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Effect of Radiation Heat Transfer on Thermal Diffusivity Measurements[1]

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Experimental data on thermal conductivity and thermal diffusivity of a semitransparent material generally include an error due to the radiation heat transfer. This error varies in accordance with the experimental conditions such as the temperature level of the sample and the measuring method. In this paper, research on the influence of radiation heat transfer on thermal diffusivity are reviewed, and as an example, the method to correct the radiation component in the apparent thermal diffusivity measured by the stepwise heating technique is presented. The transient heat transfer by simultaneous thermal conduction and radiation in a semitransparent material is analyzed when the front surface is subjected to stepwise heating. The apparent thermal diffusivity, which includes the radiation component, is calculated for various parameters.

KEY WORDS: radiation effect; semitransparent material; stepwise heating method; thermal diffusivity; thermal radiation; transient heat conduction.

1. INTRODUCTION

When the thermal diffusivity of a semitransparent material is measured by a transient method such as the laser flash method or the stepwise heating method, the simultaneous transient heat transfer by conduction and radiation takes place through the sample and we observe the temperature response as the sum of both of these heat transfer modes. Thermal diffusivity calculated from this temperature response varies in accordance with the measuring conditions such as the temperature level, the shape of the sample, and the measuring method; consequently the determined thermal diffusivity includes an error due to the radiation heat transfer.

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Several investigations on the radiation effects on thermal diffusivity measured by the laser flash method have been performed as follows. Ohta and collaborators measured the thermal diffusivity of molten slags in the range 1273–1723 K [1] and molten alkaline metal silicates in the range 900–1400 K [2] and analyzed the radiation component assuming perfectly transparent material. Darby [3] presented a theoretical method for analyzing the radiation component in the data from laser flash diffusivity experiments for molten glass layers. Kishimoto et al. [4] performed measurements on metallurgical slags in the range 300–1750 K and evaluated the radiative component. Bentsen et al. [5] analyzed the radiative contribution to the thermal diffusivity of a silicone carbide fiber reinforced glass ceramic.

The present author and his collaborators have also been engaged in the anaytical and experimental study of the radiation component in thermal diffusivity measurements using the stepwise heating method as follows. A theoretical method to correct the radiation effect in the three-layered cell filled with a molten salt as a sample was presented [6]. The thermal diffusivity of soda glass plates having various thicknesses was measured and the contribution of the radiative heat transfer was analyzed [7]. For simplifying the correction method and saving the computing time, the P-N approximation by using the Legendre function was applied [8]. The other transient methods, such as the periodic heating method and the hot wire method, are not included here.

In spite of the above-mentioned several investigations, there is a lack of systematic research on the radiation effects, and a simple correction method for the radiation component in the apparent thermal diffusivity measured by the transient technique remains to be established.

In this paper, as an example of the transient methods the stepwise heating method is adopted, namely, the transient heat transfer by simultaneous conduction and radiation in an absorbing and emitting material is analyzed when the front surface is subjected to stepwise heating. The apparent thermal diffusivity is calculated for various parameters. It is emphasized that the thermal radiation properties such as the absorption coefficient, the refractive index, and the emissivity of the sample surfaces or the interfaces are needed in order to correct the apparent thermal diffusivity.

2. THERMAL RADIATION EFFECTS

Consider a one-dimensional system consisting of an absorbing and emitting medium with gray and parallel surfaces. The transient heat transfer by simultaneous thermal conduction and radiation through this medium is solved with the use of the following equations:

$$\frac{\partial \Theta}{\partial Fo}=\frac{\partial^2 \Theta}{\partial X^2}-\frac{\tau_0 \cdot T_0^*}{N}\frac{\partial q_R^*}{\partial X} \tag{1}$$

where

$$\begin{aligned} q_R^*(\tau_0 Xn) = {} & 2B_f^* E_3(\tau_0 Xn) - 2B_b^* E_3[\tau_0(1-Xn)] \\ & + \frac{1}{2}\tau_0 \int_0^{Xn} T^{*4}(\tau_0 X_0)\, E_2[\tau_0(Xn-X_0)]\, dX_0 \\ & - \frac{1}{2}\tau_0 \int_{Xn}^{1} T^{*4}(\tau_0 X_0)\, E_2[\tau_0(X_0-Xn)]\, dX_0 \end{aligned} \tag{2}$$

$$T_0^*=\frac{T_0}{Q\cdot l/\lambda}, \qquad \Theta=\frac{\theta}{Q\cdot l/\lambda}, \qquad Fo=\frac{a\cdot t}{l^2}, \qquad B_i^*=\frac{B_i}{4n^2\sigma T_0^4} \qquad (i=f, b)$$

$$N=\frac{\lambda\cdot\kappa}{4n^2\sigma T_0^3}, \qquad q_R^*=\frac{q_R}{4n^2\sigma T_0^4}, \qquad \tau_0=\kappa\cdot l, \qquad X=\frac{x}{l} \tag{3}$$

and a, thermal diffusivity; B_b, radiosity of a back surface; B_f, radiosity of a front surface; $E_n(t')$, exponential integral function; Fo, Fourier number; l, thickness of the sample; N, dimensionless conduction-radiation parameter; n, refractive index; Q, heat flux supplied at the front surface; q_R^*, dimensionless radiative heat flux; q_R, radiative heat flux transfered in the sample; T_0, initial temperature; T_0^*, dimensionless temperature; X, dimensionless distance; x, distance; Θ, dimensionless temperature rise; θ, temperature rise; κ, radiative absorption coefficient; λ, thermal conductivity; σ Stefan-Boltzmann's constant; and τ, optical thickness.

The stepwise heating method is considered as an example. Equation (1) is nonlinear, integropartial differential equation for which analytical closed-form solutions do not appear possible, and therefore the finite difference method was employed to solve it with the appropriate boundary conditions.

2.1. Appropriate Parameters

An apparent thermal diffusivity, a', is defined as the property which includes the radiative heat transfer component. The results of the calculation for the effects of various parameters on the apparent thermal diffusivity are mentioned in the following paragraphs.

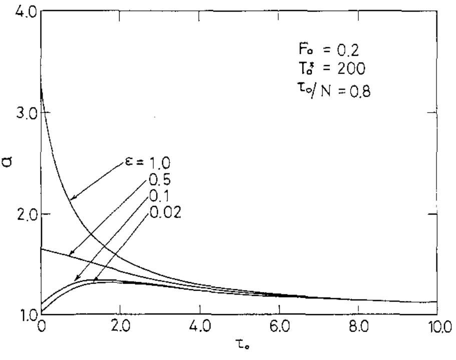

Fig. 1. The effect of emissivity of the interfaces.

2.1.1. Emissivity of the Interfaces

Both surfaces of the sample are coated with very thin layers, such as evaporated films of a metal, and the thermal radiation is reflected, absorbed, and emitted at these interfaces which face the inner portion of the sample, and therefore, the radiosity varies with the emissivity of the interface.

An example of the results of the apparent thermal diffusivity which were calculated considering emissivity as a parameter is shown in Fig. 1. The change in the value of the x axis corresponds to the change of the

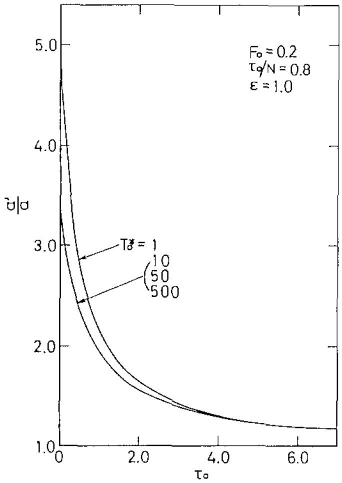

Fig. 2. The effect of dimensionless temperature T_0^*.

absorption coefficient since the sample thickness is kept constant. The apparent thermal diffusivity increases with emissivity. This tendency is very significant for small values of the absorption coefficient.

2.1.2. Dimensionless Temperature, T_0^* (Supplied Heat Flux)

The dimensionless temperature T_0^* includes the heat flux supplied in a stepwise manner and is strongly influenced by the heat flux value. The apparent thermal diffusivity is little affected by T_0^* in the range of large T_0^* as shown in Fig. 2. Since the value of T_0^* in actual measurements is greater than 30, the influence of T_0^*, namely, the supplied heat flux, can be left out of consideration. The fact that the amount of the supplied heat flux is not needed in correcting the radiation component is a great advantage.

2.1.3. Fourier Number, Fo *(Measuring Time)*

Figure 3 shows the effect of Fourier number, namely, the measuring time. The effect on the apparent thermal diffusivity increases with

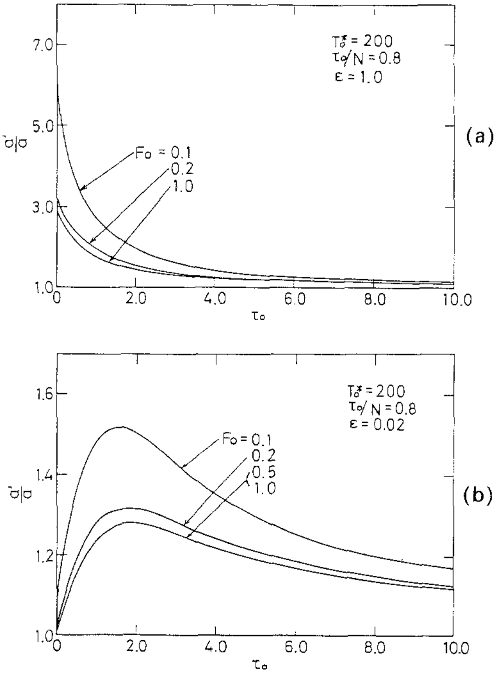

Fig. 3. The effect of the Fourier number. (a) $\varepsilon = 1.0$; (b) $\varepsilon = 0.02$.

decreasing Fourier number, because the radiation transfer is faster than the conduction heat transfer.

2.1.4. Dimensionless Parameter $\tau_0 T_0^*/N$ (Initial Temperature)

Dimensionless parameter $\tau_0 T_0^*/N$ $(=4n^2\sigma T_0^4/Q)$ is a coefficient of the radiation term in Eq. (1). Since the effect of Q can be neglected as described above, this parameter is regarded as a representative parameter of the initial temperature. The effect of this parameter on the apparent thermal diffusivity is large as shown in Fig. 4. The numerical values of 120, 500, and 1500 correspond to the initial temperatures of 700, 1000, and 1300 K, respectively.

2.1.5. Sample Thickness

When the thermophysical properties, the supplied heat flux, the initial temperature, and the measuring time are kept constant and only the thick-

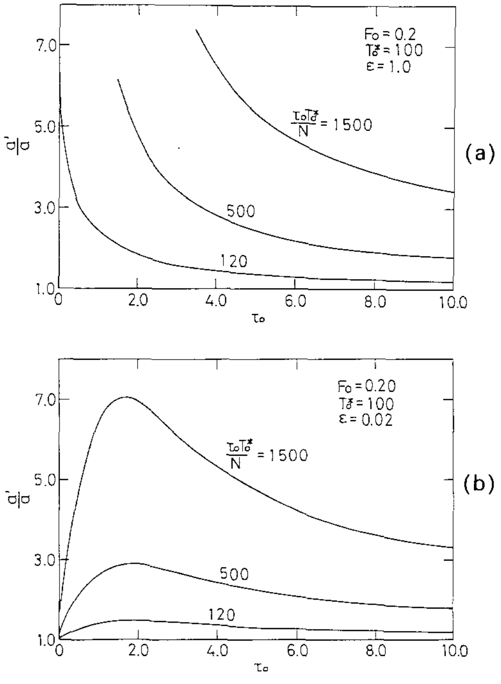

Fig. 4. The effect of dimensionless parameter $\tau_0 T_0^*/N$.
(a) $\varepsilon = 1.0$; (b) $\varepsilon = 0.02$.

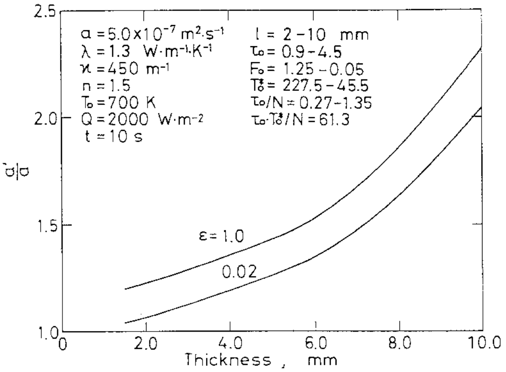

Fig. 5. Variation of apparent thermal diffusivity with sample thickness.

ness of the sample is varied, the apparent thermal diffusivity increases as shown in Fig. 5. The reason is that the total heat flux in the sample decreases as the thickness increases, however, the ratio of the radiative to the conductive heat flux increases with the thickness. When the thickness changes from 2 to 10 mm, the change in each parameter is shown in Fig. 5. The Fourier number rapidly decreases as the thickness increases and the decrease in the Fourier number may contribute to increasing the apparent thermal diffusivity.

2.2. Experimental Example

As an example, the apparent thermal diffusivity of soda glass plates measured by the stepwise heating method is shown in Fig. 6 [7, 9].

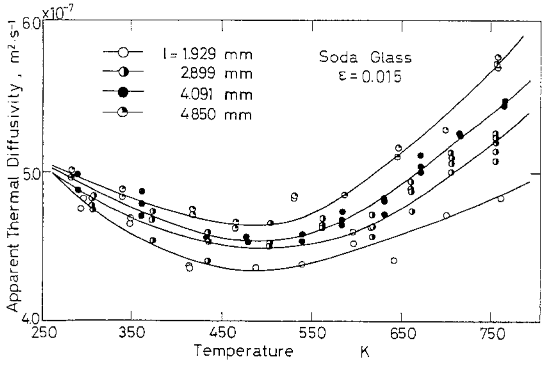

Fig. 6. Apparent thermal diffusivity of soda glass plates.

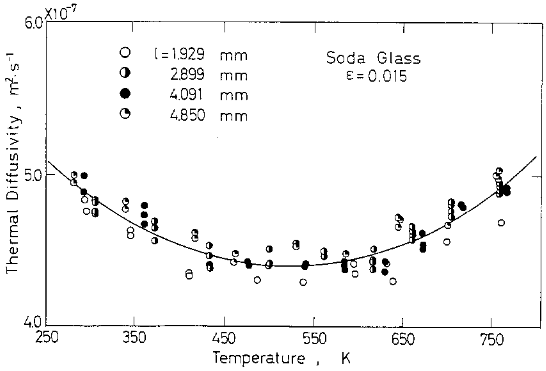

Fig. 7. Thermal diffusivity of soda glass.

Samples with four different thicknesses were fabricated from the same lot. The absorption coefficient of the sample was divided into three bands as 45, 450, and ∞ m^{-1} for the wavelengths in the range 0–2.7, 2.7–4.5, and 4.5–∞ μm, respectively. Both surfaces of the sample were coated with evaporated films of copper, and furthermore, a dry carbon paint was splayed on the film to improve absorption of the supplied heat flux. The emissivity of the interface was considered constant (0.015) for the calculations. The apparent thermal diffusivity gradually increases with increasing sample thickness. After correcting for the thermal radiation effects, the thermal diffusivity values become independent of the sample thickness as shown in Fig. 7.

3. SUBJECTS OF FUTURE INTEREST

For performing corrections for the thermal radiation effects, the absorption coefficient and the refractive index of the sample and the emissivity of the interface are required. If scattering plays an important role in the radiation transfer, the scattering coefficient or extinction coefficient is needed. There are only a very limited smount of data on these properties reported in the literature, especially for high-temperature melts such as molten salts and semiconductor melts.

The correction methods developed at present are somewhat complicated and restricted, so a simpler yet a more general correction method is desired. Also, analytical and experimental studies of the transient radiation heat transfer through semitransparent high-temperature melts and ceramics for the far infrared region of radiation may be interesting.

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