International Journal of Heat and Mass Transfer 52 (2009) 1105–1111

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Thermal conductivity measurement of insulating materials with a three layers device

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ARTICLE INFO

Article history:
Received 25 May 2008
Received in revised form 25 May 2008
Available online 26 December 2008

Keywords:
Thermal conductivity
Measurement method
Insulating material
Transfer function
Convolution
Vacuum

ABSTRACT

This paper presents a new method dedicated to thermal conductivity measurement of low-density insulating materials. The three layers experimental device (brass/sample/brass) and the principle of the measurement based on a pulsed method are presented. The three-dimensional modelling of the system is used for a sensitivity analysis. The estimation method is described and applied to experimental measurements carried out at atmospheric pressure and under vacuum. We conclude that the thermal conductivity is estimated with a precision better than 5% and that the precision of the thermal diffusivity estimation depends on the density of the material.

1. Introduction

The existing methods are not suited to thermal conductivity measurements of low density insulating materials. The contact transient methods using plane or linear heating element: hot disk [1–2], hot wire [3], hot plate [4], hot strip [5–6] cannot measure precisely thermal conductivity of low density insulating materials for the following reasons:

- The thermal capacity and the thermal resistance of the heating element (often heterogeneous and made of a metal wire inserted between two plastic films) is not known with precision and is often taken into account by a simplified model.
- The sensitivity of the measured temperature to the thermal capacity of the heating element is very high if the thermal capacity of the insulating material is low (case of a low density material)
- The thermal conductivity of the heating element is higher than the conductivity of the insulating material. The longitudinal heat transfer (parallel to the contact surface between the heat source and the sample) in the heating element that is not taken into account in the models may be and lead to estimation errors.

The Flash method [7] is difficult to use for the following reasons:

- The insulating materials are often semi-transparent to the radiations of the Flash lamp,
- It is very difficult to measure precisely a surface temperature on a low density material,
- The heat transfer on the heated face is often very different of the heat transfer on the other faces (very important temperature differences).

To avoid the first two disadvantages, the sample may be inserted between two heat conducting plates; a device based on this principle has already been used for the liquids [8]. For very low-density materials, one can show that the sensitivity of the unheated face temperature to the thermal conductivity is highly correlated to the sensitivity to the convective losses and that the sensitivity to the thermal diffusivity is low.

The aim of this work was to develop a new method suited to the thermal conductivity (and eventually diffusivity) measurement of low- and very-low-density insulating materials.

2. Principle and experimental device

The experimental device includes a cylindrical sample ($R = 2$ cm, $e = 5–10$ mm) of the material to be characterized inserted between two brass discs with a thickness, $e_b = 0.4$ mm and the same radius (cf. Fig. 1). Two type K thermocouple with wire diameter 0.05 mm are welded on the external face of each brass disc by the technique of the separated contact (with a distance of 5 mm between the two wires). The lower disc is in direct contact with a plane circular heating element having the same diameter

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0017-9310/$ - see front matter
doi:10.1016/j.ijheatmasstransfer.2008.09.017

Nomenclature

a	thermal diffusivity ($m^2\,s^{-1}$)	θ	Laplace transform of the temperature
c	specific heat ($J\,kg^{-1}\,°C^{-1}$)	φ_0	heat flux density ($W\,m^{-2}$)
D	diameter (m)	Φ_0	Laplace transform of the heat flux density
e	thickness (m)	λ	thermal conductivity ($W\,m^{-1}\,°C^{-1}$)
h	convection heat transfer coefficient ($W\,m^{-2}°C^{-1}$)	ρ	density ($kg\,m^{-3}$)
H	transfer function		
p	Laplace parameter	*Subscripts*	
R_c	thermal contact resistance ($°C\,W^{-1}$)	air	air
S	area (m^2)	b	brass
t	time (s)	1	heated face
t_{max}	time at which maximum temperature is reached (s)	2	unheated face
t_{ub}	upper bound of the time estimation interval (s)	3	lateral faces
T	temperature (°C)	s	solid matrix of the porous medium
ε	porosity	v	vacuum

and set on an insulating material. A pressure is applied on the unheated brass disc by four PVC (chosen for its low thermal conductivity) tips with a very low contact surface area. The upper surface of the unheated brass disc exchanges with the ambient air by natural convection and radiation.

A heat flux is applied during a few seconds to the heating element and the temperatures, $T_{b1}(t)$ and $T_{b2}(t)$ of the brass discs are recorded. A three-dimensional model associated to an inverse method is then used to estimate the thermal conductivity and the thermal diffusivity of the insulating material inserted between the two brass discs.

The heat flux is produced by a plane heating element during a few seconds instead of being produced by a flash lamp (device initially tested) during a few milliseconds for the following reasons:

- The temperature increasing of the heated face must not be too fast to be compatible with the thermocouple response time.
- A uniform pressure may be easily applied on the brass discs through the plane heating element.
- A light part of the flash may reach the lateral surfaces by reflection, this disadvantage is avoided with a plane heating element.

3. Model and estimation method

3.1. Assumptions

- The temperatures, T_{b1} and T_{b2} in the brass discs are uniform and
- The thermal contact resistances (typically $10^{-4}\,m^2\,K\,W^{-1}$) between the sample and the brass discs are negligible in comparison with the thermal resistance of the sample (greater than $5 \times 10^{-2}\,m^2\,K\,W^{-1}$ for the tested samples).

As a first step, the following case is considered: a unique sample with heat transfer by convection with the ambient air on all its faces receives a direct and short heating on one face (no brass discs as represented in Fig. 2).

Setting $\bar{T}(r,z,t) = T(r,z,t) - T_e$

The equation of heat becomes:

$$\frac{\partial^2 \bar{T}(r,z,t)}{\partial r^2} + \frac{1}{r}\frac{\partial \bar{T}(r,z,t)}{\partial r} + \frac{\partial^2 \bar{T}(r,z,t)}{\partial z^2} = \frac{1}{a}\frac{\partial \bar{T}(r,z,t)}{\partial t} \quad (1)$$

Initial and boundary conditions may be written as:

$$z = 0 \rightarrow \lambda \frac{\partial \bar{T}(r,0,t)}{\partial z} = h_1 \bar{T}(r,0,t) - \phi_0(t) \quad (2)$$

$$z = e \rightarrow -\lambda \frac{\partial \bar{T}(r,e,t)}{\partial z} = h_2 \bar{T}(r,e,t) \quad (3)$$

$$r = 0 \rightarrow \frac{\partial \bar{T}(0,z,t)}{\partial r} = 0 \quad (4)$$

$$r = R \rightarrow -\lambda \frac{\partial \bar{T}(R,z,t)}{\partial r} = h_3 \bar{T}(R,e,t) \quad (5)$$

$$t = 0 \rightarrow \bar{T}(r,z,0) = 0 \quad (6)$$

The Laplace transform applied to relation (1) with $L[\bar{T}(r,z,t)] = \theta(r,z,p)$ leads to:

$$\frac{\partial^2 \theta(r,z,p)}{\partial r^2} + \frac{1}{r}\frac{\partial \theta(r,z,p)}{\partial r} + \frac{\partial^2 \theta(r,z,p)}{\partial z^2} = \frac{p}{a}\theta(r,z,p) \quad (7)$$

The Laplace transforms of the boundary conditions are:

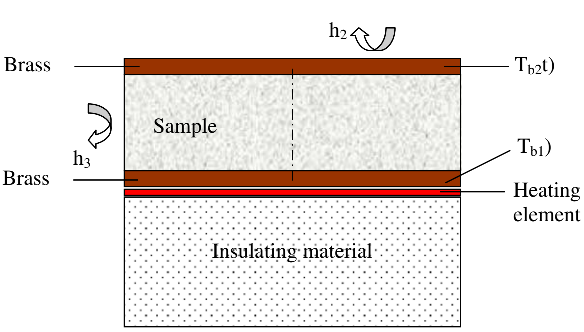

Fig. 1. Experimental device.

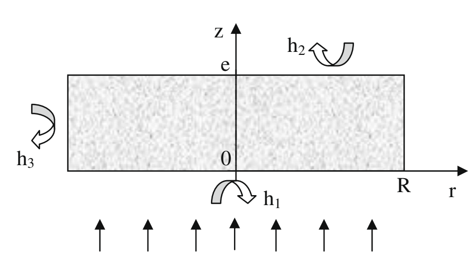

Fig. 2. Experiment schema for a unique sample.