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Research Paper

Effect of radiative heat transfer on determining thermal conductivity of semi-transparent materials using transient plane source method

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HIGHLIGHTS

- Experiment process of applying TPS method to semi-transparent materials is mimicked.
- Influence of radiative heat transfer on the thermal conductivity test is revealed.
- Test accuracy relies on the extinction coefficient and temperature of materials.
- Low extinction coefficient sample measured at high temperature is overestimated.

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ABSTRACT

The theoretical basis of transient plane source method is the unsteady differential equation of heat conduction which is suitable for opaque medium. Extremely low density materials such as aerogels and foaming materials are not opaque for thermal radiation at high temperature. For these semi-transparent materials, radiation will participate in the thermal transport process. When applying transient plane source method to measure the thermal conductivity of semi-transparent materials, the existence of thermal radiation within the materials will affect the test accuracy. In present study, the effect of radiative heat transfer on determining thermal conductivity of semi-transparent materials using transient plane source method is numerically studied. The results show that the thermal conductivity of semi-transparent materials measured by transient plane source method will be overestimated at temperature higher than 600 K and extinction coefficient less than 2000 m^{-1} where radiative heat transfer is dominant. The deviation increases with temperature and reaches to 19.6% at 1000 K for materials with extinction coefficient of 500 m^{-1}. It illustrates that the thermal conductivity of semi-transparent materials measured by transient plane source method has taken into account part of the influence of radiative heat transfer within the materials.

1. Introduction

Thermal conductivity is one of the most important thermo properties. Methods of measuring thermal conductivity can be divided in two categories, steady state method and unsteady state method. Unsteady method includes laser flash method, transient hot wire/strip method, transient plane source (TPS) method, etc. These methods are based on the Fourier diffusion law and the energy equation is an unsteady differential equation of heat conduction which is designed for opaque medium [1]. TPS method has many unique advantages such as wide test range: 0.005–500 W/m K; different sample states: solid, powder, liquid or porous materials; different sample shape: bulk, slab, thin film; and high sensitivity [2]. In recent years, Hot Disk utilizes TPS method has attracted widely application [3–8]. Although the nominal test accuracy of TPS method is 3% for thermal conductivity, 5% for thermal diffusivity, it was only validated for specific materials at or around room temperature.

Aerogels and foaming materials have superior insulation performance and thus have widespread application value and prospect in thermal insulation field. However, these kinds of materials have spectral extinction coefficient of only a few hundred to several thousand m^{-1} which are nearly transparent at certain wavelength range [9–13]. These materials have high porosity and nano-scale or micro-scale porous structure. Radiative heat transfer within the porous semi-transparent medium is complex since radiation will be transmitted by the pores, absorbed, scattered and re-emitted

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Nomenclature

a	thermal diffusivity, mm^2/s
c	specific heat capacity, J/kg k
$D(\tau)$	dimensionless time
I_0	modified zero order Bessel function, $I_0(x) = \frac{1}{2\pi}\int_0^{2\pi} e^{x\sin\theta} d\theta$
$I(r, z, \theta, \varphi)$	radiant intensity at point (r, z) in the direction (θ, φ), W/m^2 Sr
$I_0(T)$	radiant intensity emitted by a black body at temperature, W/m^2 sr
k, l	intermediate variable
m	number of the concentric rings
n	refractive index of medium
$P(\theta)$	scattering phase function
P_0	heating power of the sensor, W
Δp_{prob}	probing depth $\Delta p_{prob} = 2\sqrt{at}$, mm
q	heat flux, W/m^2
$\vec{q}, \vec{q}_c, \vec{q}_r$	total heat flux, conductive heat flux and radiative heat flux, W/m^2
R_0	initial resistance of the sensor before heating, Ω
$R(t)$	resistance of the sensor at time t, Ω
r	radius of outermost ring of the sensor, mm
T	temperature, K
ΔT	temperature increase of the sensor, K
ΔT_i	temperature difference across the heat sensor insulation layer, K
$\Delta T(t)$	the temperature increase of the sensor outer surface, K
t	heating time, s

Greek symbols

α	temperature coefficient of the resistance, 1/K
β, κ, σ	extinction, absorption and scattering coefficients,1/m
δ	sample thickness, m
η	$\eta = \sin\theta\sin\varphi$, direction cosine
λ	thermal conductivity, W/m K
λ_r	radiative thermal conductivity, W/m K
λ_s	thermal conductivity via conduction, W/m K
$\lambda_{e-Rosseland}$	thermal conductivity obtained from Rosseland model, W/m K
λ_{e-DOM}	thermal conductivity obtained from 1D steady heat transfer simulation, W/m K
λ_{e-TPS}	thermal conductivity obtained from transient plane source method simulation, W/m K
μ	$\mu = \sin\theta\cos\varphi$, direction cosine along the radial coordinate
ρ	density, kg/m^3
σ_s	Stephen Boltzmann constant, 5.67×10^{-8} W/m^2 K^4
$\sigma_{e,R}$	Rosseland extinction coefficient, 1/m
τ	dimensionless time given by $\tau = \sqrt{t/\Theta}$
ξ	$\xi = \cos\theta$, direction cosine along the axial coordinate
Θ	characteristic time, $\Theta = r^2/a$, s
Ω	solid angle, sr

by the solid structures. Many researchers have adopted TPS method to measure thermal conductivity of aerogels at high temperature [6–8]. In their studies, although the error bars are showed on the measured thermal conductivity in their figures, without providing any validation.

Many works have been conducted to reveal the uncertainty brought by parameter determination, data reduction and theoretical assumptions [14–24]. Although lots of research have been conducted to reveal the influences of these factors, the overall accuracy is still difficult to estimate because the uncertainty varies with materials and temperature. Due to the limitation of the test theory, whether TPS method is applicable to semi-transparent materials or not will affect the thermal conductivity accuracy measured by this method. Because the existence of radiation within the materials will affect heat transfer when performing the measurement, so the measured thermal conductivity contains the effect of radiative heat transfer if not all. However, the quantitative impact is unknown and is an urgent research problem. Attentions also have been paid on the influence of radiative heat transfer on the thermal conductivity measure by unsteady methods. Cohen and Glicksman [10] studied the thermal properties of silica aerogel and found that radiation heat transfer in the hot wire test failed to reveal the same contribution as in large scale applications when measuring semi-transparent media where heat penetration depth is short and optical thick assumption cannot be fulfilled. Coquard et al. investigated the possibility of applying laser flash method [25], hot wire method [26] and TPS method [22] to semi-transparent materials and concluded that the measured thermal conductivity could reveal the contribution of radiative heat transfer directly or after some improvement.

For TPS method, only Coquard et al. [22] analyzed the accuracy when applied to low density insulating materials by reproducing the heat transfer process and recording the thermal response of the probe as the practical experiment. The thermal conductivity accuracy of two low density thermal insulators, polyvinylchloride foam (ρ = 55 kg/m^3, c = 1200 J/kg K, λ = 0.03 W/m K) and extruded polystyrene foam (ρ = 35 kg/m^3, c = 1200 J/kg K, λ = 0.03 W/m K) with extinction coefficient ~2000 m^{-1} were numerically analyzed. The result shows that the presence of radiative heat transfer within the low density insulating materials has no effect on the accuracy of the thermal conductivity identified. The measured thermal conductivity actually corresponds to the effective thermal conductivity. However, the conclusion does not have generality since the analysis is only conducted at room temperature where radiation is not the dominant heat transfer process and usually can be neglected. The radiative heat flux is proportional to T^4 (according to Stefan-Boltzmann's Law), so radiative heat transfer may become a dominant heat transfer process and cannot be neglected at high temperature. Whether the radiative heat transfer has significant influence on the thermal conductivity accuracy of semi-transparent materials at high temperature is still questionable for TPS method. Therefore, the aim of present study is to investigate the reliability of TPS method applied to semi-transparent materials with different extinction coefficient at different temperature.

2. Principle of TPS method

TPS technique is proposed by Gustafsson [27] to measure thermal conductivity and thermal diffusivity simultaneously via a single transient test. TPS method became an ISO standard in 2008 (ISO22007-2) [28]. The TPS technique utilizes a sensor both as a heat source and a temperature sensor (Fig. 1). The sensor consists of a double spiral structure which is made of nickel and coated by kapton or mica insulation layer. The sensor is placed between two pieces of samples and forms a sandwich structure. When heated, the electric resistance of sensor, $R(t)$, increases with temperature which is a function of time:

$$R(t) = R_0(1 + \alpha\Delta T) = R_0[1 + \alpha(\Delta T_i + \alpha\Delta T(t))] \tag{1}$$