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Characterization of the thermal properties of millimeter-sized insulating materials

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ABSTRACT

The work deals with the thermal characterization of low conductivity millimeter-sized samples. Regarding the increasing of the technical problems when the sample sizes decrease and become millimetric, an analytical solution obtained from the fin model and adapted from previous work is developed to estimate the thermal diffusivity and a modified Biot number by least-squares method. Then separated calorimetric and density measurements enable the calculation of the thermal conductivity. During experiment, the sample is heated from one side for a few seconds. An infrared thermography is used to measure the temperature field of the sample surface. At first, the method is tested with polycarbonate and balsa samples, which thermal properties are well-known. Then, the thermal diffusivity and conductivity of the hemp shiv are estimated, which values are of the same order of magnitude as those encountered in the literature for cellulosic materials of same density. If the estimation of the thermal diffusivity of the samples is in good agreement with a low uncertainty, the uncertainty on the thermal conductivity is about 10% due to the difficulty to consider the heat exchange coefficient when the tested material becomes a better insulator. Nevertheless, this method seems relevant to characterize millimeter samples of low thermal conductivity.

1. Introduction

The development of accurate and simple experiments dedicated to the thermal characterization of millimeter-sized materials is of great importance. In the domain of building, there is a lack of knowledge concerning the thermal properties of hemp shiv, one of the component of hemp concrete. Hemp concrete, increasingly used, is a porous heterogeneous material composed of millimeter-sized hemp shives mixed in a lime binder. With appropriate proportions, it can cover different uses in the building: roof insulation, wall and ground floor insulating slabs [1]. The hemp concrete can also be projected (Fig. 1). Many studies concern, on the one hand, the characterization and the behavior of the hemp concrete versus temperature and humidity and, on the other hand, the development of predictive numerical models, which need these data [2]. If the physical properties of the binder can easily be measured, it is not the case for the hemp shives. To our knowledge, the only available data concern the estimation of an effective thermal conductivity of loose hemp shives (Fig. 2) through the hot-wire technique [3]. There is no direct experimental measurement of the hemp shiv itself. However, literature mentions the estimation of an effective conductivity by inverse method between experimental results and a complete numerical model of the hemp concrete considering the size and the orientation of the hemp shives [2].

Experiments dedicated to the thermal characterization of materials of small thicknesses are difficult and the technical problems increase when the samples become millimeter-sized and less. The encountered problems concern for example the type of solicitation, the measurement of the heat flux dissipated in the sample, the size and the location of the thermocouple. Rémy et al. proposed an original method to circumvent the problem of boundary conditions based on a particular treatment of the theoretical problem of the fin model and performed transient measurements of temperature on low conductive material (vitroceramic) using an IR camera [4]. Miettinen et al. modified this method by studying the effect of the air convection around the sample and the position of the sample, and they validated their approach with conductive materials of large dimensions [5,6].

From these considerations, the study proposed here is mainly based on the work of Rémy et al. and adapted to millimeter-sized insulating materials. First, section 2 presents the theoretical development of the method to perform the parameter estimation and the sensitivity analysis. Section 3 concerns the presentation of the experimental apparatus and of the tested samples. Three materials are tested: an isotropic polycarbonate, an anisotropic balsa, and a hemp shiv. The method is validated with the two firsts and is then used to characterize the hemp shiv sample. Finally, results are presented and discussed in section 4 and compared with data published in literature.

2. Theoretical development

The goal of this study is to estimate the thermal properties of low

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Nomenclature

Latine letters

Bi	Biot number
c	light speed, m·s^{-1}
c_p^m	specific heat, J·kg^{-1}·K^{-1}
e	half-thickness, m
E	emittance, W·m^{-2}
g	gravity acceleration, m·s^{-2}
G	irradiance, W·m^{-2}
h	heat exchange coefficient, W·m^{-2}·K^{-1}
h_P	Planck constant, J·s
H_y	modified Biot number, m^{-2}
I	identity matrix
k	thermal conductivity, W·m^{-1}·K^{-1}
k_B	Boltzmann constant, J·K^{-1}
l	half-height, m
L	length, m
m	weight, kg
N	number of measurements
p	pressure, Pa
s	Laplace parameter, s^{-1}
t	time, s
T	temperature, °C
u	velocity, m·s^{-1}
x	Cartesian coordinate
X	reduced sensitivity, °C
y	Cartesian coordinate
z	Cartesian coordinate

Greek letters

α	absorptivity
α_y	thermal diffusivity, m^2·s^{-1}
β	air thermal expansion coefficient, K^{-1}
δ	eigenvalue
ε	emissivity
ζ	parameter
θ	temperature, °C
λ	wavelength, μm
μ	dynamic viscosity, Pa·s
ξ	radiative property
ρ	density, kg·m^{-3}
ρ	reflectivity
σ	noise standard deviation
τ	transmittivity
φ	flux density, W·m^{-2}
Φ	flux density, W·m^{-2}

Indices and subscripts

0	initial
h	heating
i	position indice
j	position indice
m	number of the eigenvalue δ
n	number of the eigenvalue β
λ	spectral
∞	environment

thermal conductivity samples (less than 0.5 W·m^{-1}·K^{-1}). The parameter estimation lays on the minimization of the quadratic error between the experimental and the theoretical temperatures by least squares method coupled with a Levenberg-Marquardt algorithm. The theoretical temperature expression must be as simple and as faithful as possible with the experiment in order to perform quick estimation. The purely conductive heat equation is considered with constant parameters.

Three models are developed: i) a purely conductive 3D model developed analytically and numerically (section 2.1), ii) a fin model (section 2.2), and iii) a heat transfer and fluid flow model developed with Comsol® Multiphysics. Both the first and the second models, which consider a constant heat exchange coefficient, are compared to each other. The fin model validity leads to use the estimation model proposed by Rémy et al. [4] adapted to our study (section 2.3). The sensitivity study is discussed in section 2.4. Then the third model, which considers the airflow around the sample, calculates temperatures from which the estimation method is tested (section 2.5). Finally, section 2.6 concerns the quality of the estimated parameter regarding the positions of the temperatures used to perform the estimation.

Fig. 1. Projected hemp concrete.

Fig. 2. Loose hemp shiv.

In the next sections, the theoretical tests are performed with the following geometric data and physical properties: $k_x = k_y = k_z =$ 0.15 W·m^{-1}·K^{-1}, $\alpha_y = 0.5$ mm^2·s^{-1}, $h = 10$ W·m^{-2}·K^{-1}, $L = 20$ mm, $2l = 5$ mm and $2e = 2$ mm. The sample is heated during a time $t_h = 4$ s with a heat flux density $\Phi_0 = 1000$ W·m^{-2} prescribed on the surface located at $y = 0$ (Fig. 3).

2.1. The 3D model

At first, the sample is generally considered anisotropic (k_x, k_y, and