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Dynamic Calibration of the Transient Plane Source - sensor

S. Malinarič

Department of Physics, Constantine the Philosopher University, Nitra, Slovakia
Email: smalinaric@ukf.sk

Abstract. *The Extended Dynamic Plane Source (EDPS) method is one of transient methods for measuring thermal conductivity and diffusivity in solids. This technique uses a transient plane source (TPS) sensor, which serves as the heat source and thermometer. Its calibration consists in measuring the temperature dependence of the TPS sensor resistance and computing the temperature coefficient of resistance (TCR) using the least squares (LS) estimation. The goal of this work is to calibrate the TPS sensor directly in the apparatus for EDPS measurement.*

Keywords: *transient method, thermophysical parameters, transient plane source - sensor, temperature coefficient of resistance*

1. Introduction

Transient methods [1] are used for measurement of thermophysical parameters, e.g. thermal conductivity λ and diffusivity a. Measurements are based on generation of the dynamic temperature field inside the specimen. The theoretical model of the method is characterized by a temperature function, which is a solution of the heat equation with boundary and initial conditions corresponding to the experimental arrangement. The principle of the evaluation is based on fitting of the temperature function to the experimental points (temperature response), determined by the TPS sensor resistance measurement. Hence, the calibration of the sensor is necessary for obtaining reliable values of thermal conductivity measurement.

2. Extended dynamic plane source (EDPS) method

The EDPS [2-4] method is characterized by one-dimensional heat flow into a finite solid body with low thermal conductivity. Fig.1 shows the TPS sensor in the form of a meander, made from a 20 μm thick nickel foil and covered on both sides with 25 μm kapton layer. The sensor is placed between two identical specimens with the same cross section. Heat sink, made of a very good heat conduction material (aluminium), provides isothermal boundary conditions for the experiment. Heat is produced by the passage of an electrical current in the form of a step-wise function through the TPS sensor.

The apparatus enables to increase the temperature of the experimental set-up. The electronics of the apparatus consists of a platinum thermometer (Pt100), 2 heating elements, a multichannel PC plug-in card (PCL-816) and a power DA converter. A proportional integral (PI) controller realized by PC software is used for temperature control. It is based on periodic measurement of the temperature and computing the manipulated variable (heating power). PI control allows good temperature stability and homogeneity in the heat sink and specimens (better than 5 mK).

The resistance of the platinum thermometer and TPS sensor are calculated by formulas

$$R_T = R_1 \cdot \frac{U_T}{U_1} \qquad R_S = R_3 \cdot \frac{U_S}{U_3} \tag{1}$$

where $R_1 = 136\ \Omega$ and $R_2 = 1.00\,\Omega$ are the constant resistors and voltages are measured as shown in Fig.2. To suppress quantization and electrical noise, voltages U_1, U_T and U_3, U_S are sampled and averaged 4000 and 1500 times per channel over the period of 1s and 60ms, respectively. Currents in the circuits were set to $I_1 = 1.2\,\mathrm{mA}$ and $I_3 = 300\,\mathrm{mA}$. The temperature of the Pt100 was determined by using the following formula [5]

$$R_T = R_0 \cdot \left(1 + \alpha_T \cdot T + \beta_T \cdot T^2\right), \tag{2}$$

where $R_0 = 100.00\,\Omega$, $\alpha_T = 3.9092 \cdot 10^{-3} \cdot K^{-1}$ and $\beta_T = -5.917 \cdot 10^{-7} \cdot K^{-2}$.

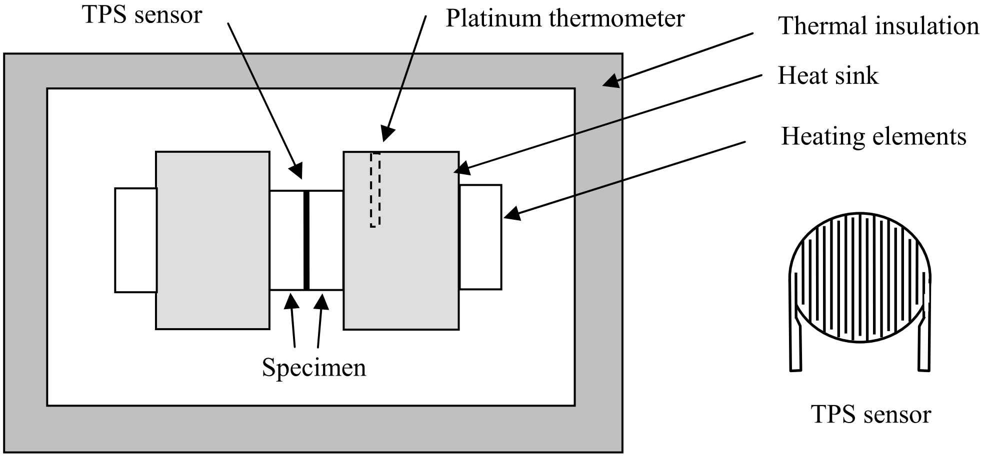

Fig. 1 The arrangement of the experiment

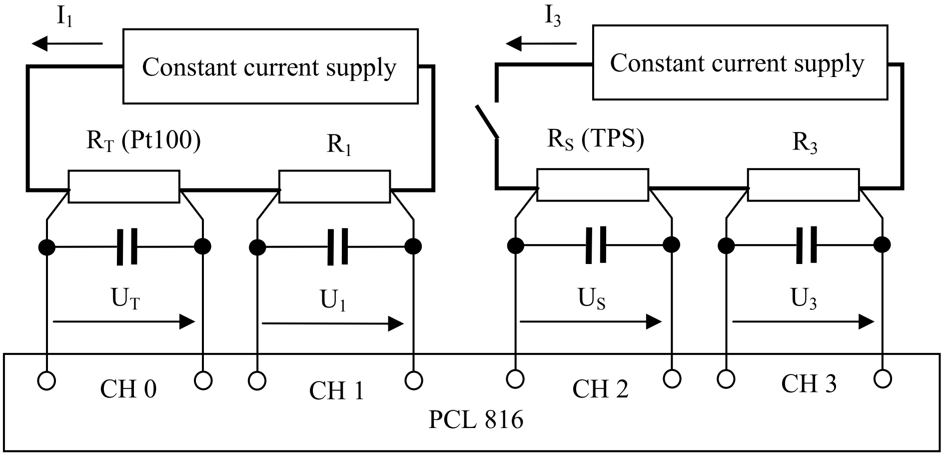

Fig. 2 Experimental circuit design

3. Temperature coefficient of resistance (TCR) measurement

In order to use the described apparatus for TCR measurement, the specimens were replaced by aluminium ones and coated with silicon oil to improve thermal contact between the TPS sensor and the heat sink. As the current I_3 caused the heating of the sensor itself, the extrapolation to the zero time was applied, as illustrated in Fig. 3. The measured data were fitted to the following polynomial [6]

$$R_S = a_0 + a_1 \cdot T + \cdots + a_k \cdot T^k. \tag{3}$$

The LS estimate of the parameter vector is given by [7]

$$\vec{a}_{\mathrm{LS}} = \left(\mathbf{X}^T \cdot \mathbf{X}\right)^{-1} \cdot \mathbf{X}^T \cdot \vec{R} \tag{4}$$

where $\vec{R}$ is the observation vector of the TPS sensor resistance measured at 6 points T_i in the interval from 20 to 45°C and **X** is a sensitivity matrix defined by

$$\{\mathbf{X}\}_{ij} = T_i^{\,j} \tag{5}$$

Once we have the parameter estimates, the TCR of the TPS sensor can be computed using the relation

$$\alpha(T) = \frac{1}{R_S(T)} \frac{dR_S(T)}{dT} \tag{6}$$

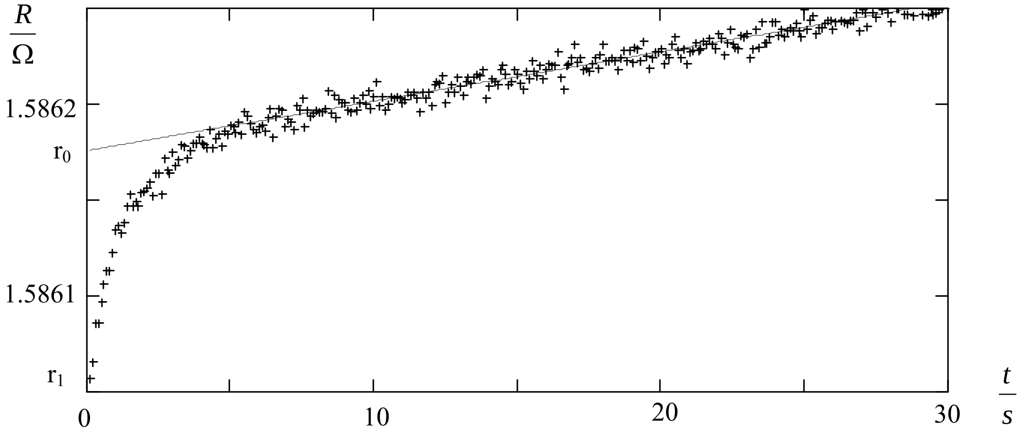

Fig. 3 Temperature dependence of the TPS sensor resistance after switching the current I_3 on.

Type A standard uncertainty (LS component) of the TCR estimate can be computed by [8,9]

$$u_A(\alpha) = s\sqrt{\vec{c}^{\,T} \cdot \left(\mathbf{X}^T \cdot \mathbf{X}\right)^{-1} \cdot \vec{c}} \tag{7}$$

where s is a standard deviation of residuals, $\vec{c}$ is a vector of sensitivity coefficients defined by

$$c_j = \frac{\partial \alpha}{\partial a_j}, \tag{8}$$

and α is given by Eq. 6 and 3.

4. Results and discussion

The evaluation was performed with both extrapolated values r_0 and first sample (0.1 s after switching) values r_1. Table 1 shows the results of fitting for three values of polynomial order k. A simplified uncertainty assessment is presented in Table 2. The total standard uncertainty of TCR estimation at temperatures from 20 to 45°C does not exceed $0.035 \cdot 10^{-3} \cdot \mathrm{K}^{-1}$ (0.7%), which is sufficient for thermal conductivity measurement of materials.

Acknowledgment

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Table 1. Results of LS estimation, k is the polynomial degree, α is the TCR of TPS sensor and s is the standard deviation of residuals.

	extrapolated values r_0			first sample values r_1		
k	2	3	4	2	3	4
$\alpha_{20°}\cdot 10^3\cdot K$	4.828	4.842	4.840	4.828	4.840	4.829
$\alpha_{40°}\cdot 10^3\cdot K$	4.618	4.618	4.618	4.617	4.618	4.616
$s\cdot(\mu\Omega)^{-1}$	20.7	1.5	1.2	20.2	10.6	8.2

Table 2. Uncertainty budget for TCR of TPS sensor measurement (k = 2, extrapolated values)

Source of uncertainty	Standard uncertainty	Value	Standard uncertainty $u(\alpha_{20°})\cdot 10^3\cdot K$
LS component (Eq.7)	$u_A(\alpha)$		0.003
R_1 measurement + temperature stability	$u_B(R_1)$	26 mΩ	0.001
R_3 measurement + temperature stability	$u_B(R_3)$	4.4 mΩ	0.023
Pt100 calibration	$u_B(T)$	100mK	0.027
Combined uncertainty			0.035

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