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Application of the flash method to rods and tubes

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Abstract. The flash method is the most used technique to measure the thermal diffusivity of solids. It consists of heating the front face of an opaque slab by a short light pulse and detecting the temperature evolution at its rear surface, from which the thermal diffusivity is retrieved. In this paper we extend the classical flash method to be used with rods and tubes. First, the temperature evolution of the surface temperature of solid and hollow cylinders is calculated. Then, experimental measurements of a set of stainless steel samples using an infrared camera confirm the validity of the method.

1 Introduction

The flash method is the most acknowledged technique to measure the thermal diffusivity at high temperatures. It consists of heating the front surface of an opaque slab by a short laser pulse and detecting the temperature evolution at its rear surface. The thermal diffusivity is obtained by measuring the time corresponding to the half maximum of the temperature rise ($t_{1/2}$), that is related to the thermal diffusivity through the expression [1]: $t_{1/2} = 0.1388L^2/D$, where L is the sample thickness and D is the thermal diffusivity. This procedure works under ideal conditions: negligible laser pulse duration and heat losses.

We have extended the classical flash method to be used with rods and tubes. We proceed as follows. First, the temperature distribution when these samples are illuminated by a modulated light beam is calculated. Then, using the inverse Laplace transform, the temperature evolution of the sample after being heated by a short light pulse is obtained.

2 Theory

Let us consider an infinite and opaque hollow cylinder with an outer radius a and an inner radius b, that is illuminated by a modulated light beam of intensity I_o and frequency f ($\omega = 2\pi f$). Its cross-section is shown in Fig. 1. The temperature oscillation at any point of the cylinder can be written as [2]:

$$T(r,\phi,\omega) = \sum_{m=-\infty}^{\infty} A_m J_m(qr)e^{im\phi} + \sum_{m=-\infty}^{\infty} B_m H_m(qr)e^{im\phi}, \quad (1)$$

where $q = \sqrt{i\omega/D}$ is the thermal wave vector, and J_m and H_m are the mth order of the Bessel and Hankel functions of the first kind respectively. The first term in Eq. (1) represents the ingoing cylindrical thermal wave starting at the sample surface, while the second one is the corresponding reflected wave at the inner surface. A_m and B_m are obtained from the heat flux

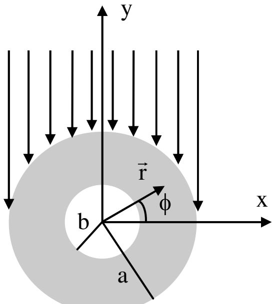

Fig. 1. Cross-section of a hollow cylinder.

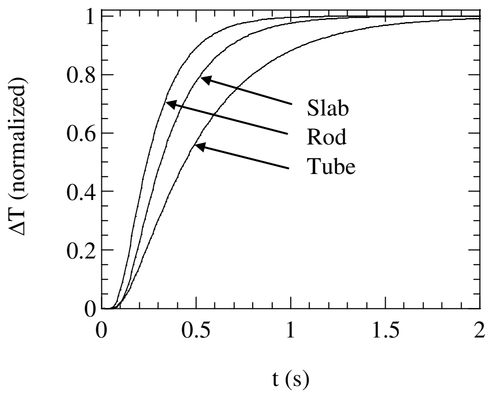

Fig. 2. Calculation of the normalized temperature rise.

continuity at the cylinder surfaces. In this way an analytical solution is obtained [2]:

$$T(r,\phi,\omega)=\frac{I_o}{2Kq}\sum_{m=-\infty}^{\infty}\frac{(-i)^m}{\pi\left(1-m^2\right)}\cos\left(m\frac{\pi}{2}\right)e^{im\phi}\frac{H_m'(qb)J_m(qr)-J_m'(qb)H_m(qr)}{J_m'(qa)H_m'(qb)-J_m'(qb)H_m'(qa)} \tag{2}$$

where J_m' and H_m' are the derivatives of the Bessel and Hankel functions respectively. A simplified expression can be found for a solid cylinder by making $b = 0$:

$$T(r,\phi,\omega)=\frac{I_o}{2Kq}\sum_{m=-\infty}^{\infty}\frac{(-i)^m}{\pi\left(1-m^2\right)}\cos\left(m\frac{\pi}{2}\right)e^{im\phi}\frac{J_m(qr)}{J_m'(qa)}. \tag{3}$$

Now, using the inverse Laplace transform, the temperature evolution after the absorption of a light pulse can be calculated. Following this procedure the temperature rise (ΔT) of the rear surface of three stainless steel samples ($K = 15\,\mathrm{Wm^{-1}\,K^{-1}}$, $D = 4.0\,\mathrm{mm^2\,s^{-1}}$) after the absorption of a Dirac pulse has been simulated: (a) a 3 mm-thick-slab, (b) a rod of 3 mm in diameter whose temperature is measured at the bottom pole, $\phi = -\pi/2$, and (c) a tube with an outer diameter of 3 mm and an inner diameter of 2 mm, whose temperature is measured at $\phi = -\pi/2$. Their normalized temperature histories are shown in Fig. 2. As can be seen the temperature rise is faster for the rod than for the slab. This is due to the fact that in the rod the illumination is closer to the bottom pole than in the slab. On the other hand, the tube shows the slowest temperature rise. Calculations performed for a wide variety of materials indicate that the time required by the back surface to reach the half of the maximum temperature rise ($t_{1/2}$) only depends on the thermal diffusivity and on the sample size, through the equation:

$$t_{1/2}=A\frac{d^2}{D}, \tag{4}$$

where d is the thickness in the case of a slab or the diameter ($2a$) in the case of a cylinder. For slabs A is the well-known 0.1388, while for solid cylinders we found $A = 0.1068$ [2]. On the other hand, hollow cylinders satisfy the following expression:

$$t_{1/2}=\frac{A(2a)^2+B(2b)^2}{D}, \tag{5}$$

where $A = 0.1068$, the same as for a solid cylinder, and B is a function of (b/a) given by:

$$B=0.23418-0.04069\frac{b}{a}-0.0196\left(\frac{b}{a}\right)^2. \tag{6}$$

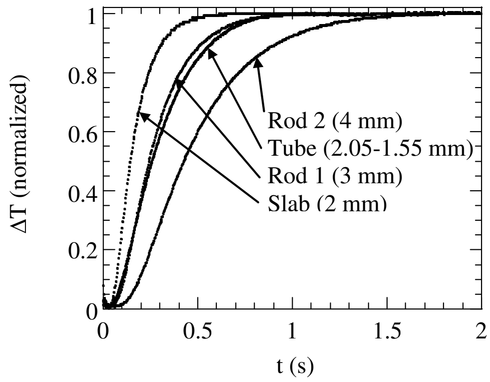

Fig. 3. Measurements of the temperature rise. The dimensions of the samples are given in parenthesis.

Table 1. Thermal diffusivity of the AISI-304 samples measured in this work (mm^2/s).

Sample	Using $t_{1/2}$	Model fit
Slab	3.98 ± 0.03	4.03 ± 0.03
Rod 1	4.01 ± 0.03	3.97 ± 0.03
Rod 2	4.03 ± 0.03	3.96 ± 0.03
Tube	3.92 ± 0.05	3.96 ± 0.05

3 Experimental results and discussion

The validity of the theory has been tested experimentally by measuring the following AISI-304 stainless steel samples: Two rods with diameters 3 mm and 4 mm (rod 1 and rod 2 respectively), a tube with an outer diameter of 2.05 mm and an inner diameter of 1.55 mm, and a 2 mm-thick-plate that has been used as a reference. The samples have been illuminated by a 3 kJ flash lamp and their rear surface temperature has been measured by an infrared camera (JADE J550M from CEDIP) at frequency rates varying from 100 to 800 frames per second. An infrared filter in front of the flash lamp is used to cut its infrared emission. In the case of cylindrical samples a variable slit is placed between the lamp and the sample. Its width is fitted to the sample diameter in order to guarantee uniform illumination of the sample. A second slit is placed between the sample and the infrared camera in order to prevent direct light from reaching the detector. A 50 mm lens with two extension rings has been used to collect the infrared emission from the sample surface. In these conditions the minimum working distance is 7.5 cm allowing us to sample a rectangle as small as 1.3 cm $\times$ 1.0 cm. This means that each pixel measures the average temperature over a square on the sample whose side is 40 μm. Therefore for rods whose diameters are 4, 3 and 2 mm the pixel that corresponds to the center of the cylinder does not measure the temperature just at $\phi = -\pi/2$, but the average temperature over a sector of about 1°, 1.5° and 2° respectively. Theoretical calculations of the average temperature over such sectors indicate that the error in the thermal diffusivity is less than 0.2%.

Fig. 3 shows by dots the normalized temperature rise with respect to the ambient, after the flash light, for the samples under study. In the case of the cylindrical samples, the temperature is the average of 50 pixels placed along the cylinder axis ($\phi = -\pi/2$). As can be seen the temperature reaches a constant value at long times after the flash light, indicating that the influence of heat losses is negligible. The thermal diffusivity of each sample has been obtained from two different methods: (a) By using the $t_{1/2}$ value and (b) by fitting the complete temperature history to the theoretical model, i.e. to Eqs. (2) and (3) for the tube and the rods respectively. The results are summarized in table 1. They are consistent and in excellent agreement with the literature values for AISI-304 (3.95–4.05 mm^2/s) [3,4].

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