Inverse approach for nondestructive determination of thermal conductivity of solid materials

Ziemowit Ostrowski[1], **Zbigniew Buliński**[1], **Arkadiusz Ryfa**[1], **Wojciech P. Adamczyk**[1*]
[1] *Institute of Thermal Technology, Silesian University of Technology, Gliwice, Poland*
Konarskiego 22, 44-100 Gliwice, Poland
e-mail: wojciech.adamczyk@polsl.pl

Abstract

The knowledge about thermal conductivity (TC) is essential in numerous applications. It can be used as the parameter which describes the quality of the materials, it plays crucial role as well in numerical simulations, where heat transfer process need to be evaluated. The method presented in this paper was developed based on the classical Parker flash method which is classified as the transient measurement technique. The idea of measurement procedure is to locally heat up a small portion of a sample surface by a laser pulse and record the resulting transient temperature field using an IR camera. In contrary to classical flash method the laser and IR camera are located in the same side of the sample. The measurements and inverse procedure presented in this work treats the thermal conductivity components as decisive variables, which are retrieved by minimization of the discrepancy between experimental and modeled data. The reduced order model of considered system is used as direct solver in presented work. The proper orthogonal decomposition technique (POD) is coupled with radial basis functions (RBF) to build the dependence on decision parameters into the low order model. The results obtained using proposed approach were validated using additional experimental data obtained in commercially available apparatus.

Keywords: thermal conductivity, thermal diffusivity, nondestructive tests, inverse analysis, reduced order model, trained POD-RBF

1. Introduction

Robustness, relatively low cost and rapidness made numerical simulations a primary technique of engineering analysis. Numerical models can replace expensive and time consuming experimental methods. The reliability and accuracy of the numerical results depends strongly on the input data. In case of simulation of heat transfer within a solid body, the exact definition of the material properties, for instance heat diffusivity (TD) is extremely important. There is a vast and constantly increasing literature on the available experimental techniques of determining TC and TD [5, 6]. The most popular techniques are the transient ones [7, 8, 9] where advantages and disadvantages of different measurement concepts have been widely discussed. One of the most popular, and widely used, 1D transient technique for measuring of the TD is the laser flash method [1, 14]. This method has found application in commercial Laser Flash Apparatus (LFA). Other examples of transient method application can be found in [4, 10]. The method presented in this work also belongs to the transient technique and should be seen as continuation of works [2, 3, 11] which ultimately should lead to development of the procedure capable for rapid measurement of the TC of the body with arbitrary shape and with anisotropic structure.

2. Materials and methods

Initially the numerical FVM model was proposed as direct solver within inverse procedure. The major drawback of such approach is long computation time which considerable limits it's practical application. To speed-up the simulation an application of a reduced order technique was proposed. The POD empirical vectors were used as approximation basis, while dependency of reduced model on input parameters is obtained by means of Radial Basis Functions (RBF). This technique, introduced by coauthor of current research [12] is known as truncated POD-RBF approximation [13]. The usage of POD modes as approximation basis makes this approximation optimal, i.e. for given approximation order, POD base produces minimal error. This comes from the fact that the approximation vector basis is not chosen arbitrary, but is derived from approximated data. Thanks to proposed approach, the inverse procedure of retrieving the TC can be accelerated by several orders of magnitude. The results presented in this work should be seen as the preliminary study of the POD-RBF technique for retrieving components of the TC tensor of anisotropic materials.

2.1. Experimental setup

The initial tests were performed using steel cuboid samples. The in-house apparatus was used to collecting experimental data, and is shown in Fig. 1. As the heat source the IPG Photonics laser is used. The spatial and temporal temperature distribution after laser emission is recorded by the Infrared (IR) camera (FLIR A325, Flir Systems, Inc., USA). To reduce the geometrical distortion of the spot of the laser ray and the image of the temperature field, the optical axis of both devices are orthogonal to the heated spot (rotation of the probe to the optical axis of the camera).

2.2. Objective function

The objective function used in this study was defined as

$$\min \sum_{i=1}^{N} \left(\Theta_{\mathrm{POD,i}} - \Theta_{\mathrm{EXP,i}}\right)^2 \qquad (1)$$

where N stands for the total number of sampling points used by inverse analysis to retrieve TC of the material. The $\Theta_{\mathrm{POD,i}}$ and $\Theta_{\mathrm{EXP,i}}$ are ratios of temperature excess in chosen times.

3. Results

Proposed calculation algorithm was validated against experimental data acquired using commercial LFA device, see Fig. 2.

*The research has been supported by National Science Centre (Poland) within SONATA scheme under contract No 2014/15/D/ST8/02620.

To ensure stable and accurate solution an appropriate time instants of measurements have to be selected as the input for objective function (1). The possible answer for formulated question can be obtained by muli-variant calculations where different time ratios and pixel ranges are used. Thanks to the POD-RBF low-order model it is possible to quickly estimate the TC for wide range of different times ratios as well as sensor locations.

The evaluation of the model parameter was done based on experimental data acquired at the in-house experimental rig for steel sample. The set of retrieved TCs for different times and sensor locations (range) is illustrated in Fig. 2. It can be seen that for carried out calculations in time range 0.8 s – 1.17 s the solution fluctuates around constant average value. For each time the standard deviation of the retrieved TCs was calculated. It can be observed that for two time instants, 0.98 s and 1.02 s, the lowest standard deviation is present, showing the convergence of the solution. The average value of TCs calculated in the vicinity of above mentioned time instants (see ellipse in Fig.2) is equal to 26.2 W/(m·K). This is different form validation (LFA) data by 1.1% only.

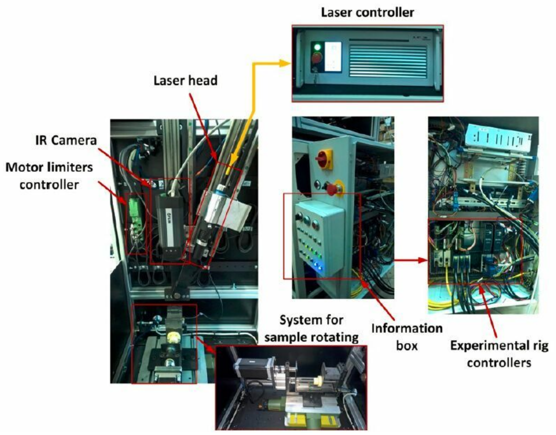

Figure 1: Experimental test rig.

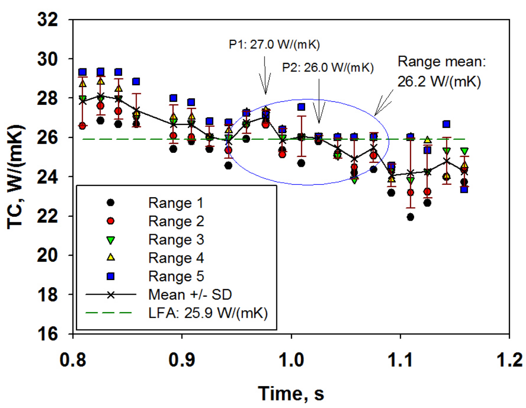

Figure 2: Calculated thermal conductivity for different times of measurement

4. Summary

A non-destructive technique for measuring TC was presented. ANSYS Fluent code was used to generate input data for training POD-RBF reduced order model. The developed measurement procedure accommodates the finite dimension of laser spot diameter, heat loses due to the convection and radiation and emission time. Furthermore, main advantage of the developed measurement procedure is its possibility of future application for fast evaluation of the TC of the material without necessity of sample extraction (i.e method is nondestructive). Presented results should be seen as the preliminary one where the calculation procedure still need to be improved to ensure more reliable and stable solution. Nevertheless, presented method and its application has high application potential and should be studied and developed.

References

[1] ASTM 1461-13, Standard Test Method for Thermal Diffusivity by the Flash Method, 2013

[2] Adamczyk, W.P., Bialecki, R.A., Kruczek, T., Retrieving thermal conductivity of isotropic and orthotropic materials, *Appl Math Model* 40(4), pp.1-12, 2015.

[3] Adamczyk, W.P., Bialecki, R.A., Kruczek, T., Measuring thermal conductivity tensor of orthotropic solid bodies, *Measurement*, 101, pp.93-102, 2017

[4] Bianco, N. and Manca, O., Theoretical comparison of two-dimensional transient analysis between back and front laser treatment of thin multilayer films. *Int J Therm Sci*, 43, pp.611-621, 2004

[5] Cernuschi, F., Bison, P.G., Figari, A, Marinetti, S. and Grinzato, E., Thermal diffusivitymeasurements by photothermal and thermographic techniques. Int J Thermophysics, 25(2), pp.439-457, 2004

[6] Cezairliyan, A., Maglic, K.D., and Peletsky, V.E., *Compendium of Thermo-physical Property Measurement Methods. Volume 2: Recommended measurement Techniques and Practices*, New York, 1992

[7] Gustafsson, S.E. , Karawacki, E., and Khan, M.N., Transient hot-strip method for simultaneous measuring thermal conductivity, thermal diffusivity of solids, liquids. *J Appl Phys*, 12, pp.1411-21, 1979

[8] Germany NETZSCH-Geratebau GmbH. www.netzsch-thermal-analysis.com

[9] Hammerschmidt, U. and Sabuga, W., Transient hot strip (ths) method: Uncertainty assessment, *Int J Thermophysics*, 21, pp.217-248, 2000

[10] Milosevic, N.D., Raynaud, M., and Maglic, K.D., Simultaneous estimation of the thermal diffusivity and thermal contact resistance of thin solid films and coatings using the two-dimensional flash method, *Int J Thermophysics*, 24, pp.799-819, 2003

[11] Kruczek, T., Adamczyk, W.P., and Bialecki, R.A., In situ measurement of thermal diffusivity in anisotropic media, *Int J Thermophysics*, 34(3), pp.467-85, 2013

[12] Ostrowski, Z., Bialecki, R.A., and Kassab, A.J., Estimation of constant thermal conductivity by use of Proper Orthogonal Decomposition. *Comput Mech*, 37(1):52-9, 2005

[13] Ostrowski, Z., Bialecki, R.A., and Kassab, A.J., Solving inverse heat conduction problems using trained POD-RBF network inverse method, *Inv Probl Sci Eng*, 16(1), pp.39-54, 2008

[14] Parker, J.W., Jenkins, R.J., Butler, C.P., and Abbott, G.L., Flash method of determining thermal diffusivity, heat capacity and thermal conductivity, *J Appl Phys*, 32(9), pp.1679-84, 1961