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Thermal characterization of anisotropic materials by integral transforms taking into account the thermal coupling with the sample-holder

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A B S T R A C T

In this paper, a method for thermal characterization of anisotropic materials taking into account the coupling between the sample and its holder is presented. The originality of this work is to use temperature measurements made by infrared camera on the edges of the sample and introduce them as boundary conditions to get rid of the presence of the support. Using the principle of superposition and adapted integral transforms, it is then possible by an iterative method to obtain simultaneously the material properties in its different anisotropy directions by a least squares method applied to the spatial harmonics of the temperature field. This method is validated and compared with a classical Fourier-Cosine transform through a simulation before being applied to experimental measurements.

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1. Introduction

In 1961, Parker [1] developed the flash method for estimation of transverse diffusivity a_z of homogeneous and isotropic materials. This method was extended in 1975 and 1991 by Donaldson [2], and Lachi [3] in order to allow the thermal characterization of anisotropic material using a localized heat flux. The in-plane diffusivity measurement has been improved between 1964 and 1966 by Harmathy [4] and Steere [5] by taking the ratio at two different time of two temperatures measured at a same location, assuming a semi-infinite medium with insulated boundaries. Katayama [6] proposed in 1969 to take the ratio of the time evolution of two temperatures but at two different locations. All these methods being realized in the space and time domains (with thermocouples), the heat flux is assumed as being known in space and in time. In order to overcome the in-time distribution of the heat flux, Kavianipour & Beck [7] in 1977, and Hadisaroyo [8] in 1992, work in the Laplace-space (transformation of the time domain) of the temperature, but the spatial shape of the heat flux is yet to be known. Noting that it is easier to determine the temporal flux distribution that its spatial shape, Philippi in 1995 [9], Krapez in 2004 [10], and Remy in 2005 [11], proposed to work in the Fourier-space (transformation of the space domain) in order to get rid of the heat flux spatial distribution. But [9,10] assume a Dirac excitation in time, and [11] the fact that there is no sources between temperature measurements. Finally, in 2013, Souhar [12,13] improve this methods working in Fourier-space and performing estimations directly on in-time variations of temperature's harmonics. Nonlinear estimation is performed harmonic by harmonic. The value of the diffusivity is given by weighting mean of estimated values in Gauss-Markov sense. The estimation method is independent of the excitation spatial distribution, but assumes homogeneous Neumann's boundaries conditions. There also exist methods of characterization which are not based on the integral transforms. For example, Plana [14] proposes a method using Alternated Directions Implicited finite differences, Thomas [15] uses a method based on the finite elements method, and the

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Nomenclature

x,y,z	spatial coordinates, m
t	time, s
T	temperature, K
T^*	$T - T_{ext}$, K
$\overline{T}^*$	T^* averaged along y, K
$\tilde{T}^*$	Fourier transform of $\overline{T}^*$
θ	Laplace transform of $\overline{T}^*$
$\tilde{\theta}$	$\overline{T}^*$ in Fourier–Laplace space
a	thermal diffusivity, $m^2\ s^{-1}$
h	global heat transfer coefficient, W m^{-2} K^{-1}
L	length of the study area
L^{-1}	inverse Laplace transform
$\otimes$	time convolution

Greek symbols

ϕ	flux, W
$\overline{\varphi}$	flux averaged along y, W
$\tilde{\Phi}$	$\overline{\varphi}$ in Fourier space
λ	thermal conductivity, W m^{-1} K^{-1}
ρ	density, kg m^{-3}
C_p	specific heat, J kg^{-1} K^{-1}

Subscripts and superscripts

i	index number of sub-problems
k	index number of iterations
x,y,z	spatial directions (Ox), (Oy), (Oz)
ext	external
SPi	sub-problem N°i
flash	flash
z_0, z_L	thermal losses (at $z = 0$ and $z = Lz$)

method of Demange [16] is based on the method of separation of variables. However, these methods assume known spatial and temporal shape of the excitation.

Thus, when seeking to identify heat flux distributions [17,18] or to characterize anisotropic materials at high temperatures by Flash method 3D [12,13,18] and inverse methods, integral transforms are often used because they allow to get rid of the heat flux spatial distribution. They assume that lateral surface of the sample is perfectly insulated ("Cosine" or "Hankel") and the entire rear surface is accessible to measurement. However, for the characterization of materials at high temperature, we are often led to use a sample holder whose thermal conductivity is close to that of the material to characterize (ceramics, ceramics insulators) and therefore, the assumption of zero flux on the lateral surface is not valid. In addition, the presence of the support, does not always allow access to the entire rear surface of the sample (Fig. 1). Under these conditions, the classical cosine transform is not really adapted and leads to a bias on estimated diffusivities. In a first part, a method to take into account in-time variation of heat flux and temperature at the boundary conditions will be presented. The idea consists to use the temperature measurement given by the infrared camera close to the edges of the sample and introduce it as boundary conditions of the thermal problem, and to get by superposition a simple case with homogeneous boundary conditions of imposed temperature. The estimation of parameters will be realized on all harmonics simultaneously. In a second part, this method will be validated by comparing it with the classical method (cosine transform) on numerical simulations. It will be also proposed an improved method "Cos AH" with respect to the classical "Cos H/H" [13] method using simultaneously all harmonics for the estimation. Note that the "Cos AH" method presented is analogous to the "DEH" estimator used by Ruffio [19]. In the last section, the method will be applied to experimental measurements performed on an anisotropic conductive carbide composite material.

1.1. General problem

The sample to be characterized is of parallelepipedal shape, holded by its lateral sides. Its front face is stimulated by a non uniform heat flux with separable variables $\phi_{flash}(x,y,t) \equiv \varphi(x,y).\psi(t)$ and measurement of the temperature is done on a part of the opposite face to the excitation ("rear face") as shown in Figs. 1 and 2. In addition, the external temperature T_{ext} is assumed to be constant.

Let, $\{L_x,L_y,L_z\}$ the dimensions of the studied zone (less than or equal to those of the whole sample). Heat losses by conduction and

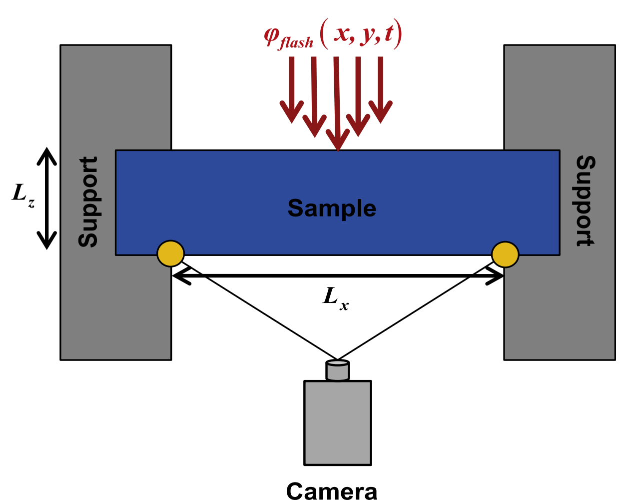

Fig. 1. The measurement principle.

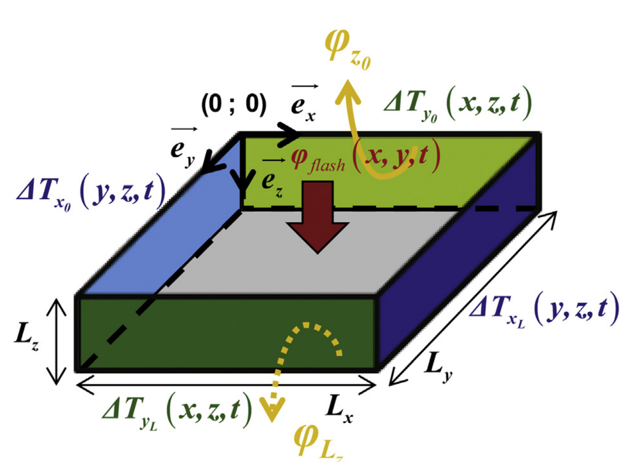

Fig. 2. Measurement zone.

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