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Using ANNs in calibrating the measurements of a simplified hot-plate method

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ABSTRACT

A simplified hot-plate method (SHOP) using single constant high temperature region in measuring materials' thermal conductivity, *k*, has been developed. This method is characterized by its simplicity that it can be used to fabricate portable devices for in-situ measurements and its ability to perform steady-state and non-destructive measurement of composite materials. However, the systematic error introduced by the one-dimensional approximation extended to two-dimensional problems requires a calibration method for the measurement using the SHOP. In this paper, an artificial neural network (ANN) for improving the accuracy of the SHOP is presented. It was devised using the data of 720 measurement cases performed with an experimentally verified numerical model. The experiments of measurement using a prototype instrument fabricated according to the SHOP were carried out. The *k* values were predicted with the ANN and compared with those using the Hot Disk® apparatus to verify the ANN. The results showed that the ANN improved the accuracy of the SHOP and resolved the composite materials that could not be resolved by the Hot Disk® apparatus. The coefficients of *k* as linear functions of temperature can also be obtained by two independent measurements with two high temperature setups corresponding to a fixed ambient temperature. The rules of setting two high temperatures are also given so that the coefficients can be determined within 1% of relative error.

1. Introduction

For the systems of complex thermal mechanism, artificial neural networks (ANNs) have been successfully used for predicting the outcomes or the properties of the systems. Using ANNs, Islamoglu predicted the heat transfer rate of a wire-on-tube type heat exchanger [1], Nasr et al. built a gasoline consumption model [2], Kalogirou optimized solar systems [3], Islamoglu and Kurt analyzed the air flow in corrugated channels [4] and modeled the thermal performance of a cooling tower [5], and Ayata et al. explored the potential use of natural ventilation in buildings [6]. Encouraged by the successful application of ANNs in thermal engineering problems, we applied ANNs for the prediction of materials' thermal conductivities with the measured results of a simplified hot-plate method (SHOP in short here after) which was first developed by Chuah and Sun [7]. This method is characterized by its simplicity that it can be used to fabricate portable devices for in-situ measurement and its ability to perform steady-state and non-destructive measurement of composite materials.

Further analysis of the SHOP by Sun and Chang [8] concluded that a calibrating mechanism is needed before final applications of the method. In the analysis, an experimentally verified numerical model was established to investigate the systematic error introduced by the one-dimensional approximation extended to two-dimensional problems. The accuracy of measurement decreases as the ratio of the test samples' thickness to the constant-temperature region's diameter increases. A calibration function was sought to calibrate the measured thermal conductivity. It was found that this function was sensitive to the material's thermal conductivity and was thus unusable for real measurements. However, the numerical model is useful in simulating measurements with vast varieties of parameters. Therefore, in this study, the numerical model is used to generate simulated experimental data in order to construct the ANNs for calibrating the measurements of the SHOP.

2. The simplified hot-plate method

Since the principle of the SHOP was presented in great detail by Sun and Chang [8], it is described briefly in the followings. Referring to Fig. 1, a circular constant-temperature region is formed on one side of the test sample. On the other side, a Teflon disk plate installed with five temperature sensors is placed for measuring the maximum temperature, T_{max}. The three heaters, Heater 1–3, are controlled to maintain a high temperature, T_0, through the feedback of T_6 through T_8, and are arranged in a way that the heat generated by Heater 1 transfers only into the test sample. The high temperature T_0 is analogous to the temperature of the heat source

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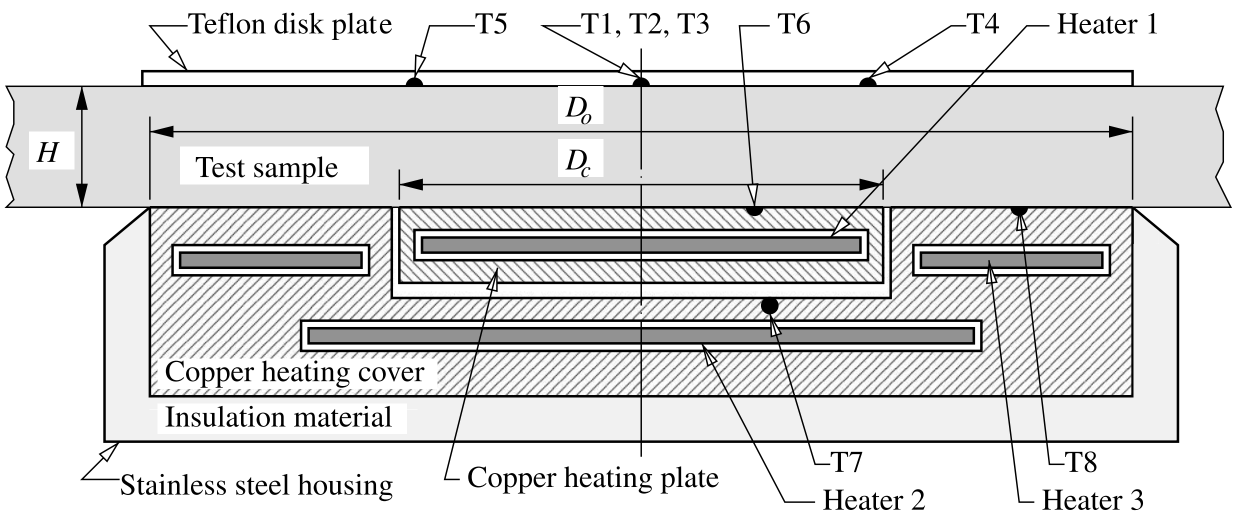

Fig. 1. The descriptive diagram of the device that measures steady-state thermal conductivity.

of a standard guarded-hot-plate method. Furthermore, the diameter of the copper heating plate, D_c, is smaller than the diameter of the whole constant-temperature region (including the copper heating plate and the copper heating cover), D_o, so that the translational heat transfer from Heater 1 is greatly reduced. This makes it possible that the one-dimensional heat conduction equation is used to calculate the test sample's thermal conductivity as

$$k_E(T_m) = \frac{H\dot{Q}}{A(T_0 - T_{max})} = \frac{H\dot{Q}}{2A(T_m - T_{max})} \quad (1)$$

where the subscript E represents the results from measurement, $T_m = (T_0 + T_{max})/2$ is the mean temperature, $\dot{Q}$ is the heating power of Heater 1, H is the sample thickness, and A is the area of the heating plate. T_{max} is achieved with the least square method in case the Teflon disk is misaligned with the heating plate and expressed as

$$T_{max} = T_1 - \frac{(T_2 - T_3)^2 + (T_4 - T_5)^2}{4(T_2 + T_3 + T_4 + T_5 - 4T_1)} \quad (2)$$

In Eq. (2), T_1 is the temperature measured at the center of the Teflon disk. T_2 through T_5 are the temperatures measured at four equally spaced points on a circle that is concentric with the Teflon disk.

3. The numerical model for measurement simulation

An experimentally verified numerical model is built for measurement simulations. The geometric parameters of the measuring apparatus are D_c, D_o, and the diameter and thickness of the Teflon disk. They are listed in Table 1.

To simulate measurements, the measuring parameters are varied. The measuring parameters are the room temperature, T_0, H, and the coefficients of the linear function that describes the thermal conductivity of the test samples. The thermal conductivity as a linear function of temperature is

$$k_R(T) = \alpha T + \beta \quad (3)$$

where the subscript R represents the real properties, α and β have the units of W/m K °C and W/m K, respectively. The values of the measuring parameters used in the simulation are listed in Table 2.

The combination of the measuring parameters in Table 2 create 720 cases of measurement. In every case, a set of data that includes $\dot{Q}$ and T_{max} is produced. The measuring parameters, T_0 and H, the geometric parameter, A, together with the produced data, $\dot{Q}$ and T_{max}, are used as inputs to Eq. (1) for evaluating the thermal conductivity. Since the systematic error produced by using Eq. (1) is nonlinear and dependent on ambient temperature T_a and k_R values, an ANN is the most reasonable way to predict the thermal conductivity of the test samples. This eliminates the need of calibrating k_E that is evaluated with Eq. (1). The predicted thermal conductivity is denoted by k_{ANN}.

The room temperatures, T_a, are selected from the range of ambient temperature for normal measurements in a laboratory or field measurements. The high temperatures, T_0, are selected to be higher than T_a. The k values measured from the simulations are considered to be the thermal conductivity of the test sample evaluated at T_m, which varies from 27.8 °C to 59.2 °C in the cases of this study. This temperature range means the limits of validity of k values predicted by the ANN trained with the results and the parameters of the simulations. For special applications that require a wider range of temperature, the procedures in this paper can be followed with wider ranges of T_a and T_0 to obtain a suitable ANN.

4. The artificial neural networks

The ANN devised for this purpose is shown in Fig. 2. It contains four layers, which are an input layer of five neurons, two hidden layers of eight and four neurons, respectively, and an output layer of one neuron. From the input layer to the first hidden layer and from the first hidden layer to the second hidden layer, logsigmoid

Table 1
The geometric parameters of the measuring apparatus

Geometric parameter	Dimension (mm)
Heating plate diameter	100
Heating cover diameter	200
Teflon disk diameter	200
Teflon disk thickness	6

Table 2
The values of the measuring parameters used in the measurement simulations

Measuring parameter	Values
T_a (°C)	15, 20, 25, 30
T_0 (°C)	40, 50, 60
α (W/m K °C)	10^{-2}, 10^{-3}, 10^{-4}
β (W/m K)	10^{0}, 10^{-1}, 10^{-2}, 10^{-3}
H (mm)	8, 16, 24, 32, 40