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Applying infrared measurements in a measuring system for determining thermal parameters of thermal insulation materials

S. Chudzik

Institute of Electronics and Control Systems, Czestochowa University of Technology, 17 Armii Krajowej Avenue, 42-200 Częstochowa, Poland

HIGHLIGHTS

- Method applies a periodic heating as an excitation.
- Infrared sensors are used to measure the temperature distribution on the surface of tested material.
- To solve the coefficient inverse problem an approach using artificial neural network is proposed.
- The effect of measurement errors on the results of the identification of thermal parameters.

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ABSTRACT

The paper presents results of research on an innovative method for determining thermal parameters of thermal insulating materials. The method is based on harmonic thermal excitations. Temperature measurements at selected points of a specimen under test are performed by means of semiconductor infrared sensors. The study also employs a 3D model of thermal diffusion. To obtain a solution of the coefficient inverse problem a method based on an artificial neural network is presented. The heat transfer coefficient on the specimen surface is estimated on the basis of a reference specimen. The validity of the adopted model of heat diffusion and the usefulness of the method proposed are verified experimentally.

1. Introduction

Environmental concerns such as the risk of global warming and atmosphere contamination incited many countries to take measures aimed at reducing greenhouse gases emission into the atmosphere. The best way to do so is to use energy which has already been produced as effectively as possible. A significant portion of energy produced globally is heat used in a number of industrial processes and in housing. As far as the latter is concerned, it is essential to minimize the amount of heat lost to the outside through barriers such as walls and roofs, by applying special thermal insulation materials inside those barriers. Thus, the quality of thermal insulation materials is of vital importance for lowering the cost of energy and for saving the environment, too.

At present, the most popular method for assessing the quality of insulation materials is the contact method based on the steady state conditions of heat exchange and using a heat flow meter apparatus [1]. But this method enables obtaining only the heat transfer coefficient of the material under test and requires large-size and weight measuring equipment to be used in a laboratory. Besides, it is time consuming.

The thermal conductivity k of a medium is defined by the Fourier law (7). In this formula k is defined as property of a homogeneous medium (effective thermal conductivity). In the case of nonhomogeneous materials, like foamed polystyrene, the hest conductivity mechanism is more complex. The following heat transfer mechanisms should be taken into account in this case: heat conductivity by the polystyrene as well as the gas filling 90% of the medium volume, free convection in the gas for the bubbles size large enough, radiative heat exchange between inner surfaces of the gas bubbles, contact thermal resistance at contacts of the pressed foamed polystyrene particles. Therefore, for materials whose thermal conductivity can be different at different points, the effective thermal conductivity is usually used. It refers to volumes that are much larger than the material inhomogeneities includes all the mentioned heat transfer phenomena.

The heat transfer coefficient is a parameter characterising heat transfer in a material under steady state. To assess the dynamic state of thermal diffusion, it is necessary to know the thermal diffusivity coefficient a. With these two parameters known, it is pos-

E-mail address: chudzik@el.pcz.czest.pl

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sible to determine the third fundamental thermal parameter, which is the thermal capacity $\rho{\cdot}c_p$. These parameters are tied by means of the following formula:

$$a = \frac{k}{\rho \cdot c_p} \tag{1}$$

Since the thermal capacity coefficient $\rho{\cdot}c_p$ of a thermal insulation material is small, it is difficult to obtain by means of the calorimetric method. Because of that, calculating it on the basis of the thermal diffusivity coefficient is a viable alternative solution.

The author is carrying out research aimed to develop compact-size measuring instruments which would be free from such limitations. The research includes testing the possibilities offered by neural networks for solving the inverse problem to the heat diffusion processes in selected models of measuring stands, employing the theory of non-steady state of heat transfer [1–3].

2. Characteristics of the thermowave method

The method presented in the paper utilises the phenomenon o thermal wave diffusion in a specimen under test in response to an external harmonic temperature excitation:

$$T = T(0,t) = (T_m - T_0) \cdot \cos \omega t \tag{2}$$

For small penetration depth of the periodic thermal excitation, the problem can be considered as a one-dimensional heat transfer in a flat semi-infinite object [4]:

$$T(x,t) = T_0 + (T_m - T_0) \cdot \exp\left(-\sqrt{\frac{\omega}{2a}}x\right) \cdot \cos\left(\omega t - \sqrt{\frac{\omega}{2a}}x\right) \tag{3}$$

Fig. 1 presents a diagram of the phenomenon discussed.

As can be observed, the temperature inside a semi-infinite object varies in accordance with the cosine function with a decreasing amplitude and phase shift.

The penetration depth of the temperature waves can be described as a distance at which the wave amplitude decreases *e* times:

$$\mu = \sqrt{\frac{2 \cdot a}{\omega}} \tag{4}$$

Since the penetration depth decreases together with increase in the thermal wave frequency, there are no restrictions on the thickness of a material specimen which can be examined.

Knowing the oscillation period t_0 and having measured the speed v of thermal wave amplitude displacement, it is possible to obtain the value of the thermal diffusivity coefficient [4–6]:

$$a = \frac{t_0}{4\pi} v^2 \tag{5}$$

The solution presented above for the one-dimensional model of thermal diffusion is based on the assumption that the specimen is a semi-infinite object, i.e.

$$\frac{\partial T}{\partial y} = \frac{\partial T}{\partial z} = 0 \tag{6}$$

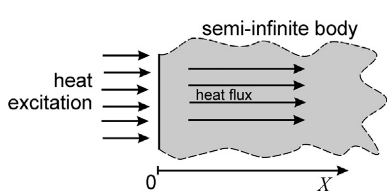

Fig. 1. One-dimensional heat transfer in a flat semi-infinite object.

This ideal condition can be difficult to meet in real experiments, in which a specimen of finite dimensions is used [4,5] and ideal boundary conditions on the lateral surfaces of the specimen are assumed to hold, with the heat transfer coefficient $\alpha = 0$.

For an experiment carried out in a gas, such as air, the value of the heat transfer coefficient on the surface for free convection is in the range 5–30 W/(m^2·K) [6]. If the specimen under test is of high thermal conductivity (e.g. it is made of metal of $k > 100$ W/(m·K)), the boundary conditions on the lateral surfaces of the specimen have only a slight impact on the temperature distribution in the specimen. The density of the heat flux received through the lateral surfaces is significantly smaller than the density of the heat flux flowing along the specimen (Fig. 1, axis X).

When the specimen under test is made of a thermal insulation material, such as foamed polystyrene of $k = 0.04$ W/(m·K), the impact of the boundary conditions on the temperature field distribution is significant and the solution of the inverse problem (5) can be inaccurate. In publication [7] simulation experiments are presented in which a 3D model of the specimen corresponding to real boundary conditions was used. The results obtained indicate that Eq. (5) is inadequate for obtaining the thermal diffusivity coefficient of thermal insulation materials.

3. Model of thermal diffusion in a specimen

In order to model the phenomenon of heat diffusion in a specimen under test, a 3D mathematical model based on the general Fourier-Kirchhoff equation was developed

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q \tag{7}$$

where ρ – density, c_p – specific heat, k – heat transfer coefficient, Q – volumetric efficiency of the heat source, T – temperature, t – time, and ∇ – the Hamiltonian.

A specimen of the dimensions (xyz) 0.04 × 0.04 × 0.12 m was modelled in a rectangular, three-dimensional 3D system of coordinates, as a section of a symmetrical quarter – Fig. 2. The model was subsequently discretized into finite elements.

For the surface of the rectangular base of the specimen $z = 0$, a harmonic temperature excitation was assumed as defined by Eq. (2). For the other surfaces, the boundary conditions of the third

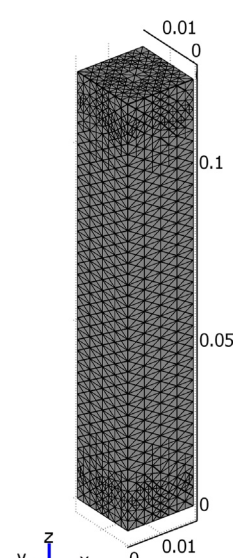

Fig. 2. Model of a section of a symmetrical specimen quarter in a XYZ system and its discretization into finite elements.