Novel, nondestructive techniques of determining heat conductivity

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Abstract

Variants of a novel, non-destructive technique of measurement of heat conductivity in both isotropic and anisotropic materials are presented. The principle of the measurement relies on a flash laser heating of a small surface area of the sample and recording the spatial and temporal variation of the so induced temperature field using an IR camera. Solution of an inverse problem yields then the thermal conductivity of the investigated body. The technique has been used to bodies of different shapes, starting from a semi-infinite domain, through arbitrary shapes grabbed by a 3D scanner and thin layers deposited on the substrate material. Analytical model of the associated direct problem has been applied in the case of large bodies, while in the case of arbitrary shapes, numerical techniques have been used. The influence of heat exchange with the environment has been accounted for by solving a CFD problem in the air in contact with the sample. To speed up the calculations, Proper Orthogonal Decomposition technique has been applied. An attempt has also been made to apply Bayesian technique using Monte Carlo Markov Chain. Good agreement of the retrieved values of thermal conductivity with that measured using commercial apparatus implementing the Powell flash method have been achieved

Keywords: inverse methods, heat conductivity, measuring device, arbitrary shapes, anisotropic, thin layers

1. Introduction

Reliable values of material properties are necessary for setting up a faithful mathematical model of any physical problem. In some cases the material property is a measure of the quality of the material (heat conductivity of insulating or carbonaceous materials). In practice the material properties are determined via experiments accompanied by a solution of an inverse problem. The experimental facilities used to measure the properties are designed to handle specially manufactured samples of a simple shape. This simplifies the solution of the resulting inverse problem but makes the approach destructive.

The paper deals with nondestructive techniques of evaluation of thermal conductivity that resorts to the principle of active thermography. The idea relies on short heating of a small surface area of the surface of the investigated body by a laser impulse and recording the changes of the temperature field by an IR camera. Based on the measured temperatures, an inverse problem of heat transfer is solved to retrieve the values of the heat conductivity. The equations of the mathematical model describing the heat transfer in the investigated body are solved by analytical or numerical methods of different complexity.

The types of inverse techniques discussed in the paper are shown in Fig 1

2. Analytical model

Massive bodies of flat surface can, due to the short duration of heat flash and short times of temperature recording, be treated as semi-infinite media of insulated surface. Laser heating is in this case modeled as Dirac's delta in space and time. The resulting solution for orthotropic media with two principal components of the conductivity tensor parallel to the surface, can be obtained as a superposition of fundamental solution and reads

$$T(x,y,z=0,t) = \frac{q\exp\left[-\frac{x^2/k_x + y^2/k_y}{4c\rho t}\right]}{8(\pi t)^{3/2}\sqrt{k_x k_y k_z}} + T_{init} \qquad (1)$$

where: x, y, z Cartesian coordinates, t time, q energy absorbed by the body. k_x, k_y, k_z principal values of heat conductivities in directions x, y, z, T_{init} initial temperature, c, ρ specific heat and density.

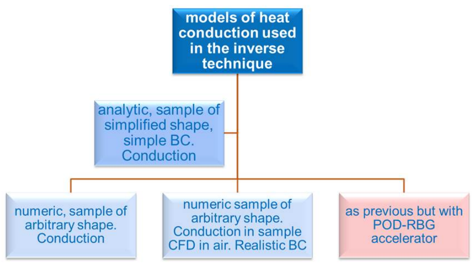

Figure 1: Types of direct problems associated with the inverse model

The scheme of the experiment is shown in Fig. 2

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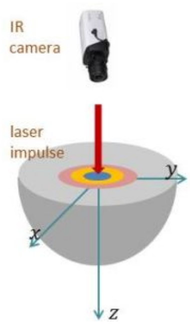

Figure 2: Scheme of experiment using semi-infinite model

The difficulty in using eq. 1 comes from the need of determining q, the amount of heat absorbed by the sample. To assess this value both the energy of the laser flash and the reflectivity of the surface of the probe should be known. Specifically the second quantity is difficult to obtain. To circumvent this problem, a new variable has been introduced. This quantity is defined as the ratio of the temperature excess over the initial state at the same location $x_i, y_i, z = 0$ but different times t_1, t_2. This quantity is defined as

$$\Theta = \frac{T(x_i, y_i, z = 0, t_1) - T_{init}}{T(x_i, y_i, z = 0, t_2) - T_{init}} =$$

$$\sqrt{\left(\frac{t_2}{t_1}\right)^3} \exp\left[\frac{c\rho}{k_y}\left(k_x x_i^2 + y_i^2\right)\left(t_2^{-1} - t_1^{-1}\right)\right] \tag{2}$$

The resulting inverse problem has been solved using Levenberg Marquardt technique.

Based on this technique [1] apparatus has been built and installed in an industrial environment. The equipment measures the heat conductivity of carbonaceous anisotropic, massive blocks. The solution is protected by a patent.

To investigate the influence of neglecting the heat losses from the boundary, a more sophisticated numerical model has been developed. Here the heat losses to the surrounding air have been evaluated by solving a CFD problem in the air. Thus, the computational domain encompassed both the sample and the air in contact with the heated surface (c.f. Fig 3. The influence of the heat losses turned out to be negligible.

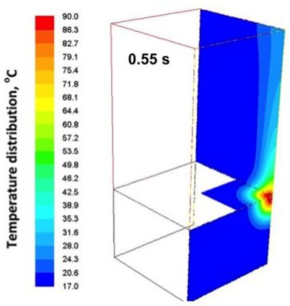

Figure 3: CFD model of sample and surrounding air

3. Bodies of arbitrary shape

The application of analytical solution is limited to bodies of simple shapes. To measure the conductivity of bodies of arbitrary shape, numerical techniques should be used. The geometry of the body is grabbed by a laser scanner and transferred to IGES format. The resulting geometry is then imported into a commercial FEM solver. In the next step, the least squares problem of adjusting the results of simulations and experiments is solved by Levenberg Marquardt method.

The technique is used to find the heat conductivity in isotropic and anisotropic bodies. In the latter case the experiment is extended by recording the temperature field resulting from laser flash impinging more surfaces of the investigated body.

Another extension of this technique is the measurement of the heat conductivities of thin layers of insulating materials (Thermal Barrier Coating) deposited on a substrate metal material of arbitrary shape. This is accomplished by first determining the heat conductivity of the substrate using the already described technique. Next the geometry of the probe after the coating hes been deposited is grabbed. Laser heating of the so prepared probe and recording the resulting temperature field, produces data used by an inverse solver to retrieve the heat conductivity of the thin layer.

4. Speeding up the solution of the direct problem

The numerical solver used to solve the direct problem leads to very long computing times. Such times prevents from using the technique for on-line measurements. The remedy turned out to be the application of the Proper Orthogonal Decomposition - Radial Basis Function network [2]. By solving off-line a sequence of direct problems taking properly selected values of the heat conductivity, a learning set for the POD-RBF network has been generated. The result is a simple formula giving the temperature at the location of temperature sensors. The expression has a form of a product of known matrix and a vector of radial basis functions. This formula is then used in the loop of the inverse solver, shortening the computation time by three orders of magnitude.

5. Bayesian formulation

Standard inverse techniques yield single values of the retrieved parameters. Bayesian formulation not only uses the prior knowledge about theses parameters, but also yields the results in a form of a distribution of the probability of the retrieved values. These is achieved by repeating the solution of the direct problem many times using Monte Carlo Markov Chain. The sampler used in this paper was the Metropolis Hastings one. Speed up the computations have been achieved by implementing the POD RBF network.

6. Conclusions

The developed method can retrieve heat conductivity within the 5-40W/mK range with high accuracy. The obtained values of the conductivity have been compared with that produced using commercial apparatus based on the Parker's flash method. Good accuracy has been achieved.

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