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A method of measuring the effective thermal conductivity of thermoplastic foams

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Abstract. An inverse method for determining the in-plane effective thermal conductivity of porous thermoplastics was implemented by coupling infrared thermography experiments and numerical solution of heat transfer in straight fins having temperature-dependent convective heat transfer coefficient. The obtained effective thermal conductivity values were compared with previous results obtained using a numerical solution based on periodic homogenization techniques (NSHT) in which the microstructure heterogeneity of extruded polymeric polyethylene (PE) foam in which pores are filled with air with different levels of open and closed porosity was taken into account and Transient Plane Source Technique (TPS) in order to verify the accuracy of the proposed method. The new method proposed in the present study is in good agreement with both NSHT and TPS. It is also applicable to structural materials such as composites, e.g. unidirectional fiber-reinforced plastics, where heat transfer is very different according to the fiber direction (parallel or transverse to the fibers).

NOMENCLATURE

k: Thermal conductivity (W/m.K), h_{conv} : Convective heat transfer coefficient (W/m².K), h_1 : Constant
 M : Fin module (m^{-1}), PE: Polyethylene, ϕ : Pore diameter (μm), ρ_f : Foam density (kg/m³)
 φ : Porosity (%), c : Foam thickness (mm), x,y,z: Space variables coordinates (m), A_s : Cross-sectional area
 B : Length of fin, n: Nodal point, p: Perimeter of fin, T: Temperature (°C), T_o : Base temperature, T_n : Node temperature, T_∞ : Ambient temperature, $\theta(x)$: Excess temperature ($T(x) - T_\infty$), θ_o : $T_o - T_\infty$, $\bar{\theta}(x)$: Numerical stationary temperature profile, $\theta(x)$: Measured stationary temperature profile

INTRODUCTION

Porous materials are used in many applications, e.g., as insulators, filters and separators. So, knowledge of their heat transport properties is of great practical interest. The thermal conductivity of a porous material may greatly differ from that of the solid “bulk” material forming its skeleton [1] and strongly depends on the relative density, the cellular characteristics such as cell size, cell density, cell anisotropy, and on the presence of additional phases and/or fillers (concentration, orientation and dispersion) [2-3]. The thermal conductivity of polymeric foams varies considerably because of the existence of two phases (gas phase and solid phase) and the presence of pores (cells) causes inherently anisotropy and usually the orthotropy of thermal conductivity tensor. Many experimental methods already exist to measure the thermal conductivity of heterogeneous materials. We can cite the case of the flash method [4-7]. For this method, the temperature of the rear side of a planar sample is measured with an infrared camera while the front side is heated with a flash lamp or a laser pulse. Then, the thermal diffusivity / conductivity in the thickness direction of the sample can be determined from the measured temperature evolution. The flash method can also be applied to determine the in-plane thermal conductivity [8-9]. However, in that case, because the signal-to-noise ratio must be quite high (at least 10 [9]), a sensitive infrared camera or a high heating temperature are required. However, one has to note that using high heating

temperature leads to complications with modeling the heat-loss effects. The present paper therefore proposes a new design of a simple experimental set-up as well as the corresponding analysis method, adapted to the measurement of the thermal diffusivity/conductivity in the longitudinal direction of cellular materials and overcoming this drawback.

DESIGN OF THE NEW EXPERIMENTAL SETUP

The experimental device consists of a constant thermal energy source (a heated aluminum plate) into which the end of a straight fin of uniform cross-section is fixed. The very simple and quick experimental procedure consists in heating the sample by the heated aluminum plate in perfect contact with the sample base, while measuring temperature field by an infrared camera in steady state regime. It involves a coupling of numerical finite difference solution of fin method and infrared thermography, applied to the foam materials. Instead of measuring the temperature at different points by means of individual temperature sensors [10-12], the whole temperature distribution profile in a planar sample in steady state regime is measured, which increases the accuracy of the method. The fin method uses a longitudinal direction of heat transfer with the consideration of heat loss on the upper and lower faces. Generally, the convection heat transfer coefficient varies along the fin as well as its circumference, but the usual assumption that the heat transfer by convection is constant is no longer valid [12]. The velocity and thermal boundary layers increase towards the hot end of the sample, and, consequently, the convective heat transfer coefficient also changes. Thus, the present study takes into account of the position dependence of this coefficient by introducing a temperature-dependent heat transfer coefficient in the fin model which becomes nonlinear. Exact solutions are often difficult to obtain for nonlinear problems with variable thermal properties [13]. So, it is relevant to use a numerical finite difference solution in order to easily solve the problem. This issue will be addressed in the following section (§3). A motivation for designing this experimental setup is that it is relatively simple and accurate. The experimental procedure is also very simple, robust and quick to determine thermal conductivity. In practice, the material is thin and the temperature gradient in the thickness is negligible [14] (fin method assumption with small Biot value). So, the measuring geometry allows one-dimensional modeling (providing that the sample can be regarded as isothermal in the thickness direction), and different heat transfer mechanisms can more easily be included in the model. Temperature changes in the longitudinal direction are much larger than those in the transverse direction (one-dimensional conditions are assumed, even though conduction within the material is actually two dimensional) and the propagation in the sample can be easily produced.

FIN METHOD ANALYSIS

Method principle

A constant temperature energy source is applied on the end of a rectangular cross-section plate (Figure 1). When temperature of the sample has reached the steady state regime (verified by the temperature profile remaining constant), the temperature profiles measurement (thermograms) is performed on one face of the sample using an infrared camera. A post-processing of these experimental data is realized and finite difference solution allows the identification the thermal conductivity of the material.

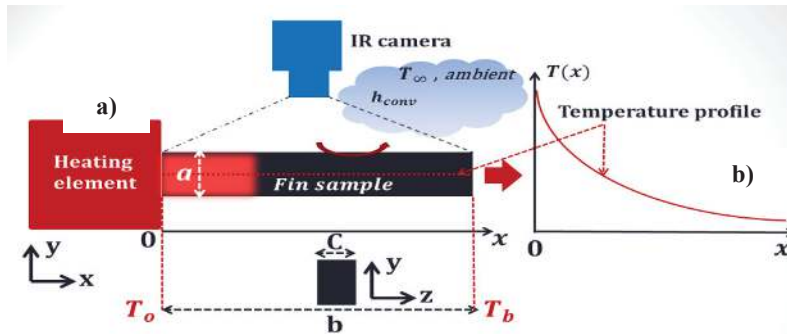


FIGURE. 1 : Fin method principle (a) – Temperature profile (b)

Problem formulation

The models considered in the present work are based on a heat conduction problem resulting in a fin approach [15-16] in a bar with rectangular cross section and dimensions a , b , and c , associated with x , y , and z directions,

respectively (Figure 1). The analysis for fins of uniform cross-sectional area can be found in any standard heat transfer textbook [14-15]. It is assumed that the fin can be treated as adiabatic at the end ($x=L$), that the convective heat loss from the fin tip is negligible and that the temperature at the base ($x=0$) is constant, T_0 . The analysis is simplified by the following assumptions: one dimensional conduction in the x direction, steady-state conditions, thermal conductivity independent of the temperature, no heat generation, temperature-dependent convection heat transfer coefficient on the surface and negligible radiation from the surface. Moreover, the fin is assumed to be thin, which implies that temperature variations in the longitudinal direction are much larger than those in the transverse direction [15-18]. This assumption can be made when Biot number (Bi) $\ll 1$ and means that temperature gradients within the solid are small and at the initial time, the sample is at the same temperature as the ambient air. Under these assumptions, the system of energy equation and boundary conditions take the form:

$$\frac{d^2T(x)}{dx^2} - \frac{ph_{conv}(x)}{kA_s}(T(x) - T_\infty) = 0 \quad (1)$$

where $T = T(x)$ is the temperature of the plate where x is the distance from the heated end of the plate, $M = \sqrt{\frac{h_{conv}p}{kA_s}}$ is an homogeneous quantity to the inverse of a length, called the fin module which characterizes the rapidity with which the heating fades away along the plate for increasing abscissa axis, T_∞ is the ambient air temperature, $h_{conv}(x)$ is the nonlinear convective heat transfer coefficient (it is position dependent, because of the boundary-layer effects on the air flow across the plate). p is the fin perimeter, A_s the surface area measured from the base to x , and k the thermal conductivity. It is also assumed that the temperature profile $T = T(x)$ is a monotonic function, and thus there is a one-to-one correspondence between x and T , or rather x and $\theta(x) = (T(x) - T_\infty)$. This also means that x can be considered as a function of θ , $x = x(\theta)$. Thus Equation (1) can be expressed in the form:

$$\frac{d^2\theta(x)}{dx^2} - \frac{ph_{conv}(\theta)}{kA_s}\theta(x) = 0 \quad (2)$$

with an unknown function $h_{conv} = h_{conv}(\theta)$. Also, $h_{conv}(\theta)$ can be replaced by a linear function (as a temperature-dependent heat-loss coefficient, $h_{conv}(\theta) = h_1\theta$). It is assumed that h_{conv} equals to 0 at the ambient temperature (T_∞) (no heat exchange between the environment at the ambient temperature and the sample) and h_{conv} tends towards its maximum value at the sample base (T_0), where h_1 is, in principle, function of T_∞ . However, variation of T_∞ is so small during the experiments that it can be considered as constant. The Equation (2) is a nonlinear differential heat transfer equation and can easily be solved numerically. So, in this equation the initial and boundary conditions are imposed as follows:

$$\begin{cases} \theta(0) = \theta_0 \\ \frac{\partial\theta}{\partial x} = 0 \quad (x = L) \end{cases} \quad (3)$$

The temperature distribution is determined a numerical scheme using the finite difference method described by Chapra and Canale [19]. The resulting general form of the finite-difference equation for the internal nodes (i.e., $n=1, 2, \dots, N-1$) is:

$$\begin{cases} \frac{kA_s}{\Delta x}(T_{n-1} - T_n) + \frac{kA_s}{\Delta x}(T_{n+1} - T_n) - h_{conv}p\Delta x(T_\infty - T_n) = 0 \\ h_{conv} = (T_n - T_\infty)h_1 \end{cases} \quad (4)$$

In order to determine the thermal conductivity, an inverse problem is considered from the knowledge of stationary temperature profiles measured by infrared thermography. The method consists in minimizing the mean-square deviation between the temperature obtained by the finite-difference solution and the measured temperature (Figure 2). To minimize this objective function, the *fminsearch* MATLAB function is used, based on the simplex method which is an iterative optimization algorithm for nonlinear minimization without constraints. The experimental data provide θ_0 and h_{conv} and k parameters are determined by minimizing the integral. In addition, the surrounding air temperature T_∞ is measured using a portable thermocouple.

Measurement concept of thermal conductivity:

The determination of the effective thermal conductivity of the foamed samples relies on two steps (Figure 2). The numerical equation (4) contains two terms to be identified (convective heat transfer coefficient and effective thermal conductivity). In a first step, a reference thermoplastic material is used whose thermal conductivity is known so that the nonlinear convective heat transfer coefficient can be experimentally obtained. In the second step, the foamed sample whose effective thermal conductivity is unknown is placed in the same conditions and its effective thermal conductivity can be determined with the known heat transfer coefficient. In our tests, we impose the same experimental conditions in order to have the same convective heat transfer coefficient: we imposed the same temperature gradient or heating rate on the samples, we also imposed the same exchange surfaces and the nature of surrounding medium (air) are the same.

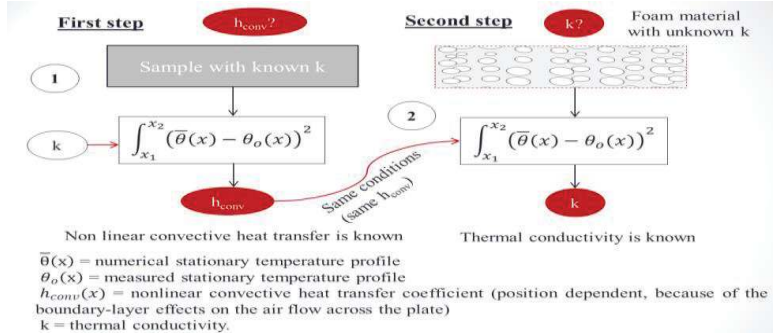


FIGURE. 2 : Identification procedure of foam effective thermal conductivity

EXPERIMENTAL

The cellular samples used in the present study were manufactured by extrusion foaming of a low density polyethylene (Flexirene FG 23 F, Polymeri Europa) dry mixed with 1 or 2wt% of a chemical blowing agent (CFA) (Hydrocerol® ITP848, Clariant) using a single screw extruder (Kaufmann, screw length 840 mm, screw diameter 30 mm) equipped with a flat die (width 55 mm, gap 2.2 mm) at a die temperature of 110°C, a rotation speed of 40 RPM. Specimens were plates with uniform rectangular cross section and nominal dimensions of 150 mm×30 mm×2.65 mm. The experimental setup is shown in Figure 3 (left). The sample is placed horizontally and is heated on one end in Figure 3 (right). All specimens are covered by a black coating, in order to standardize the emissivity ($\epsilon > 0.9$) of the surface facing the infrared camera. Thermographic images were recorded when the steady state regime is reached by an infrared camera (Flir CEDIP JADE, Spectral response: 3.6µm – 5.1µm, Sub windowing: 320x256 pixels, Frequency: 50Hz). A PC computer is connected to the camera for image grabbing and further data analysis (by using Altair software).

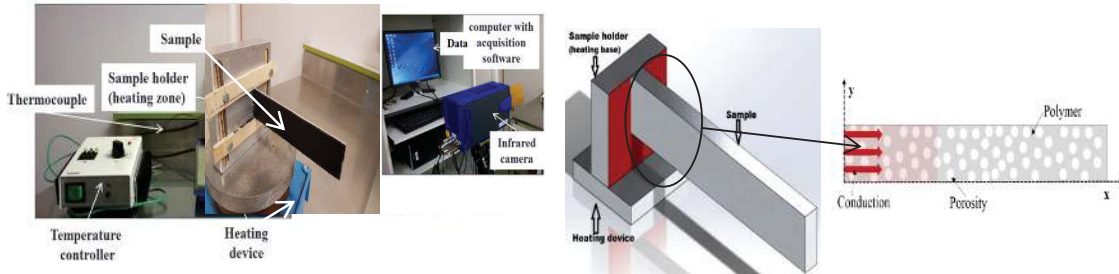


FIGURE. 3 : Experimental set-up 5 (left)- Design of the experimental device (right)

RESULTS AND DISCUSSION

In order to determine the thermal conductivity of the sample, it is necessary to calibrate the heat transfer coefficient (h_{conv}) at first. For this purpose, a neat PE sample is used whose thermal diffusivity value (0.34 W/m.K) [21] is known. The air temperature T_{∞} is measured at 25°C. The resulting temperature profile in the x direction is shown in Figure 4 (left) together with the numerical finite difference solution. There is a very good agreement between numerical and experimental results. The optimization between the temperature obtained

numerically by the stationary fin model and the measured temperature gives value of the parameter $h_1 = 0.44 \text{ W/m}^2\text{K}$. The relative error between both values is lower than 1%. Figure 4 (right) shows the evolution of convection (h_{conv}) along the x axis in the 2.65 mm neat PE sample. The convective heat transfer is high at the base of the sample where the flow velocity is the largest. This value of h_{conv} is used in the second inverse problem to find out the effective thermal conductivity of the unknown foam materials. The use of same h_{conv} parameter for the analysis of experimental data of all the unknown samples is justified as the surface area in contact with the surrounding and all other experimental conditions such as heating rate, nature of surrounding medium (air) are the same.

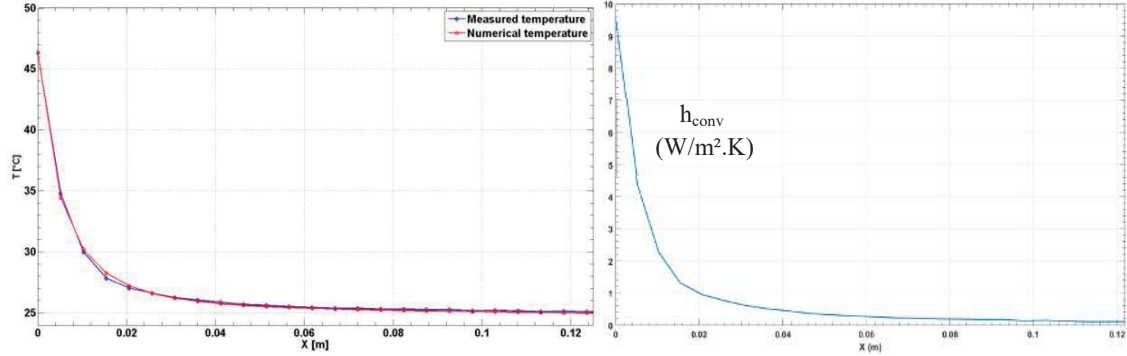


FIGURE. 4 : Stationary temperature profiles in the 2.65 mm thick neat PE sample with the numerical solution of the inverse problem (left) - Temperature dependent convection along the x axis in the 2.65 mm thick neat PE sample (right).

The identification of the effective thermal conductivity of the foam material is performed using the same procedure for identifying the convective heat transfer coefficient (second step on the Figure 1). The experimental and the numerical temperature distributions for the base temperature ($T_o = 45^\circ\text{C}$) of PE foam with porosity equals to 45% are presented in Figure 4. The measured values also match favorably the numerical solution. Figure 9b shows the evolution of the relative error between the temperature obtained numerically by the stationary fin model and the measured temperature versus the fin length, which remains lower than 1%. The effective thermal conductivity of PE foams with porosity equals to 45% by the inverse fin method is $k = 0.164 \text{ W/(m.K)}$. This result is compared with previous one, obtained by a numerical finite element solution (NSHT) [21] and validated with the Transient Plane Source Technique (TPS) method (Table 1).

Sample	Porosity (%)	k (NSHT) [21] (W/(m.K))	k (Inverse fin method) (W/(m.K))	Deviation (%)	k (TPS) [21] (W/(m.K))	Deviation (%)
Sample 1	45.1	0.176	0.164	6.8	0.170	3.5
Sample 2	50.4	0.163	0.156	4.3	0.160	2.5
Sample 3	96	0.042	0.044	4.5	0.041	6.8

Table 1: Comparison between experimental results with fin method, and previously [21] developed numerical finite element solution (NSHT) and Transient Plane Source Technique (Hot Disk)

The relative error between numerical solution and experimental results is lower than 6%, as well as the relative error between numerical solution and TPS (Hot Disk). The experimental values are close to numerical solution. The experimental fin apparatus described in the present paper is consequently successfully validated.

CONCLUSION

Inverse method for determining the effective thermal conductivity of foams samples was developed. The techniques used were based on heated sample at one end and the steady state recording of the temperature field of the sample by an infrared camera. These fields were then fitted by a numerical finite difference solution to a one-dimensional heat equation describing the experimental setup, temperature dependent convection heat transfer and effective thermal as two fitting parameters. The relative error between numerical solution developed in previous study and experimental results is lower than 6%. Therefore, it was proved that this experimental

method is well designed and is a good alternative for determining thermal conductivities. The method developed can also be extended to other heterogeneous materials such as structural composites, for example unidirectional fiber-reinforced plastics, where heat transfer is very different according to the fiber direction (parallel or transverse to the fibers).

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