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Simultaneous measurements of the thermal diffusivity and conductivity of thermal insulators using lock-in infrared thermography

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ABSTRACT

Optically excited lock-in infrared thermography provides fully non-contact methods to measure the thermal diffusivity of solids. However, measuring the thermal conductivity requires precise knowledge of the energy absorbed by the sample and of the absolute temperature rise. We have found that the temperature profile of poor thermal conductors illuminated by a modulated and focused laser beam is greatly affected by heat conduction to the surrounding air. In this work, we take advantage of the thermal coupling between the sample and the adjacent air to retrieve simultaneously the in-plane thermal diffusivity and conductivity of the sample. A sensitivity analysis demonstrates that the accuracy in the value of the thermal conductivity dramatically increases as it approaches the thermal conductivity of the air and/or when experiments are performed at very low modulation frequencies (<0.1 Hz). This means that this method is specially suited to determine the thermal transport properties of thermal insulators. Experiments performed on homogeneous polymers, on paper sheets and on extruded polystyrene foams confirm the validity of the method.

1. Introduction

The complete characterization of the thermal transport properties of a material requires the knowledge of two independent parameters: thermal diffusivity (D) and thermal conductivity (K) [1,2]. Whereas steady-state methods are used to measure the thermal conductivity, transient methods are sensitive to the couple D and K. Transient methods based on optically excited infrared (IR) thermography are nowadays largely widespread in laboratories and industry to characterize the thermal diffusivity of all kind of materials.

Lock-in IR thermography consists in illuminating the sample by an intensity modulated light beam and detecting the oscillating component of the temperature rise by means of an IR video camera. In particular, by tightly focusing a laser beam onto the sample surface and recording the temperature as a function of the radial distance to the laser spot (r), the thermal diffusivity can be retrieved. In the absence of heat losses, the natural logarithm of the temperature amplitude multiplied by the radial distance, $\mathrm{Ln}(|T|r)$ and the temperature phase, Ψ, behave linearly with respect to r. From their common slope $m = -\sqrt{\pi f/D}$, the thermal diffusivity can be obtained. Here f is the modulation frequency. This is the so-called "slopes method" [3,4], which has been used to measure the in-plane thermal diffusivity of solids.

Recently, we found that the thermal conduction to the surrounding air modifies the solid temperature, breaking the above mentioned linear behaviour. This effect is especially strong in the case of thin plates, thermal insulators and/or low modulation frequencies [5], and has been confirmed independently [6]. Accordingly, measuring the thermal diffusivity of insulators thin plates using the "slopes method" requires suppressing the disturbing effect of the air by performing the experiment in a vacuum chamber [7].

Measuring the thermal conductivity (K) by lock-in thermography, instead, is a more challenging task since it requires a precise knowledge of the power absorbed by the sample together with a measurement of the absolute temperature rise. Actually, in the equation governing the surface temperature of an opaque sample illuminated by a modulated and focused laser beam, in the absence of heat losses, the thermal conductivity only appears in a factor

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containing the laser power absorbed by the sample [8]: $\eta P_o/K$, where P_o is the laser beam power and η is the fraction of the laser power absorbed by the sample. In most cases, with diffusive surfaces, ηP_o cannot be obtained accurately. On the other hand, measuring the absolute temperatures with an IR camera is difficult since it requires knowledge of the surface emissivity, the transparency of the sample to IR wavelengths, the background temperature, the atmosphere transmission, etc.

Alternatively, the thermal coupling between the sample and a liquid backing of known thermal properties can be used to measure both thermal properties simultaneously [9]. Following this idea, in this work we take advantage of the effect of the heat conduction to the air on the sample temperature to retrieve simultaneously D and K. We have obtained an analytical solution for the sample temperature that includes the effect of heat losses by convection and radiation, as well as by conduction to the surrounding air. We have analyzed the sensitivity of the surface temperature (amplitude and phase) to D and K. We have confirmed that the surface temperature is very sensitive to D, regardless the sample properties. The sensitivity to K, instead, varies from zero for good thermal conductors and high frequencies to a high enough value for thermal insulators ($K < 1$ Wm^{-1}K^{-1}) and low frequencies ($f < 0.1$ Hz). This means that this method is specially adapted to measure the thermal properties of thermal insulators such as polymers, foams, fabrics, building materials, porous samples, etc. We have validated the method by performing low-frequency (5–120 mHz) lock-in IR thermography experiments on homogeneous polymers and on heterogeneous paper sheets and extruded polystyrene foams.

Before closing this introduction, let us mention that there are several methods to measure both thermal transport properties simultaneously. The Hot Wire was first introduced to deal with liquids [10], although it was then developed to work with solids [11,12]. However, it is mainly restricted to polymers, which are previously melted to insert the wire, guaranteeing a good thermal contact between the wire and the solid material. The Laser Flash method is especially suited to measure the thermal diffusivity of plates [13], but it needs a reference to obtain the thermal conductivity. Recently, a "cylindrical three layers" method was introduced to measure D and K in thermal insulators [14], but it is a contact method which needs a high amount of material. The so-called Hot Disk method [15,16] is probably the most acknowledged one and it is commercially available. However, this is a contact technique that measures the through-thickness thermal transport properties. The method we are proposing here, instead, is fully noncontact and is addressed to the in-plane thermal properties. This means that it could be applied to study the thermal anisotropy from one single experiment. Moreover, as there is not restriction regarding the thickness of the sample, this method could be extended to thin sheets and filaments.

2. Theory

Let us consider an opaque and infinite slab of thickness L, illuminated by a focused laser beam of power P_o with a Gaussian profile of radius a (at $1/e^2$) and modulated at a frequency f ($\omega = 2\pi f$). The sample is surrounded by air. The geometry of the problem is shown in Fig. 1. In what follows subscripts s, g_1 and g_2 stand for sample, gas at the illuminated surface and gas at the rear surface, respectively. Due to the cylindrical symmetry, the oscillating component of the temperature in each medium can be written in the Hankel space as

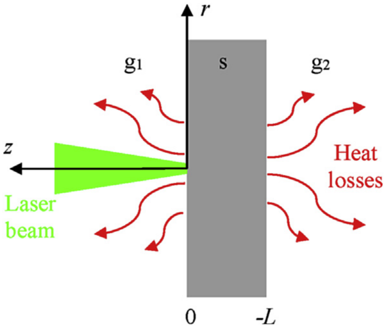

Fig. 1. Geometry of an opaque slab illuminated by a focused laser beam.

$$T_{g1}(r,z) = \int_0^\infty \delta J_o(\delta r) A e^{-\beta_g z} d\delta, \tag{1a}$$

$$T_s(r,z) = \int_0^\infty \delta J_o(\delta r)\left[B e^{\beta_s z} + C e^{-\beta_s z}\right] d\delta, \tag{1b}$$

$$T_{g2}(r,z) = \int_0^\infty \delta J_o(\delta r) E e^{\beta_g (z+L)} d\delta, \tag{1c}$$

where J_o is the Bessel function of the zero order and $\beta^2 = \delta^2 + i\omega/D$. Constants A, B, C, E are determined from the following boundary conditions

$$T_{g1}(z=0) = T_s(z=0), \tag{2a}$$

$$T_{g2}(z=-L) = T_s(z=-L), \tag{2b}$$

$$\begin{aligned} -K_s \left.\frac{\partial T_s}{\partial z}\right|_{z=0} &= -K_g \left.\frac{\partial T_{g1}}{\partial z}\right|_{z=0} + hT_s|_{z=0} \\ &\quad - \eta\frac{P_o}{2\pi}\int_0^\infty \delta J_o(\delta r) e^{-(\delta a)^2/8} d\delta, \end{aligned} \tag{2c}$$

$$-K_s \left.\frac{\partial T_s}{\partial z}\right|_{z=-L} = -K_g \left.\frac{\partial T_{g2}}{\partial z}\right|_{z=-L} - hT_s|_{z=-L}, \tag{2d}$$

where h is the combined heat transfer coefficient by convection and radiation, for which we assume the same value at both surfaces. As the surface temperature rise is small the heat rate dissipated from the surfaces can be regarded as a linear function of the temperature. The last term in Eq. (2c) is the Hankel transform of the heating power distribution of a Gaussian laser beam $\eta(P_o/\pi a^2)e^{-2r^2/a^2}$, where η is the fraction of the laser power absorbed by the sample.

By substituting Eq. (1) into Eq. (2), the four constants are determined and the resulting sample temperature writes

$$T_s(r,z) = \frac{\eta P_o}{4\pi}\int_0^\infty \delta J_o(\delta r) e^{-(\delta a)^2/8} \frac{\left(K_s\beta_s + K_g\beta_g + h\right)e^{\beta_s(L+z)} + \left(K_s\beta_s - K_g\beta_g - h\right)e^{-\beta_s(L+z)}}{\left(K_s\beta_s + K_g\beta_g + h\right)^2 e^{\beta_s L} - \left(K_s\beta_s - K_g\beta_g - h\right)^2 e^{-\beta_s L}} d\delta. \tag{3}$$