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Measurement of the thermal transport properties of liquids using the front-face flash method

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ABSTRACT

The flash method in the front-face configuration is used to retrieve simultaneously the thermal diffusivity and thermal effusivity of liquids. The thermal conductivity is determined from these measured properties. The method consists in heating with a flash lamp, the front face of an opaque cell containing the liquid sample, and monitoring the cooling process of the same face using an infrared camera. It is shown that a simple one dimensional approach, based on the Fourier's heat diffusion equation for a three layer system, can be used to determine the thermal properties of the liquid. Measurements performed on several non-metallic liquids covering a wide range of thermal properties validate the method. Good agreement is found between the retrieved values of the thermal properties and previously reported values in literature. Moreover, measurements under the front-face configuration are less time consuming than using the classical (rear-face) flash method. Due to its noncontact nature, this method may find practical application for the thermal characterization of complex fluids even when applying external electric or magnetic fields.

1. Introduction

Heat transfer in liquids has attracted the attention of the scientific community in the last decades due to its important role in industry. Particularly, in the design and operation of heat exchangers, for power generation, air-conditioning, cooling devices in microelectronics, among many others [1,2]. The three most relevant parameters for these applications are: thermal conductivity K, thermal diffusivity α and thermal effusivity ϵ (or the heat capacity c) which are linked [3] by the relationship $K = \rho c \alpha = \epsilon \sqrt{\alpha}$, where ρ is the density of the material. Consequently, only two thermal transport properties have to be measured in order to perform a complete characterization of a given material.

For steady-state heat conduction, thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$) is the property of interest. It measures the material's ability to transport thermal energy across a temperature gradient [3,4]. On the other hand, α and ϵ are thermal properties associated with transient heat conduction. Thermal diffusivity ($\mathrm{m^2\,s^{-1}}$) measures the propagation speed of thermal energy in a material [5] and thermal effusivity ($\mathrm{W\,s^{1/2}\,m^{-2}\,K^{-1}}$) is a surface property that measures the ability of the material to exchange heat with its surroundings [4].

There are several methods to measure the thermal properties of liquids [2,5–12]. However, methods like hot wire or 3ω are invasive to the liquid and they may be more sensitive to convective heat transfer rather than for heat conduction [11,13]. Nevertheless, the photopyroelectric method (which is also contact based) has shown to be very accurate for determination of thermal properties [8,14,15]. On the other hand, non-contact methods present an advantage for studying the thermal properties of fluids under the action of magnetic or electric fields. This is a challenging and interesting research topic in complex fluids. Accordingly, there have also been several investigations focused in the rear-face (classical) flash method [16] for measuring the thermal properties of liquids. However, some limitations have been found, for example, when using a laser flash apparatus, the presence of air bubbles in a required closed cell induces hardly accountable errors in the measurements [17]. Additionally, when using a measurement cell, made of two thin metallic cylindrical walls enclosing a liquid, it was found that the thermal diffusivity and thermal effusivity of liquids cannot be retrieved simultaneously [11]. However, when using this methodology α and ρc could be estimated.

In this work, the front-face flash method [18] is successfully used for the first time to retrieve simultaneously α and ϵ of liquids. The measurement cell consists of two metallic slabs enclosing a liquid layer. One-dimensional heat conduction is considered through this three-layer system. The effect of the liquid thermophysical properties on the front surface temperature, after applying a uniform heating pulse, is

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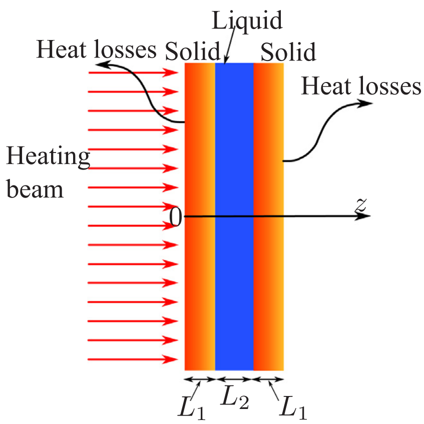

Fig. 1. Diagram of a three-layer system consisting of a solid slab, a fluid layer and another solid slab. The surface $z = 0$ is uniformly illuminated by a brief flash lamp pulse.

explored. Sensitivity analysis of the illuminated surface temperature evolution to the changes of thermal diffusivity and thermal effusivity is done. This provides information about the optimum layers' properties, which allows to obtain both thermal properties from a single measurement. Several common non-metallic liquids and a thermal compound based on silicone (silicone grease) covering a wide range of thermal effusivities are studied.

2. Theoretical model

Fig. 1 shows the geometry of a three-layer system made of two metallic slabs of thickness L_1 each and a liquid layer of thickness L_2. One metallic surface is illuminated uniformly by a flash lamp pulse and the corresponding Laplace transform of the temperature rise at that surface ($z = 0$) is calculated using the thermal quadrupole method [19]:

$$\begin{bmatrix} \overline{T}_1(0) \\ \overline{\phi}(0) \end{bmatrix} = \begin{pmatrix} 1 & 0 \\ h & 1 \end{pmatrix} \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} 1 & 0 \\ h & 1 \end{pmatrix} \begin{bmatrix} \overline{T}_1(L) \\ \overline{\phi}(L) \end{bmatrix}, \tag{1}$$

where $\overline{T}_1(z)$ and $\overline{\phi}(z)$ are the Laplace transforms of the solid slab temperature and heat flux at positions $z = \{0, L\}$, respectively. $L = 2L_1 + L_2$ is the total length of the three-layer system, i.e., $z = L$ is the rear-face of the system. The heat transfer by convection from the solid surfaces, in contact with the surrounding atmosphere (air), is taken into account by the quadrupole matrices involving the heat transfer coefficient h. Note that heat transfer by convection at the solid-liquid interfaces have been neglected since the temperature rise at both interfaces is small. The quadrupole matrix with coefficients A, B, C and D is obtained from the product of the transfer matrices corresponding to the three layers in the system [19,20],

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} A_1 & B_1 \\ C_1 & A_1 \end{pmatrix} \begin{pmatrix} A_2 & B_2 \\ C_2 & A_2 \end{pmatrix} \begin{pmatrix} A_1 & B_1 \\ C_1 & A_1 \end{pmatrix}. \tag{2}$$

From Eq. (2), it can be inferred that:

$$A = A_1(A_1A_2 + B_1C_2) + C_1(A_1B_2 + B_1A_2), \tag{3a}$$

$$B = A_1(A_1B_2 + B_1A_2) + B_1(A_1A_2 + B_1C_2), \tag{3b}$$

$$C = A_1(A_1C_2 + C_1A_2) + C_1(A_1A_2 + C_1B_2), \tag{3c}$$

$$D = A_1(A_1A_2 + C_1B_2) + B_1(A_1C_2 + C_1A_2), \tag{3d}$$

where the quadrupole coefficients of the i-th layer are given by [19]:

$$A_i = \cosh(x_i\sqrt{s}), \tag{4a}$$

$$B_i = \frac{1}{\epsilon_i\sqrt{s}}\sinh(x_i\sqrt{s}), \tag{4b}$$

$$C_i = \epsilon_i\sqrt{s}\sinh(x_i\sqrt{s}), \tag{4c}$$

where $x_i = L/\sqrt{\alpha_i}$, s is the Laplace variable, ϵ_i and α_i are the thermal effusivity and thermal diffusivity of the i-th layer, respectively. The subscript $i = \{1, 2\}$ stands for the solid and fluid layer, respectively. Finally, the Laplace transform of the temperature at the front surface ($z = 0$) can be expressed as

$$\overline{T}_1(0) = \frac{\overline{I}_0\chi(A + Bh)}{C + (A + D)h + Bh^2}, \tag{5}$$

which was obtained from Eq. (1) considering adiabatic boundary conditions [19,20]: $\phi(0) = \overline{I}_0\chi$ and $\phi(L) = 0$. The factor χ is the energy fraction absorbed by the front surface. $\overline{I}_0$ represents the Laplace transform of the light pulse. A Dirac delta intensity pulse $I_0(t) = Q_0\delta(t)$ was considered. Its Laplace transform is $\overline{I}_0 = Q_0$, where Q_0 is the energy per unit area ($\mathrm{J\,m^{-2}}$) delivered by the pulse and $\delta(t)$ is the Dirac delta function.

No analytical solution has been found for the inverse Laplace transform of $\overline{T}_1(0)$. Consequently, the temperature evolution of the front surface has been obtained by applying a numerical inverse Laplace transform algorithm to Eq. (5). In this case, the well-known Euler algorithm [21] has been used, which provides accurate results for smooth functions. This condition is fulfilled by $\overline{T}_1(0)$ given in Eq. (5).

The quadrupole coefficients given in Eqs. (4) can be written in terms of the following five parameters (see Eqs. (S1)–(S4) in the supplementary information): $Q_0\chi/\epsilon_1$, $x_1 = L_1/\sqrt{\alpha_1}$, $x_2 = L_2/\sqrt{\alpha_2}$, $b_{21} = \epsilon_2/\epsilon_1$ (the ratio between the thermal effusivity of the liquid to that of the solid) and h/ϵ_1. Consequently, the Laplace transform of the front-face temperature $\overline{T}_1(0)$ and the corresponding surface temperature evolution $T_1(0)$ depend on those five parameters, as shown in Fig. S1 of the supplementary information. We assume that x_1 is known and it can be fixed during the evaluation of $T_1(0)$. Accordingly, a fit of $T_1(0)$ as a function of time, involving the other four parameters, may allow to retrieve α_2 and ϵ_2 simultaneously, as long as the thickness of the fluid layer L_2 and the thermal effusivity of the solid layer ϵ_1 are also known.

3. Simulations

Simulations of the surface temperature evolution $T_1(0)$ of a three layer system, after applying a short heating pulse, are shown in Fig. 2. The modeled system consists of two stainless steel AISI-316 ($\alpha_1 = 3.6\,\mathrm{mm^2\,s^{-1}}$ and $\epsilon_1 = 7188\,\mathrm{W\,s^{1/2}\,m^{-2}\,K^{-1}}$) slabs and water ($\alpha_2 = 1.43\,\mathrm{mm^2\,s^{-1}}$ and $\epsilon_2 = 1588\,\mathrm{W\,s^{1/2}\,m^{-2}\,K^{-1}}$). The effect of the metallic slabs thicknesses on the surface temperature $T_1(0)$ is explored in Fig. 2a. An ideal Dirac pulse of intensity $1\,\mathrm{kJ\,m^{-2}}$ and a typical heat convection coefficient [22] ($h = 10\,\mathrm{W\,m^{-2}\,K^{-1}}$) is considered. Moreover, the dimensionless time t/τ_2 is introduced, in such a way that simulations are valid for any α_2 and L_2 values. The characteristic time $\tau_2 = L_2^2/(\pi\alpha_2)$, gives a measure of the time that it takes for the heat to propagate through a slab (liquid layer 'alone') after exciting with a Dirac like pulse [16]. The thickness of the liquid layer has been fixed to

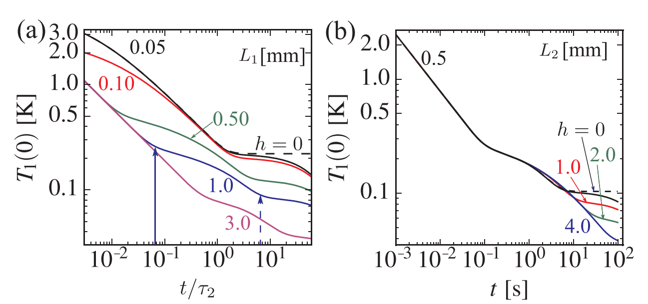

Fig. 2. Surface temperature evolution $T_1(0)$ of a three-layer system consisting of two AISI-316 slabs and a water layer in the middle: (a) the effect of the solid thickness L_1 is explored and (b) the effect of the liquid layer thickness L_2 is shown.