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Measuring thermal conductivity tensor of orthotropic solid bodies

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ABSTRACT

A non-destructive technique for measuring thermal conductivity of solid bodies is developed and described. The experiments are based on laser flash heating of two surfaces of the investigated body. The spatial and temporal temperature distributions are then measured using an infrared camera. The entries of the thermal conductivity tensor are retrieved using an inverse method, which iteratively invokes a direct numerical solver. The technique is applied to simple cuboid geometry. An extension of this method to arbitrary shapes is possible and requires capturing the geometry by laser scaling and laser heating from more directions. The special definition of the variables makes the technique insensitive to the emissivity of the surface and the laser energy absorbed by the sample.

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1. Introduction

Numerical simulations are a primary technique of engineering analysis. In particular, their robustness, relative low cost, and efficient computations are replacing, in many instances, expensive and time consuming experimental methods. The reliability of the results of numerical modeling depends strongly on the accuracy of input data, specifically, on the values of the material properties such as the thermal conductivity (TC). Tabulated material properties can be found in books [1] and on the Internet [2,3]. Commercial simulation packages are typically equipped with an option for importing material properties from libraries [4,5].

The available data on material properties are collections of experimental values obtained by generations of researchers. Although exhaustive, the literature does not cover the entire spectrum of material properties of engineering materials. Moreover, the tabulated data corresponds to certain chemical compositions and crystallographic structures. Using such data for real engineering materials, whose composition is known only within a certain degree of accuracy, produces additional errors. If financial resources and time limitations allow, the values of the material properties should be obtained by direct measurements of the materials of construction.

There is a vast amount of literature pertaining to the available experimental techniques for determining TC [3,6,7]. Herein, we do not attempt to make a thorough review of all relevant references; what follows is merely a short overview of the most popular measurement techniques. Since TC cannot be measured directly, the values of these parameters are obtained by solving an inverse problem [8,9]. The principle of this technique relies on finding the best fit of the output of the model of heat conduction in the sample (solution of a direct problem) with the measured temperatures. The decision variables in this optimization problem are the TC values.

The currently used techniques for measuring the TC of solids are, as a rule, time consuming and require expensive research infrastructure and qualified staff. Moreover, very few methods are non-destructive. Depending on the temporal dependence of the temperature field in the sample during the experiment, the available methods for measuring TC fall into three main categories:

- steady state,
- periodic,
- transient.

The development of steady state methods has a very long history dating back to the nineteenth century [10]. Equipment based on various principles has been developed [11–15]. Although the theoretical background behind steady state methods is simple, achieving accurate results using these methods is a challenging task. Such difficulties are due to the presence of contact resistance, heat losses to the environment, and the assumption of one-dimensional heat flow. Moreover, the measurements are time consuming, as reaching a steady state may take a long time. Ref. [16] gives a comprehensive description of the steady state methods.

In periodic state techniques, external oscillatory heating is applied, generating a quasi steady state periodic temperature field.

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Measuring the phase and amplitude of the temperature changes is used to retrieve the TC of the sample. An extensive survey of periodic state solutions is given in Ref. [17]. Small amplitudes of the temperature field make the technique especially suitable for cases where the TC is strongly temperature dependent. However, the results are prone to boundary condition errors. Some examples of this techniques can be found in Refs. [18,19]. This technique can typically be used only in controlled lab environments.

The main advantage of transient methods is that a relatively short time is required to run an experiment. Moreover, they are insensitive to boundary conditions and can be applied to a wide range of temperatures and TC values. Since temperature fields can be acquired at every time instant, transient methods collect more measurement data compared to their steady state counterparts.

A popular version of this technique is based on using heaters located on the surface or inside the sample and retrieving the TC from the registered spatial and temporal variations of the measured temperature field. Heaters may be in the form of a wire, strip, or plane. Detailed information about variants of the transient method can be found in [20–23], where the advantages and disadvantages are widely discussed. The difficulties of using this group of methods are associated with the presence of contact resistance between a heater and sample and accounting for the heat capacity of the heater.

Laser flash methods and their numerous variants also fall into the category of transient techniques. The idea of the classic version [24] is heating the front surface of a sample using a short laser impulse while recording the temperature excess of the rear side. Though this technique is destructive, it is the most popular method of TC measurement, and many attempts have been made to enhance it [25–27].

2. Novelty of the present approach

The present article describes a technique that belongs to the laser flash methods and is an extension of earlier works [28–30] published by the authors of this paper. The motivation of these works was to develop a non-destructive, rapid, and accurate technique for the measurement of TC. The idea was to heat a small portion of a plane surface by a laser impulse and then record the temperature field of this plane. The solution of an appropriately defined inverse problem yielded the values of the heat conductivity. Earlier works could only retrieve the in-plane components of the TC tensor of orthotropic media.

Ref. [28] treated the domain under consideration as an orthotropic semi-infinite medium whose insulated boundary was heated by Dirac's impulse. These simplifications led to a simple, closed-form solution. For this specific case, the temperature on the surface of the body depended only on the in-plane components of the TC tensor.

In order to assess the errors introduced by neglecting the heat losses due to convection and radiation, numerical techniques were used in [29,30]. The radiation losses were assessed by a surface-to-surface model, while the convection was modeled using a computational fluid dynamic (CFD) model of the surrounding air. In both cited papers, the normal to the boundary component of the TC tensor was known and equal to the larger of the two in-plane components. Such behavior of the TC tensor was a result of the applied technological process of production of the specimens. Unlike this approach, in the present paper, all three components of the TC tensor are retrieved simultaneously.

The results obtained in [30] show that while the influence of convection is negligible, radiation plays a more significant role. The present paper is an attempt to reduce the influence of radiation on the results of the inverse technique.

This is achieved by:

- redefining the objective function so that the result becomes weakly dependent on the radiative losses, and
- selecting measurement points far from the laser beam spot.

By using this simplification, the extremely long computing times associated with using the CFD solver are significantly reduced as the computational domain is limited only to the portion of the sample. Moreover, a linear equation of heat conduction must be solved. However, in view of further applications of the developed technique to bodies of an arbitrary shape, a numerical solver is used in this study.

3. Experiment

The experimental setup with marked apparatus is illustrated in Fig. 1. Opposite to the standard Parker method, in the designed test apparatus, both the heat source and temperature detector are located on the same side of the observation plane. For the heat source, an IPG Photonics laser is used, which can operate in the power range from 20 W to 200 W with an adjusted emission time period. Both parameters ensure that the power of the laser pulse can be appropriately adjusted to the expected material properties. The spatial and temporal temperature distributions after laser emission is recorded using an infrared (IR) 60 Hz camera (FLIR A325, Flir Systems, Inc.). The measurement and data acquisition processes are controlled using an *in-house* personal computer (PC) application written using the LabVIEW environment (National Instruments Corp., USA). In order to reduce the error associated with the non-circular shape of the heat source, a measurement procedure is designed to ensure that both the optical axes of the laser and camera are orthogonal with respect to the observation plane. This is ensured by rotating the sample using a step motor (Fig. 1) to laser the orthogonal position. After emission, the sample is moved to a position orthogonal to the IR camera optical axis. The communication flow chart between particular devices and measurement procedures is visualized in Fig. 2. The algorithm used for retrieving TC components is implemented in the control code as a separate subroutine working in asynchronous mode. Such an approach makes parallel processing possible.

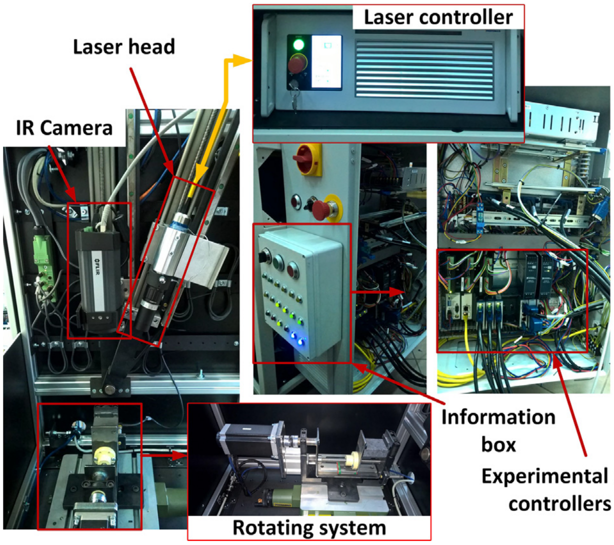

Fig. 1. Experimental setup.

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