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Transient hot wire measures thermophysical properties of organic foam thermal insulation materials

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ABSTRACT

A device based on the transient hot wire (THW) method was developed to measure thermal conductivity and thermal diffusivity of organic foam thermal insulation materials. EPS board and XPS board were used as the experimental samples. The simulation results show that the calculation errors of thermal conductivities with cross hot wire (CHW) method, parallel hot wire (PHW) method and cross-parallel hot wire (CPHW) method are 0%, and the calculation errors of thermal diffusivities with these three methods are small. The experimental results show that for PHW method, the calculation results of thermal conductivity and thermal diffusivity of EPS board fluctuate greatly with the selection of computation time. For CHW method and CPHW method, the measurement errors of thermal conductivities of EPS board are less than 3.5% and that of XPS board are less than 6.5%. The experimental values of thermal diffusivities with CPHW method are close to the reference values, but the experimental values with CHW method are much smaller than the reference values. The measurement errors of thermal diffusivities with these two methods were analyzed theoretically and experimentally. The measurement error with CPHW method is approximately between 27% and 13% with the error of thermal conductivity from −5% to 5%, however, the measurement error with CHW method is more than 99%. The proposed device offers some significant advantages such as economy, flexibility, and the repeatability of measurement accuracy. If applied properly, CPHW method is promising to measure the thermal conductivity and thermal diffusivity of many other types of solid materials.

1. Introduction

At present, organic foam thermal insulation materials such as EPS board and XPS board are widely used in building insulation applications because of their low water absorption and low thermal conductivity (λ) properties. λ, together with thermal diffusivity (*a*) are two important physical properties to estimate the heat preservation ability of thermal insulation materials. In order to obtain these two properties for an application, measuring thermophysical properties of the medium is necessary and THW method is a well-developed method for this purpose.

THW method was firstly proposed by Schieirmacher in 1888 [1]. It was first used to measure the λ of gases. Later, THW method was suggested by Stalhane and Pyk to measure solids and powders [2] and was applied to measure liquid in the early 1940s [1]. In THW method, a very thin hot wire is inserted into the test sample, and the heat transfer parameter of the sample can be determined by observing the change of the temperature of the hot wire with time. The temperature of the wire can be obtained by indirectly measuring resistance change with temperature or directly with a thermocouple. The former is also called resistive hot-wire (RHW) test method, and the latter is cross hot-wire (CHW) test method.

For RHW method, the wire acts as both a heat source and as a temperature resistance thermometer. The advantage in using the hot wire as a temperature probe is basically that the mean temperature of the wire is measured along its length leading to elimination the influence of local non-homogeneities of the measured material. However, disadvantages include the requirements of a high operating power on the low resistance condition, which may produce large uncertainty of λ [2,3]. RHW method has been developed rapidly in the follow-up studies; it has been widely used to measure the λ of gases, liquids, melts and solids, such as hydrogen [4], deionized water and ethylene glycol [5,6], nanofluids [7–9], polymer melts [10], solids [11–14], and phase changing materials [15–18], etc. In general, a complex apparatus and a careful calibration work are required for this method.

For CHW method, usually there are two thermocouples welded on the central part of the hot wire and the average temperature is represented as the temperature of the wire, which provides a good

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Nomenclature

C	Constant, = 1.7810…
c_p	Specific heat capacity (J/kg K)
d	Diameter of hot wire (m)
h	Convective heat transfer coefficient (W/m^2 K)
H	Sample height (m)
I	Electric current (A)
L	Sample length (m)
m	Slope of the curve of $\theta(r_0,\tau)$-ln(τ) (°C)
n	Intercept of the curve of $\theta(r_0,\tau)$-ln(τ) (°C)
q_l	Heating power per unit length (W/m)
r_0	Radius of hot wire (m)
R_0	Distance between hot wire and thermocouple (m)
S	Cross-sectional area of hot wire (m2)
T	Test temperature (°C)
T_0	Initial temperature (°C)
U	Uncertainty
W	Sample width (m)

Greek symbols

a	Thermal diffusivity (m^2/s)
a_0	Reference value of thermal diffusivity (m^2/s)
γ	Euler constant, =0.5772156…
ε	Relative error
$\varepsilon\theta$	Measurement error of θ(R0,τ)
$\varepsilon\lambda\theta$	Measurement error of [λs,c·θ(R0,τ)]
θ	Temperature rise, θ = T-T0 (°C)
λ	Thermal conductivity (W/m K)
λ0	Standard value of thermal conductivity (W/m K)
ρ	Density (kg/m3)
ρ′	Resistivity (10-6Ω·m)
τ	Time (s)

Subscripts

c	CHW method
cp	CPHW method
max	Maximum value
min	Minimum value
p	PHW method
s	Sample
w	Hot wire

compromise between the simplicity of the apparatus and the precision requirement. This method was used to measure the thermal conductivities of the non-metallic materials with λ between 0.2 and 1.5 W/m K [19] and insulation materials with λ between 0.03 and 0.17 W/m K [20], and the measurement accuracies are within 5%. CHW method has the advantages of simple experimental operation and high measurement accuracy of the λ for insulation materials.

RHW method and CHW method can also be used to measure the thermal diffusivity. However, these two methods have a large measurement error for a, and there is little study on the measurement of a by using these two methods.

The parallel hot-wire (PHW) test method was proposed by J. de Boer [21]. In this method, the hot wire is no longer used as a temperature measurement unit, and a thermocouple is placed radially about 1.5 cm away from the center of the hot wire to register the temperature. The thermocouple can also be replaced with another wire, which acts as a temperature resistance thermometer. The two wires were identical except for their length. Hence, the end effects of the wires can be subtracted. The PHW method expands the measurement range of λ, which was used to measure both λ and a of bulk or loose materials, and liquids with high viscosity. YZ zhang et al. [22] have used PHW method to measure both thermal conductivities and thermal diffusivities of porous and heterogeneous materials.

PHW method can measure the thermal conductivity and thermal diffusivity of the material simultaneously, but the experimental operation and data processing of the conventional PHW method are complicated.

In order to overcome the shortcomings mentioned above, a simpler data processing method based on CHW method and PHW method, hereinafter referred to as CPHW method, was adopted. QH Chen [23,24] used this method to successfully measure the λ and a of a loose coal. In this paper, we used this method to measure the thermal conductivities and thermal diffusivities of EPS board and XPS board simultaneously, and analyzed the measurement results in details.

2. Testing principle

The physical model of THW method is shown in Fig. 1. A hot wire is sandwiched between two samples, and the length of the hot wire and the dimension of the samples are assumed to be infinite. Heat transfer along the wire length direction is ignored and the heat mainly transfers from the wire surface to the samples in the radial direction of the cylindrical coordinate by conduction.

The energy equation can be written as follows [25]

$$\frac{1}{\alpha_s}\frac{\partial\theta}{\partial\tau} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\theta}{\partial r}\right) \quad (1)$$

Initial condition

$$\theta(r,\tau)|_{\tau=0} = 0 \quad (2)$$

Boundary conditions

$$\lim_{r\to 0}\left(r\frac{\partial\theta}{\partial r}\right) = -\frac{q_l}{2\pi\lambda_s} \quad \text{and} \quad \frac{\partial\theta}{\partial r}|_{r=\infty} = 0 \quad (3)$$

Then, the analytical solution of Eq. (1) can be solved as follows

$$\theta(r,\tau) = \frac{q_l}{4\pi\lambda_s}\cdot E_1\left(\frac{r^2}{4\alpha_s\tau}\right) \quad \tau > 0,\ 0 < r < \infty \quad (4)$$

$$E_1(\eta) = -\gamma - \ln(\eta) - \sum_{k=1}^{\infty}(-1)^k\eta^k/(k!k) \quad (5)$$

For CHW method, the theoretical temperature rise of the surface of the wire can be expressed as following description.

$$\theta(r_0,\tau) = \frac{q_l}{4\pi\lambda_{s,c}}\left[-\gamma - \ln\left(\frac{r_0^2}{4\alpha_{s,c}\tau}\right) - \sum_{k=1}^{\infty}(-1)^k\left(\frac{r_0^2}{4\alpha_{s,c}\tau}\right)^k/(k!k)\right] \quad (6)$$

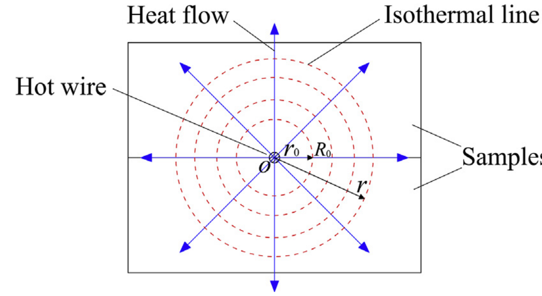

Fig. 1. Physical model of THW method.