval $[t_B, t_{\max}]$.

Here t_B corresponds to the number of points skipped at the beginning of the transient due to the insulation layers of the

sensor and t_{\max} corresponds to the maximum number of points 300 or less.

On the contrary, in the difference analysis model t_B is the varying variable within the selected t_S and the results plotted versus t_B . As it was previously shown, the principle of the difference analysis model is based on the assumptions that the time interval $[t_B, t_B + t_S]$ is optimal when the fitting is not sensitive to the interval size that cause a plateau in the plot. This can be seen by the difference analysis of the real measurements of PMMA within the time window $0.1 \leq t/\theta \leq 1$, depicted in Fig. 4. This figure shows the plot of the relative differences for both R_a and R_λ . Outside this region, R_x increases substantially and it deviates far from zero.

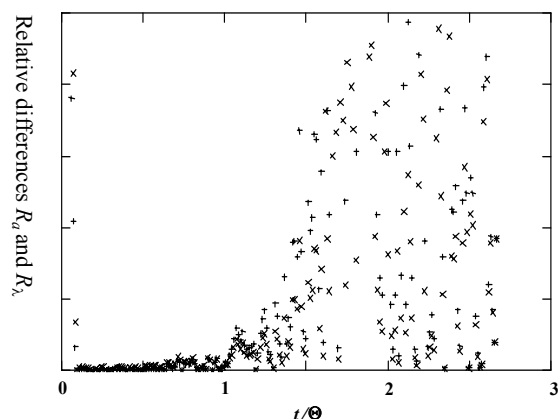


Fig. 4 Values of the relative differences of the parameters a (x) and λ (+) vs. non-dimensional time scale t/θ .

These deviations are based on different fitting intervals shifted in steps up to the total time of the measurement.

It is very obvious that these values are diminishing within the period $[0.1\theta, \theta]$. In other words, this will be the optimum time interval that will give reliable and accurate results. The distorting time in the very beginning ($t/\theta < 0.1$) of the transient event is related to the influence (defects) of the heat/sensor design. These defects are associated with the thickness and the mean thermal diffusivity of the layer/layers existing between the metallic heating

pattern in the heater/sensor and the sample. It represents the deviation from the ideal conditions stated previously in section 2. It should be mentioned that this is not only limited to the insulating layer supporting the heating element but also to any other layer between the heating element and the sample that contributes to the contact resistance. In principle, it is to all distortions that are related to the heater design, such as heat capacity of the metallic pattern in the sensor, the spacing between the successive strips in the pattern etc. Such distortions can be included and each will have its own characteristic time that will affect the beginning of the transient recording.

Figure 4, also shows that R values are very much scattered (deviates far from zero value) for all characteristic times greater than Θ . This is attributed to rare side effects such as the thermal resistance between the rear surface of the sample and the heat sink which disturb the temperature development in the heater as soon as the heat pulse reaches the rear side of the sample.

In the case of a real experiment, we must discuss the effects which can cause the deviation of the experimental set-up from the ideal model and estimate their magnitude then reduce them accordingly.

The first problem is due to the influence of the heater geometry. The theory assumes an ideal PS disc (i.e. a homogeneous hot plane of negligible thickness and mass that is in perfect thermal contact with the sample). The defects of the disc will cause the beginning of the measured temperature function to be distorted. This time interval, described by the characteristic time of the disc Θ_D , is not suitable for computing thermophysical parameters. Heat losses from the lateral sides of the sample present the second problem. We can eliminate them by optimizing the specimen thickness, according to ref [10], these losses are directly proportional to l^2 and inversely proportional λ and the radius r of the sample. Thus, by proper choice of the geometry of the sample, the heat losses through the lateral sides of the sample can

be reduced considerably just by keeping the relation l^2/r as small as possible. However, for relatively longer times when approaching the steady state condition, the heat losses increases, therefore long time interval also cannot be used. To investigate this effect we applied the model to the real measurements using the optimal size interval ($t_s = 25$ s) and two different values of heating current namely; (a) $I = 232$ mA and (b) $I = 663$ mA. The corresponding temperatures increase for these currents at the steady state condition were $T_s = 1.9$ and $T_s = 8.0$ °C, respectively.

Fig. 5(a) shows that the sensitivity of the measuring device was not sufficient at the heating current $I = 323$ mA. The results are widely scattered and reasonable values can be obtained only for $t_B = 10$ –15 s.

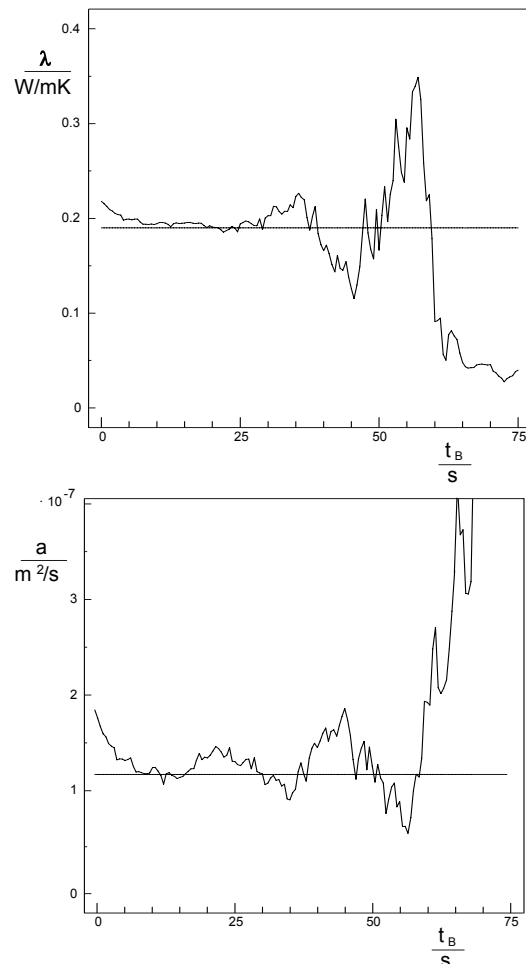


Fig. 5(a) Results of the difference analysis of real measurements of PMMA. Thermal conductivity λ and diffusivity a as a function of the time window ($t_B, t_B + t_s$), for $t_s = 25$ s, and $I=323$ mA.

However, the results in figure 5(b) are rather stable. The influence of the PS disc is clearly seen the diffusivity curves and the characteristic time of the disc can be estimated as $\Theta_D \approx 5-10$ s. In addition, the influence of heat losses from the lateral sides of the samples, for $t_B > 60$ s, is very obvious in the plots. Hence, the time window within which the fitting procedure can be applied is from 10 to 60 s which corresponding to the interval within the range $[0.1\Theta, \Theta]$. Once the optimal time window has been determined, the desired thermophysical parameters λ and a can be calculated.

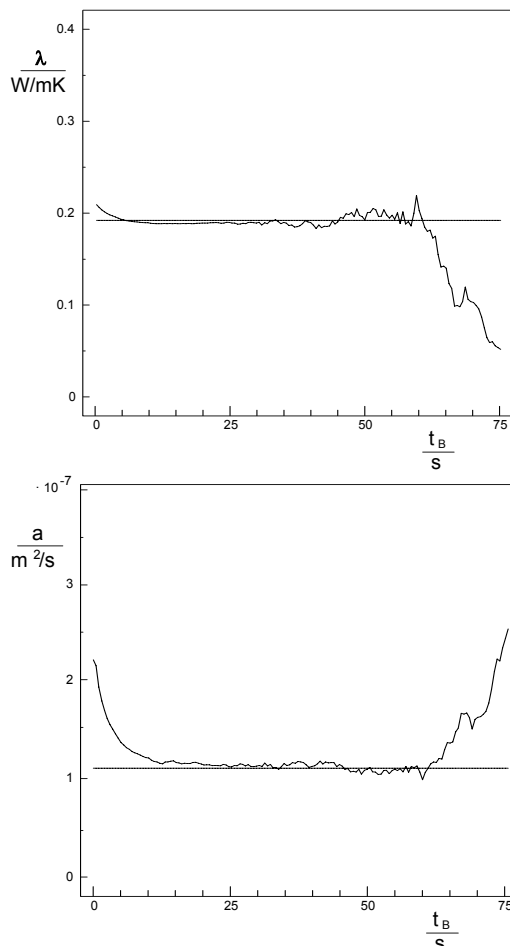


Figure 5(b) Results of the difference analysis of real measurements of PMMA. Thermal conductivity λ and diffusivity a as a function of the time window ($t_B, t_B + t_S$), for $t_S = 25$ s, and $I=663$ mA.

Using this optimal time interval, we found the following:

In the model, we obtained the values $\lambda = 0.191 \text{ W m}^{-1}\text{K}^{-1}$ and $a = 0.120 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$. In the real measurement of PMMA we obtained the values $\lambda = 0.194 \text{ W m}^{-1} \text{ K}^{-1}$ and $a = 0.122 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$. These values correspond to variations of 1.5% in thermal conductivity and variations of 1.7% in thermal diffusivity.

Furthermore, an excellent overview of the fitting process can be obtained by plotting the residuals against the corresponding time. The residual is defined as the measured value minus the predicted value [12]. Figure 6 shows the time dependence of residuals in the modeling experiment. A strange pattern is caused by the quantization noise which does not have a Gaussian distribution.

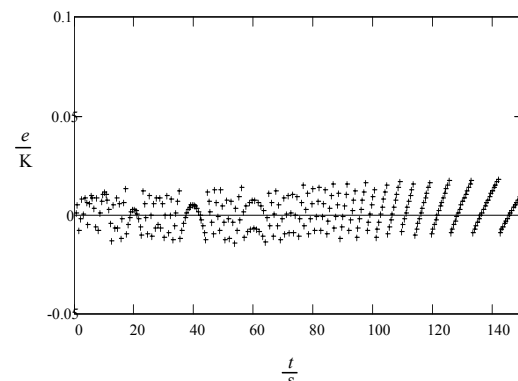


Fig. 6 Residuals in modeling the experiment.

Fig. 7 shows the same dependence in a real experiment on PMMA. It is clearly shown that the beginning of the measured temperature function is disturbed by the PS disc defects (imperfection in heater geometry) and the influence of the thermal contact resistance between the PS disc and the sample pieces. These disturbances are due to the deviations from the ideal conditions that assume the heater has a negligible thickness and mass and is in perfect thermal contact with the sample.

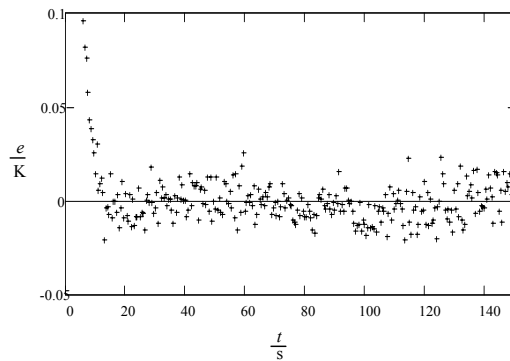


Fig. 7 Residuals in the real experiment on PMMA.

5 Uncertainty Analyses

Uncertainty assessment in transient methods is a complicated task [15- 16] and the ISO GUM [17] cannot be applied directly. Therefore, this is only an attempt to give a rough outline of uncertainty assessment in the EDPS method. More detailed uncertainty analysis is given in ref. [18]. The sources of uncertainty can be divided into three parts. The first part could be defined as the deviation from the theoretical model [19]. The influence of the thermal contact resistance between the PS disc and the sample was eliminated by skipping data points from beginning of the temperature rise in the PS disc as described previously. The influence of the heat losses from the lateral sides is eliminated by skipping data points from the end at longer times. Both influences of the PS disc and heat losses from the lateral sides were obvious in Fig. 5. We came to the conclusion that if the fitting procedure is applied in the optimal time window, the contribution to the uncertainty due to these two effects can be negligible. The second part is caused by random errors. These effects can be considered due to repeatability of the measurement results [20]. Fluctuations can be caused by electronic noise, fitting procedure, variations in temperature and other unknown variations in the time scale of measurement. Repeatability is estimated by means of 10 successive measurements carried out under the same conditions and with the same samples. The apparatus and

samples were disassembled and reassembled before each measurement. The effect of apparatus assembly is probably one of the most important factors for the resulted dispersion. The third part is caused by uncertainties in input parameter measurements. The main sources of uncertainty in this context are connected with the measurement of voltage, resistance of constant resistor, temperature coefficient of resistivity (TCR) of the PS disc and specimen dimensions. Both voltages across the PS disc and the constant resistor are measured using a PC plug-in card, which was calibrated against the Keithley 2001 DMM with an accuracy of $13 \mu\text{V}$. (see figure 1b). As the resolution of AD converter equals $300 \mu\text{V}$, the associated standard uncertainty becomes $u(U) = 300\mu\text{V}/\sqrt{12} = 87 \mu\text{V}$.

The resistance of the constant resistor was measured using the Keithley 2001 DMM with an accuracy of $180 \mu\Omega$. But the introduced uncertainty is mainly due to temperature instability of the constant resistor. Considering the maximum change in temperature of about 20 K, the associated standard uncertainty becomes $u(R) = 1.1 \text{ m}\Omega$. TCR of the PS disc, which is made of nickel, was determined by measuring the temperature dependence of disc resistance. The temperature was measured by a calibrated platinum resistance thermometer Pt 100 with the standard uncertainty of 0.1 K and the resistance was measured by the Keithley 2001 DMM. TCR is computed using polynomial regression, and the associated standard uncertainty becomes $u(\alpha) = 0.05 \times 10^{-3} \text{ K}^{-1}$. The sample diameter was measured using a caliper with a resolution of 0.1 mm. The uncertainty becomes $u(d) = 0.1\text{mm}/\sqrt{12} = 0.03 \text{ mm}$. The specimen thickness was measured by a micrometer with 0.01 mm resolution. However, the sample pieces are not exactly identical and their surfaces are not exactly parallel. The repeatability is estimated by means of 10 successive measurements of sample thickness and the associated standard uncertainty becomes $u(l) = 0.04 \text{ mm}$. Contributions to the uncertainty of the

calculated parameters λ and a are determined using the standard numerical method. The parameters are evaluated for input values and then again for the input value incremented by its uncertainty. The difference between two determinations equals the uncertainty of the calculated parameter. In order to simplify the evaluation, no correlation between input quantities is considered and the uncertainties can be combined by root sum square addition.

Table 1 shows the results of the uncertainty analysis in thermophysical parameter measurement of PMMA. The estimated uncertainties in measurement were 3.6% for thermal conductivity and 2.7% for thermal diffusivity.

Our results are in a good agreement with the parameter estimation analysis (sensitivity coefficients) model [12-14] that yielded time interval within the range $[0.07\Theta, \Theta]$ for the same material. In ref [14], the TPS- technique, known as the Hot Disk that has been used. It should be mentioned that these two models have different approaches. In the difference analysis model we use particular points with experimental or simulated noise while in the sensitivity coefficients model we directly use the temperature function response (no need for simulation).

5 CONCLUSIONS

The extended dynamic plane source (EDPS) technique is a transient technique which is based on a one-dimensional heat flow into a finite sample. This technique is used for simultaneous measurements of the thermal conductivity, diffusivity and the specific heat.

By applying the difference analysis model to measured points from the temperature response (transient recording), we were able to determine the optimal time interval to obtain more accurate and reliable results. The model is based on mathematical procedures that provide the selection of the optimal time interval within the total time of the transient recording.

The obtained optimum time interval for PMMA sample was $[0.1\Theta, \Theta]$ which was in good agreement with thy optimum time intervals obtained using other transient techniques and different evaluation model (sensitivity parameters estimations model).

The analysis of the standard uncertainty was evaluated at 3.6 % for thermal conductivity and 2.7 % for thermal diffusivity measurements. More detailed analysis is planed in the near future to investigate measurements in vacuum to reduce lateral heat losses from the surfaces.

Table I Uncertainty analysis for λ and a .

Source of uncertainty	Standard uncertainty	Value of standard uncertainty	Standard uncertainty $u(\lambda)$ (W/mK)	Standard uncertainty $u(a)$ (10^{-6} m ² /s)
Measurement repeatability			0.0060	0.0026
Voltage measurement	$u(U)$	88 μ V	0.0010	0
Resistance stability and measurement	$u(R)$	1.1 m Ω	0.0009	0
TCR of PS disc measurement	$u(\alpha)$	$0.05 \cdot 10^{-3} \text{ K}^{-1}$	0.0024	0
Diameter measurement	$u(d)$	0.03 mm	0.0011	0
Thickness measurement	$u(l)$	0.04 mm	0.0016	0.0020
Combined uncertainty			0.0069	0.0033

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