Extension of the FLASH Method to Semitransparent Polymer Foams

R. Coquard
Société Etude Conseils Calcul en Mécanique des Structures (EC^2MS),
66, Boulevard Niels Bohr,
69603 Villeurbanne CEDEX, France
e-mail: remi.coquard@ec2-ms.fr

J. Randrianalisoa
e-mail: jaona.randrianalisoa@insa-lyon.fr

S. Lallich
e-mail: sylvainlallich@yahoo.fr

D. Baillis
e-mail: dominique.baillis@insa-lyon.fr

Université de Lyon, CNRS,
INSA-Lyon, CETHIL, UMR5008,
20 Avenue Albert Einstein,
F-69621 Villeurbanne CEDEX, France

The classical photo-thermal FLASH method is a very practicable method for measurement of the conductive properties of solid materials due to its simplicity, rapidity, and to the limited size of the samples required. It has been applied successfully to a wide variety of materials. However, it is theoretically restricted to purely conductive media. Notably, it could, strictly speaking, not be used to measure the equivalent conductivity of low-density thermal insulators since a significant part of the heat transfer is due to the propagation of thermal radiation. This constitutes a major drawback of the method. Therefore, the present study investigates the possibility to extend the method to this kind of materials by estimating the errors made on the equivalent conductivity when the classical FLASH method is used. To this aim, FLASH experiments have been conducted at different temperatures on several low-density polymer foams whose radiative properties have been estimated from spectrometric measurements. By applying a least-square fit-method associated with a numerical simulation of the 1D coupled heat transfer, we managed to identify the phonic conductivities of the samples and to compute their equivalent conductivities. These values have been compared with the thermal conductivities obtained from classical FLASH method, i.e., assuming that the thermal transfer occurs only by heat conduction. It appears that the discrepancies between the conductivities stemming from the classical FLASH method and the equivalent conductivities computed are quite negligible at ambient temperature even for foams with very low densities. This demonstrates the applicability of the classical FLASH method to this type of materials for building applications. This conclusion is likely to interest foam manufacturers in view of reducing the time required for an accurate measurement of the insulating performances. On the other hand, at elevated temperatures, the errors become significant so that the method could not be considered satisfactory. [DOI: 10.1115/1.4004392]

Keywords: FLASH method, low-density polymer foams, radiation–conduction coupling

1 Introduction

The accuracy of thermal conductivities measurement takes on particular importance in numerous physical, chemical, or medical applications given that it has a direct influence on the estimation of heat losses, or temperature rise. The standard measuring method for the thermal conductivity is the so-called "guarded hot-plate method". The principle is to measure the heat flux passing through a slab of materials subjected to a one-dimensional steady-state heat transfer. This technique gives very accurate results. Nevertheless, it is restricting given that the slab must have large and standard dimensions and that it requires especially long measuring durations.

To remedy these drawbacks, experimental methods based on transient measurements have been developed. Among these methods, the well-known FLASH method is particularly fast and convenient. The principle is to generate a pulse heating of the front face of a cylindrical sample and to measure the increase of the temperature at the rear-face. The pulse heating is obtained by a pulse irradiation. The faces are covered with a black coating. When the heat transfer inside the material is purely conductive, the thermogram measured allows estimating the conductivity of the isotropic material. In the classical approach, the conductivity is obtained by analytical treatments of the thermogram using the partial time methods (Degiovanni [1]) or the partial moment methods (Degiovanni and Laurent [2]). These methods take into account the thermal losses of the sample with the external environment. The method has been recently improved using inverse identifications associated with direct transient heat transfer modeling. The principle is to determine the conductivity and other unknown parameters of the direct model, which permit to minimize the discrepancy between measured and simulated thermograms. The direct model should take into account the physical phenomenon occurring during the measurement as faithfully as possible.

Recently, André and Degiovanni [3,4], Tan et al. [5], Hahn et al. [6], or Lazard et al. [7,8] studied the application of the FLASH method for the measurement of the thermal diffusivity of semi-transparent media in which radiative heat transfer is significant.

André and Degiovanni [3,4] solved the coupled transient heat transfer problem in a plane-parallel slab of purely absorbing materials submitted to a pulse irradiation. They show that the radiative contribution leads to noticeable errors of the FLASH measurement for this kind of materials. However, under conditions of small optical thicknesses and reflecting walls, the heat transfer in the sample is completely free from any radiative contribution. This permits them to estimate the true thermal conductivity of float glass and silica glass.

Hahn et al. [6] have also modeled the transient combined radiative/conductive heat transfer and applied it to the simulation of laser-flash measurements on ceramic powder compacts. Their numerical results show that the classical laser-flash measurements may lead to a considerable overestimation of the diffusivity in heterogeneous semitransparent materials at elevated temperatures due to the radiative contribution.

Lazard et al. [7,8] proposed a methodology to adapt the FLASH method to glass, silica glass, and zinc selenide in which radiative

Contributed by the Heat Transfer Division of ASME for publication in the Journal of Heat Transfer. Manuscript received November 17, 2010; final manuscript received June 6, 2011; published online September 20, 2011. Assoc. Editor: William P. Klinzing.

 Copyright © 2011 by ASME

Downloaded From: http://heattransfer.asmedigitalcollection.asme.org/ on 04/01/2015 Terms of Use: http://asme.org/terms

transfer is significant. They used an inverse identification method associated with a semianalytical model of coupled conductive–radiative transient heat transfer in a 1D slab. The inverse method allowed them to identify the phonic conductivity of the materials and some radiative parameters from the FLASH experiment. They show that their new approach allows an accurate estimation of the phonic conductivity even when the radiative contribution is significant, whereas, classical FLASH technique overestimates this conductivity. However, the radiative properties estimated by their method are not usable.

More recently, Coquard et al. [9] proposed an identification method using the FLASH thermograms in order to evaluate, at ambient and elevated temperatures, the effective thermal conductivity and the radiative properties of various metal or ceramic foams. However, their method allows the identification of only two global radiative properties. Moreover, it gives accurate results at elevated temperature only, since the radiative contribution has to be significant enough.

Cheheb et al. [10] have also developed an original method allowing the measurement of the radiative and the conductive properties of semitransparent materials. The method is similar but somewhat different from the FLASH experiment, since it consists of applying a crenel heat flux on the front face of a semitransparent sample and recording the temperature at the rear-face using an open thermocouple junction. Thereafter, the authors applied a parameter identification minimizing the ordinary least-squares function comparing the measured and the calculated thermograms. This later is obtained from a coupled thermal model using the thermal quadrupole formalism. The authors applied their method to commercial glasses and Plexiglas samples.

In these studies, the methodologies proposed by the authors to obtain the various thermal properties are heavy and need high scientific skills to be developed. Thus, it compromises the main interests of the classical FLASH method: simplicity and quickness. Moreover, in lots of applications, people are usually interested in a unique global parameter characterizing the entire heat transfer in the material rather than in a complete set of thermal properties describing more accurately but more complexly the modes of heat transfer. As an example, in the domain of building insulators, the property of interest is the so-called "equivalent thermal conductivity" characterizing the magnitude of the total heat transfer by conduction and eventually by thermal radiation.

Therefore, the aim of the present study is to determine whether the classical FLASH method could be used to estimate accurately the equivalent conductivity of low-density polymer foams. This constitutes a key issue, since this type of foams is widely used as building thermal insulators and an accurate and rapid measurement of their thermal performances is of primary importance for manufacturers notably. To fulfill these objectives, several FLASH measurements have been conducted on commercial foam samples at ambient and relatively high temperatures. Spectrometric measurements have also been performed and allowed us to estimate accurately the equivalent radiative properties of the foams. Using these properties, we manage to identify the phonic conductivities of the foam samples from the FLASH measurements using a least-square fit-method associated with a numerical simulation of the 1D coupled conduction–radiation transient heat transfer. Thereafter, the equivalent conductivities of the samples could be computed by solving the steady-state coupled heat transfer in a slab of material submitted to a 1D temperature gradient. At the same time, we also apply the standard treatments of the thermograms to estimate the thermal conductivity stemming from the classical FLASH method in which the heat transfer is assumed purely conductive. The conductivities obtained experimentally for each foam sample are then compared with the equivalent conductivities computed. This allows us to conclude about the applicability of the classical FLASH procedure for estimating the equivalent conductivity of low-density polymer foams.

2 Experimental Investigations

2.1 Foam Samples. Three different polymer foam samples have been considered in the present study: two polyvinyl chloride (PVC) foams and one extruded polystyrene (XPS) foam. The thermal properties of the bulk materials (PVC and polystyrene, respectively) are given in Table 1. The foam samples tested are assumed isotropic according to the indication of the manufacturers.

The densities and porosities of the samples, illustrated in Table 1, have been estimated from their measured mass M (kg) and volume V (m^3):

$$\varepsilon = \frac{\rho_{\text{solid}} - M/V}{\rho_{\text{solid}} - \rho_{\text{air}}} \tag{1}$$

The specific heat C of each foam samples is estimated by

$$C_s = \frac{\varepsilon \rho_{\text{air}} C_{\text{air}} + (1-\varepsilon)\rho_{\text{solid}} C_{\text{solid}}}{\rho_s} \tag{2}$$

The thermophysical properties used for the fluid and solid phases originate from Ref. [11].

We have also calculated the uncertainty associated with the porosities and specific heats of the sample by differentiating Eqs. (1) and (2). These uncertainties can then be related to the uncertainties $\Delta\rho_{\text{solid}}$, $\Delta\rho_{\text{air}}$, ΔM, ΔV, ΔC_{solid}, and ΔC_{air} and to V and M. The uncertainties obtained are reported in Table 1.

2.2 Experimental Device for FLASH Experiments. FLASH experiments have been conducted on the three foam samples at ambient and higher temperatures using the FLASH measuring apparatus of the CETHIL Laboratory. This FLASH device is composed of four different systems: (1) a pulse-heating system, (2) a continuous heating and sample support system, (3) a measuring system, and (4) an acquisition system.

The pulse heating system includes a laser, the loading and cooling device of the laser, and a plane mirror. The laser-bar is a Nd:YAG type with wavelength 1060 nm. The other characteristics of the laser are: $\tau = 0.5$ ms, $E_{\max} = 600$ J, and $D_{\text{las}} = 40$ mm.

The temperature measuring system is made of an infrared detector and a digital thermometer. In the present study, we only use the measurements given by the thermocouple.

Finally, the acquisition system consists of a signal amplifier and a scanning electron oscilloscope.

2.3 Experimental Device for Spectrometric Measurements. The characterization of the radiative behavior of the foam samples has been performed using a Fourier transform infrared (FTIR) spectrometer BRUKER IFS66V with a wavelength range [1.6 μm and 20 μm]. This spectrometer is equipped with an integrating sphere LABSPHERE CSTM-RSABR-55ID of 76 mm in diameter coated with gold and with an aperture of 20 mm. The FTIR spectrometer is also equipped with a Germanium beam splitter with a potassium bromide support. The detector used is a HgCdTe referenced MCT D316, which is cooled with liquid nitrogen (77 K).

Measurements of the directional Td_λ and hemispherical Th_λ transmittance and of the hemispherical reflectances Rh_λ have been performed on thin and thick foam slices, respectively. The thin

Table 1 Properties of the polymer foam samples characterized experimentally

Sample	Solid phase	ρ (kg/m^3)	ε	$\Delta\varepsilon/\varepsilon$	L (mm)	e (mm)
1	PVC	75	0.946	0.008	4.83	0.045
2	PVC	130	0.906	0.008	5.15	0.045
3	PS	33	0.970	0.01	4.58	0.045

Downloaded From: http://heattransfer.asmedigitalcollection.asme.org/ on 04/01/2015 Terms of Use: http://asme.org/terms

slices have a thickness lower than 1.0 mm in order for the transmittance signal to be sufficiently important. The thick slices are several centimetres thick so that their transmittance is negligible.

3 Theoretical Considerations

3.1 Identification of Thermal Properties From FLASH Experiment. We have developed an identification procedure to estimate the effective/phonic conductivity of the foam samples from the FLASH experiments. The identification procedure is based on a least-square fit-method and requires an accurate theoretical modeling of the transient coupled heat transfer in the foam. First, we describe the model developed to simulate the thermal transfer in the sample. Then, we detail the principle of the parameter identification procedure from the experimental thermograms.

3.1.1 Direct Simulation of the FLASH Measurement. The principle of FLASH experiments is to generate a pulse heating of the front face of a cylindrical sample. Then, we measure the increase of the temperature at the rear-face (see Fig. 1). The heating is obtained by a pulse irradiation and thus, the faces have to be covered with a black coating of known thermal properties and thickness e. The thermogram measured allows estimating the thermal conductivity of the isotropic material. However, in our study, the foam samples tested could not be considered as purely conductive materials but rather as semitransparent materials, in which the propagation of thermal radiation is significant. Therefore, the theoretical model should simulate accurately the coupling between conductive and radiative transfers.

In the present study, the solution of the coupled heat transfer has been conducted using the same formalism as the one described in Ref. [9]. We find unnecessary to remind here the governing equations, initial and boundary conditions and numerical methods used and invite the reader to consult our previous study [9] for more details.

3.1.2 Identification Procedure. The identification procedure developed is based on a least-square fit-method which minimizes the difference between the temperature $T_{\exp}(t)$ measured at the center of the back side of the irradiated sample during the FLASH experiment and the temperature $T_{\text{num}}(t)$ predicted by the numerical model for given experimental conditions. The principle is to minimize the function, F representing the sum of the quadratic discrepancies between the experimental and theoretical variations of the temperature

$$F = \sum_{n=1}^{N_t} \left[T_{\exp}(t_n) - T_{\text{num}}(t_n)\right]^2 \tag{3}$$

The evolution of the temperature calculated by our theoretical model is influenced by the following parameters: L, ρ_{coat}, C_{coat}, k_{coat}, h, ρ, C, and k_c and the radiative properties β_λ, κ_λ, σ_λ, and $\Phi_\lambda(\theta)$ of the semitransparent medium. We assume that all these parameters are known except N parameters noted P_k with $k = 1,N$. Thus, $T_{\text{num}}(t)$ and F only depend on these N parameters which have to be identified by minimizing F. We have

$$F = F(P_1, ..., P_N) = \sum_{n=1}^{N_t} \left[T_{\exp}(t_n) - T_{\text{num}}(P_1, ..., P_N)\right]^2 \tag{4}$$

In order to minimize F, the parameter P_k should satisfy the relations

$$\frac{\partial F}{\partial P_k} = \frac{\partial}{\partial P_k}\left[\sum_{n=1}^{N_t} \left(T_{\exp}(t_n) - T_{\text{num}}(t_n)\right)^2\right] = 0$$
$$\Rightarrow \sum_{n=1}^{N_t} \left[\left(T_{\exp}(t_n) - T_{\text{num}}(t_n)\right).\frac{\partial T_{\text{num}}(t_n)}{\partial P_k}\right] = 0 \tag{5}$$

for $k = 1$,N.

The partial derivatives $(\partial T_{\text{num.}}(t_n))/(\partial P_k)$ are called the sensibility coefficients and represent the rate of variation of the temperature at the center of the back side at the time t_n due to a variation of the parameters P_k.

In order to solve this system of nonlinear equations, we use the iterative method of Gauss starting from initial values P_k^0. At each iteration level l, the following system of equations is solved

$$\sum_{n=1}^{N_t} \left[\left(T_{\exp}(t_n) - (T_{\text{num}}(t_n))^l\right).\left(\frac{\partial T_{\text{num}}(t_n)}{\partial P_k}\right)^l\right] = 0 \text{ for } k = 1, \text{N} \tag{6}$$

Moreover, the value $(T_{\text{num.}}(t_n))^l$ at the iteration level l can be approximated from the values at the iteration level $l-1$ by the following relation:

$$T_{\text{num}}(t_n, [P_k]^l_{k=1,N}) = T_{\text{num}}(t_n, [P_k]^{l-1}_{k=1,N}) + \sum_{k=1}^{N}\left(\frac{\partial T_{\text{num}}(t_n)}{\partial P_k}\right)^{l-1}.\Delta P_k^{l-1} \tag{7}$$

We finally have to solve the following matrix system, where the superscript l refers to the entire matrixes

$$\left[A_{k,j}\right]^l.\left[\Delta P_j\right]^l = [B_k]^l \quad \text{with} \quad A^l_{k,j} = \sum_{n=1}^{Nt}\left(\frac{\partial T_{\text{num}}(t_n)}{\partial P_k}\right)^l.\left(\frac{\partial T_{\text{num}}(t_n)}{\partial P_j}\right)^l;$$
$$B^l_k = \sum_{n=1}^{Nt}\left(\left(T_{\exp}(t_n) - T_{\text{num}}(t_n)\right).\frac{\partial T_{\text{num}}(t_n)}{\partial P_k}\right)^l \tag{8}$$

This system is solved successively for each iteration level l to calculate the values $\left[P_k^{l+1} = P_k^l + \Delta P_k^l\right]_{k=1,N}$ until the ratios $\left[\frac{\Delta P_k^l}{P_k^l}\right]_{k=1,N}$ are lower than a convergence criterion.

In the present study, the unknown parameters which have to be identified are the effective/phonic conductivity k_c of the foam sample and the coefficient of thermal exchange h.: $N = 2$; $P_1 = k_c$; $P_2 = h$.

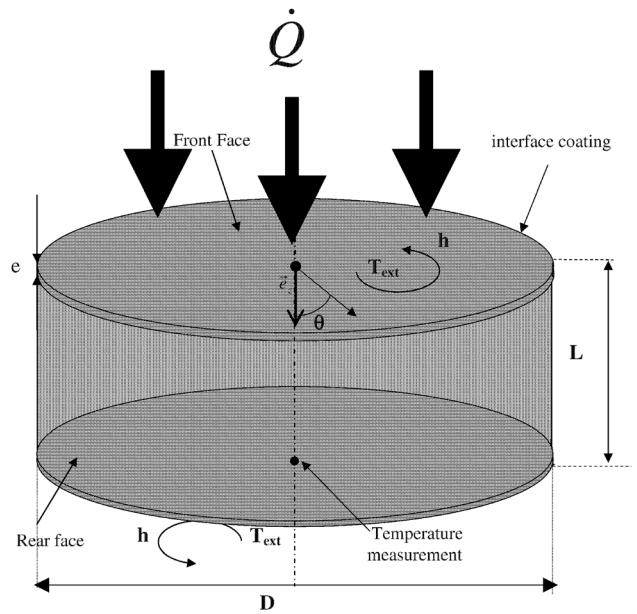

Fig. 1 Representation of the sample and of the coordinate system

Downloaded From: http://heattransfer.asmedigitalcollection.asme.org/ on 04/01/2015 Terms of Use: http://asme.org/terms

3.2 Identification of the Radiative Properties of the Foam Samples From Spectrometric Measurements. Measurements of the directional Td_λ and hemispherical Th_λ transmittance and of the hemispherical reflectance Rh_λ have been performed on thin and thick foam slices, respectively. These spectral quantities have been used to identify the radiative properties of the foam samples tested. The spectrometric measurements have been performed uniquely at ambient temperature ($T \approx 293$ K) while the spectral radiative properties of the foams are likely to vary with the temperature, due most essentially to variations of the optical properties of the solid phase. However, for the temperature range considered (293 K $< T <$ 403 K), the variations of the optical properties of the polymer are insignificant so that, we assume that the radiative properties are in fact independent of the temperature. So, in the rest of the study, the radiative properties identified at ambient temperatures would be used for all the temperatures investigated.

3.2.1 Direct Simulation of the Spectrometric Measurements. The computed transmittances and reflectances are obtained from the radiative properties by solving the 1D radiative transfer equation (RTE) inside the foam slice. For spectrometric measurements using an FTIR, the self-emission of the material is negligible and the RTE reduces to

$$\mu \frac{\delta I^\lambda_{z,\mu}}{\delta z} = -\beta_\lambda I^\lambda_{z,\mu} + \frac{\sigma_\lambda}{4\pi} \int_{\Omega'=4\pi} \Phi_\lambda(\theta') I^\lambda_{z,\mu'} d\Omega' \tag{9}$$

Given the high level of porosity of the foam samples tested, we also consider that the reflectivity of the sample at the interface between air and foam is negligible.

This leads to the following boundary conditions representing the illumination of the foam slices by the spectrometer sources

$$I^\lambda_{z=0,\mu} = \begin{cases} \exp\left[-\left(\dfrac{\mu - 1.0}{0.1}\right)^2\right] & 1 > \mu \geq \mu_{\text{source}} \\ 0 & \mu \leq 0 \end{cases} \tag{10}$$

The RTE with the preceding boundary conditions is solved for each wavelength with the discrete ordinates method described previously. The directional and hemispherical transmittances and reflectance could then be computed by

$$Td_\lambda = \frac{\int_{\mu=0}^{1} I^\lambda_{z=l}.\mu.d\mu}{\int_{\mu=0}^{1} I^\lambda_{z=0}.\mu.d\mu}; \quad Th_\lambda = \frac{\int_{\mu=0}^{1} I^\lambda_{z=l}.\mu.d\mu}{\int_{\mu=0}^{1} I^\lambda_{z=0}.\mu.d\mu}; \quad Rh_\lambda = \frac{\int_{\mu=-1}^{0} I^\lambda_{z=0}.\mu.d\mu}{\int_{\mu=0}^{1} I^\lambda_{z=0}.\mu.d\mu} \tag{11}$$

3.2.2 Identification Procedure. For each wavelength, we have three different measured values and thus, we could identify only three different radiative properties. Therefore, in order to make the identification possible, the scattering phase functions of the foams have to be simplified in order to be expressed using only one parameter. Therefore, we choose to express the scattering phase functions of the foam samples in the form of Henyey–Greenstein phase functions. These phase functions can be expressed using only one parameter noted g_λ:

$$\Phi_{H-G,\lambda}(\theta) = \frac{1 - g_\lambda^2}{\left(1 + g_\lambda^2 - 2.g_\lambda.\cos\theta\right)^{1.5}} \tag{12}$$

The radiative behavior of the samples could then be characterized by three radiative properties: β_λ, ω_λ, and g_λ.

These spectral properties are identified for each wavelength by minimizing the functions F'_λ, expressing the discrepancies between the measured and computed values of Td_λ, Th_λ, and Rh_λ.

$$F'_\lambda(\beta_\lambda, \omega_\lambda, g_\lambda) = \begin{bmatrix} \left|(Td_\lambda)_{\text{exp}} - (Td_\lambda)_{\text{num}}\right| \\ \left|(Th_\lambda)_{\text{exp}} - (Th_\lambda)_{\text{num}}\right| \\ \left|(Rh_\lambda)_{\text{exp}} - (Rh_\lambda)_{\text{num}}\right| \end{bmatrix} \tag{13}$$

In our case, given that the number of parameters to identify is equal to the number of measurements, there exists a set of radiative properties which permits to obtain the equality between experimental and numerical values

$$(Td_\lambda)_{\text{exp}} = (Td_\lambda)_{\text{num}}; \quad (Th_\lambda)_{\text{exp}} = (Th_\lambda)_{\text{num}}; \quad (Rh_\lambda)_{\text{exp}} = (Rh_\lambda)_{\text{num}}$$

In order to minimize F'_λ, we use an iterative procedure based on the iterative Newton–Raphson algorithm generalized to the 3D case. At each iteration level, we compute the correction increment $\Delta\beta_\lambda$, $\Delta\omega_\lambda$, and Δg_λ by solving the following system:

$$\begin{bmatrix} \left|(Td_\lambda)_{\text{exp.}} - (Td_\lambda)_{\text{num}}\right| \\ \left|(Th_\lambda)_{\text{exp.}} - (Th_\lambda)_{\text{num}}\right| \\ \left|(Rh_\lambda)_{\text{exp.}} - (Rh_\lambda)_{\text{num}}\right| \end{bmatrix} + \begin{bmatrix} \dfrac{\partial Td_\lambda}{\partial \beta_\lambda} & \dfrac{\partial Td_\lambda}{\partial \omega_\lambda} & \dfrac{\partial Td_\lambda}{\partial g_\lambda} \\ \dfrac{\partial Th_\lambda}{\partial \beta_\lambda} & \dfrac{\partial Th_\lambda}{\partial \omega_\lambda} & \dfrac{\partial Th_\lambda}{\partial g_\lambda} \\ \dfrac{\partial Rh_\lambda}{\partial \beta_\lambda} & \dfrac{\partial Rh_\lambda}{\partial \omega_\lambda} & \dfrac{\partial Rh_\lambda}{\partial g_\lambda} \end{bmatrix} \cdot \begin{bmatrix} \Delta\beta_\lambda \\ \Delta\omega_\lambda \\ \Delta g_\lambda \end{bmatrix} = 0 \tag{14}$$

This system is solved successively for each iteration level l to calculate the parameter values $(\beta_\lambda)^{l+1} = (\beta_\lambda)^l + \Delta\beta_\lambda$, $(\omega_\lambda)^{l+1} = (\omega_\lambda)^l + \Delta\omega_\lambda$, and $(g_\lambda)^{l+1} = (g_\lambda)^l + \Delta g_\lambda$ until the discrepancy ratios $\left|(Td_\lambda)_{\text{exp}} - (Td_\lambda)_{\text{num}}\right| / (Td_\lambda)_{\text{exp}}$, $\left|(Th_\lambda)_{\text{exp}} - (Th_\lambda)_{\text{num}}\right| / (Th_\lambda)_{\text{exp}}$, and $\left|(Rh_\lambda)_{\text{exp}} - (Rh_\lambda)_{\text{num}}\right| / (Rh_\lambda)_{\text{exp}}$ are lower than a convergence criterion with very low value (typically 10^{-4}).

4 Results and Discussions

4.1 Radiative Properties of the Foam Samples. The radiative properties of the three foam samples studied (see Table 1) have been identified using the directional and hemispherical transmittances and reflectances measured on thin and thick foam slices. The thicknesses of the thin slices are 0.87 mm, 0.98 mm, and 1.0 mm for the foam sample nos. 1–3, respectively.

In order to limit the number of figures, we depict in the same figure (Fig. 2), the variations of the weighted spectral extinction coefficient $\beta^*_\lambda = \kappa_\lambda + \sigma_\lambda \times (1 - g_\lambda)$ identified for the three foam samples and the error bars associated with the corresponding uncertainties. The weighted extinction coefficient is a good indicator of the magnitude of interaction of radiation with the porous

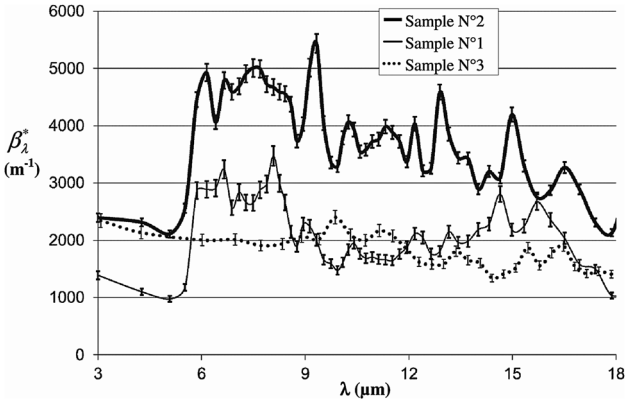

Fig. 2 Variation of the scaled extinction coefficient identified from spectrometric measurements for the three foam samples

Downloaded From: http://heattransfer.asmedigitalcollection.asme.org/ on 04/01/2015 Terms of Use: http://asme.org/terms

Table 2 Summary of the results of the identification procedure and of the equivalent conductivities computed for the three foam samples

Sample No.	T (K)	k_c ident. (mW/m/K)	h ident. (W/m^2/K)	$\langle \Delta T^* \rangle$	k_{equ} comp. (mW/m/K)
1	293	29.39	9.04	0.00405	35.69
2	293	31.25	10.61	0.00336	33.63
3	293	28.00	7.38	0.00493	32.6
1	403	36.50	27.06	0.00837	50.70
2	403	37.48	32.49	0.00866	43.76
3	373	34.60	11.06	0.00499	43.75

structure. One can remark similarities between the wavelengths profiles obtained for sample nos. 1 and 2. This is quite logical since, these two samples are made of the same solid phase (polyvinyl chloride).

4.2 Identification of the Phonic Conductivities. FLASH experiments have been conducted on the three foam samples at ambient temperature (293 K) and higher temperatures (403 K for sample nos. 1 and 2 and 373 K for sample No. 3). These latter temperatures correspond approximately to the highest measurement temperature above which the samples are damaged by the fusion of the solid phase (PVC and polystyrene, respectively).

We have applied the identification procedure described in Sec. 3.1 to the six thermograms. The spectral radiative properties used in the direct modeling of transient coupled heat transfer are the ones illustrated in Sec. 4.1. The values of the phonic conductivities k_c and heat transfer coefficients h identified are summarized in Table 2, where we also indicate the mean discrepancy between the measured and identified thermograms noted $\langle \Delta T^* \rangle = \frac{\int_0^{\Delta t} \left| T^*_{\text{exp.}}(t) - T^*_{\text{num.}}(t) \right| . dt}{t_d}$. In Figs. 3–8, we compare the experimental thermograms obtained with the thermograms computed by the transient coupled model using the thermal properties identified. Figures 3–5 correspond to the experiments at ambient temperatures while Figs. 6–8 are associated with the measurements at higher temperatures. We also illustrate in these figures the evolution of the discrepancies $\Delta T^* = \left| T^*_{\text{exp.}}(t) - T^*_{\text{num.}}(t) \right|$.

Figures 3–8 show a good agreement between the measured and computed evolutions of the temperature. The maximum discrepancies are encountered at the very beginning of the measurement and are mostly due to parasitical disturbances of the temperature sensor just when the pulse heating is generated. We have checked the consistency of the phonic thermal conductivities identified for the three foam samples by comparing them with the predictions of the simple analytical model proposed by Glicksmann and Schuetz [12] for polymer foams. The authors proposed the following formula:

$$k_c = \varepsilon \times k_{\text{air}} + (1-\varepsilon) \times \frac{(2-f_s)}{3} \times k_{\text{solid}} \tag{15}$$

For polymer closed-cell foams, the fraction of polymer in struts is between 0 and 1 and thus, the phonic conductivities are comprised between

$$\varepsilon \times k_{\text{air}} + \frac{2 \times (1-\varepsilon)}{3} \times k_{\text{solid}} > k_c > \varepsilon \times k_{\text{air}} + \frac{(1-\varepsilon)}{3} \times k_{\text{solid}} \tag{16}$$

This leads to the following ranges of variations for the phonic conductivities

- At ambient temperature ($k_{\text{air}} = 0.0257$ W/m/K, $k_{\text{PVC}} = k_{\text{PS}} = 0.16$ W/m/K at 293 K), $0.03007 > k_c > 0.02719$; $0.03331 > k_c > 0.02829$ and $0.02813 > k_c > 0.02653$ in W/m/K for sample nos. 1, 2, and 3, respectively. For these computations, we have considered $T = 293$ K.
- At elevated temperatures ($k_{\text{air}} = 0.0314$ W/m/K, $k_{\text{PS}} = 0.16$ W/m/K at $T = 373$ K; and $k_{\text{air}} = 0.0328$ W/m/K, $k_{\text{PVC}} = 0.165$ W/m/K at $T = 403$ K), $0.03775 > k_c > 0.03474$ W/m/K for sample No. 1; $0.04085 > k_c > 0.035621$ W/m/K for sample No. 2 and $0.03376 > k_c > 0.03211$ W/m/K for sample No. 3.

One can remark that the phonic conductivities identified at $T = 293$ K belong to the ranges of variations given by the analytical correlations, and thus that they are quite consistent. It is also interesting to notice that the values of f_s which lead to the phonic conductivities identified are, respectively, 0.24, 0.41, and 0.08 for sample nos. 1, 2, and 3 at $T = 293$ K. These results are in good agreement with the fact that, in closed-cell foams, the fraction of polymer in struts is close to 0 and increases with the solid fraction.

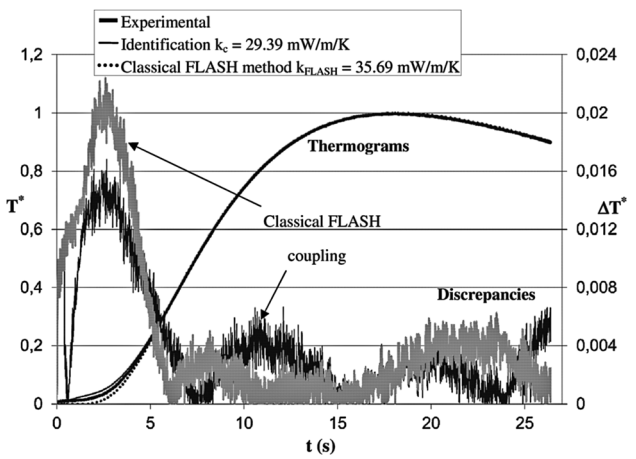

Fig. 3 Comparison of the experimental and identified thermograms for sample No. 1 at $T = 293$ K

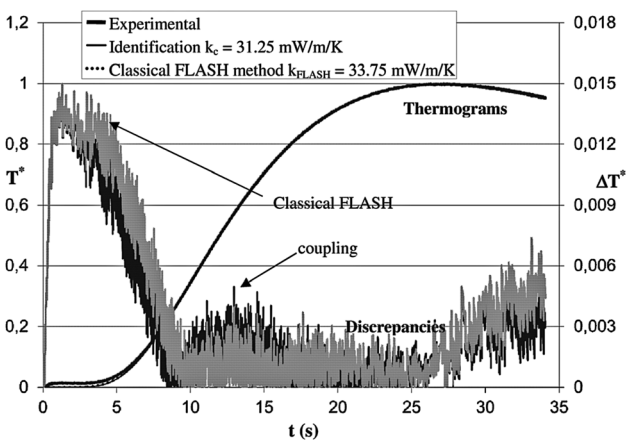

Fig. 4 Comparison of the experimental and identified thermograms for sample No. 2 at $T = 293$ K

Downloaded From: http://heattransfer.asmedigitalcollection.asme.org/ on 04/01/2015 Terms of Use: http://asme.org/terms

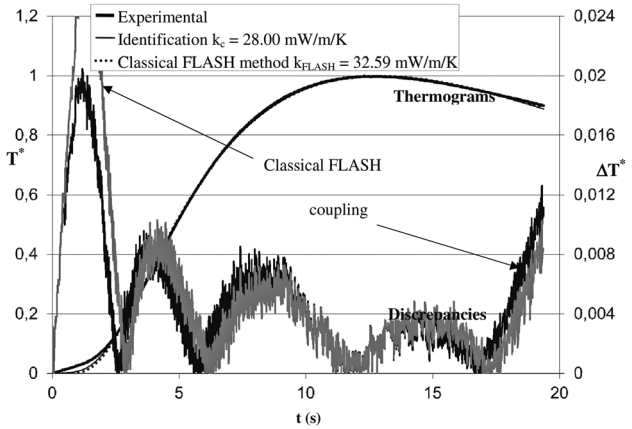

Fig. 5 Comparison of the experimental and identified thermograms for sample No. 3 at $T = 293$ K

The identified values of k_c at higher temperatures are also in acceptable agreement with the values predicted by the analytical models. All these considerations show the consistency of the values identified.

Thereafter, these phonic conductivities and the radiative properties identified from spectrometric measurements have been used to estimate the equivalent conductivities of the foam samples by solving the steady-state coupled heat transfer between two perfectly emissive infinite plates maintained at different temperatures, T_h and T_c. This heat transfer is governed by the same system of equations as the one used to simulate the FLASH experiment except that the energy equation is simplified (steady-state regime) and the thermal and radiative boundary conditions are modified to take into account the temperatures imposed at the hot and cold plates.

The system of equations is solved using the same numerical methods as the one used to solve the FLASH simulation. The equivalent conductivities of the samples could then be determined by

$$k_{\text{equ}} = \frac{\left(q_r^z + q_c^z\right) \times H}{(T_c - T_h)} \tag{17}$$

The computations of the equivalent conductivities have been conducted for a mean temperature $T_m = (T_c + T_h)/2$ corresponding to the temperature of FLASH measurement (293 and 403 K or 373 K) and for $H = 100$ mm. The values obtained are reported in Table 2 for the three foam samples. These equivalent conductivities can be taken as reference values since

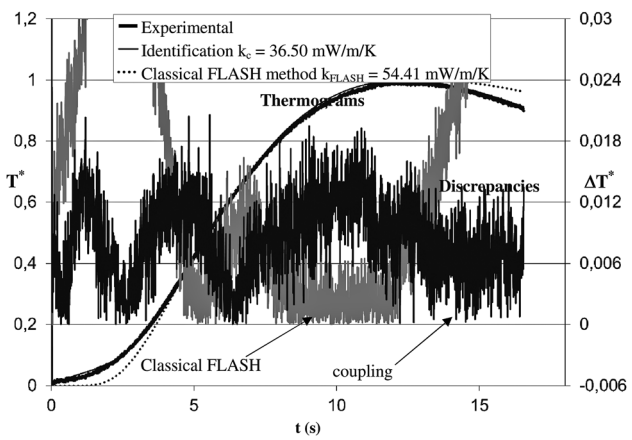

Fig. 6 Comparison of the experimental and identified thermograms for sample No. 1 at $T = 403$ K

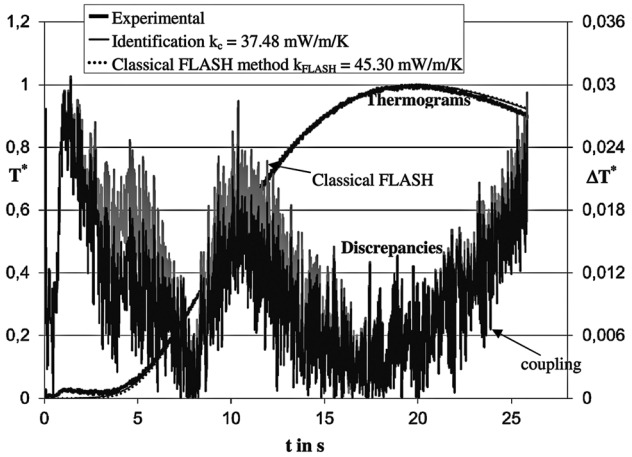

Fig. 7 Comparison of the experimental and identified thermograms for sample No. 2 at $T = 403$ K

- The phonic conductivities have been estimated by taking into account the coupled radiation–conduction coupling in the identification procedure.
- The radiative properties have been measured from direct spectrometric measurements.

In order to estimate the contribution of radiative transfer in the three foam samples, we can compute the difference between the equivalent and phonic conductivities to yield a "radiative" conductivity $k_{\text{rad}} = k_{\text{equ}} - k_c$. These contributions are, respectively, $k_{\text{rad}} = 6.3$ mW/m/K, $k_{\text{rad}} = 2.38$ mW/m/K, and $k_{\text{rad}} = 4.6$ mW/m/K for sample nos. 1, 2, and 3 at $T = 293$ K, and $k_{\text{rad}} = 14.2$ mW/m/K, $k_{\text{rad}} = 6.28$ mW/m/K for sample nos. 1 and 2 at $T = 403$ K, and $k_{\text{rad}} = 9.15$ mW/m/K for sample No. 3 at $T = 373$ K. This corresponds to a relative contribution of 17.6%, 7% and 14.1%, respectively, for sample nos. 1, 2, and 3 at $T = 293$ K, 28% and 14.3% for sample nos. 1 and 2 at $T = 403$ K and 20.9% for sample No. 3 at $T = 373$ K. Thus, the contribution of the radiative heat transfer is nonnegligible at ambient temperature and is significant at higher temperatures for the three foam samples.

4.3 Application of the Classical FLASH Method. Subsequently, we have applied the classical FLASH method to the experimental thermograms, i.e., we have identified the thermal

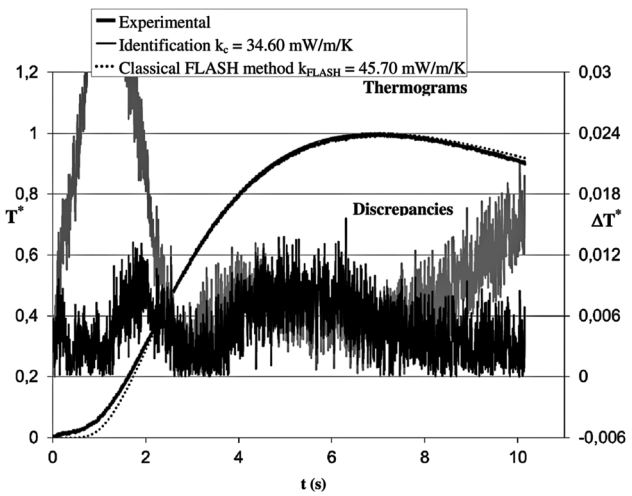

Fig. 8 Comparison of the experimental and identified thermograms for sample No. 3 at $T = 373$ K

Downloaded From: http://heattransfer.asmedigitalcollection.asme.org/ on 04/01/2015 Terms of Use: http://asme.org/terms

Table 3 Summary of the thermal properties identified by the classical FLASH method and of the relative error on the equivalent thermal conductivities

Sample No.	T (K)	k_{equ} ident. (mW/m/K)	H ident. (W/m^2/K)	$\langle \Delta T^* \rangle$	% error k_{equ}
1	293	35.64	8.31	0.00456	−0.14
2	293	33.75	10.41	0.00377	+0.3
3	293	32.59	7.22	0.00538	−0.03
1	403	54.41	13.04	0.0179	+7.3
2	403	45.30	30.10	0.0104	+3.5
3	373	45.70	9.60	0.0116	+4.4

conductivity k_{FLASH} of the purely conductive material and the heat transfer coefficient h, that permit to minimize the discrepancy between experimental and computed thermograms. This has been achieved by using the same identification procedure as the one described in Sec. 3.1.2, except that, now the radiative heat fluxes and radiative heat flux divergence have been set to 0. Indeed, one has to keep in mind that in the classical FLASH experiments, the heat transfer is assumed purely conductive. The thermal conductivities obtained are summarized in Table 3. We also indicate the values of the heat transfer coefficients identified, the mean discrepancy and the relative difference with the equivalent conductivities computed from k_c, β_λ, ω_λ, and g_λ in Sec. 4.2. This relative error is computed simply by $(k_{FLASH} - k_{equ})/(k_{equ})$. In Figs. 3–8, we have also compared the thermograms obtained by the classical FLASH method with the corresponding experimental thermograms and with the thermograms identified previously (Sec. 4.2).

4.4 Discussions. The results of Tables 2 and 3 indicate that, at ambient temperatures, the thermal conductivities obtained by the classical FLASH experiments, i.e., assuming that the heat transfer is purely conductive, are very close to the equivalent conductivities for the three foam samples. Indeed, the maximum relative difference occurs for sample No. 2 and is only 0.3%. One can also remark that for sample No. 1 in which the radiative heat transfer is the most significant (see Sec. 4.2), the relative error made by the classical FLASH experiment to estimate the equivalent conductivity is even lower. It is also interesting to notice that the numerical thermograms obtained by considering the radiation–conduction coupled heat transfer are very close to the thermograms obtained by the classical FLASH method (see Figs. 3–5). The evolutions of the discrepancies are very similar but the mean discrepancy ΔT^* is somewhat better for the numerical results which take into account the radiation–conduction coupling.

All the previous remarks clearly indicate that, at ambient temperature, the classical FLASH measurements could be used satisfactorily for estimating the equivalent thermal conductivity of low-density polymer foams.

On the other hand, at higher temperatures ($T = 403$ K for sample nos. 1 and 2 and $T = 373$ K for sample No. 3), it appears that the thermal conductivities obtained by the classical FLASH method differ noticeably from the equivalent conductivities computed numerically from the identified radiative properties and effective conductivities. Indeed, the conductivities obtained by the classical treatments of the FLASH thermograms overestimates the equivalent conductivity and it seems that the magnitude of the errors is directly related to the level of the radiative heat transfer contribution. As an example, for sample No. 1 at $T = 403$ K the relative contribution of radiation is 28% and the relative error is +7.3% while for sample No. 2, the relative contribution of radiation is 14.3% and the relative error is only 3.5%. Similarly, for sample No. 3 at $T = 373$ K, the relative contribution of radiation is 20.9% and the relative error is only 4.3%. It is also interesting to note (Figs. 6–8) that the thermograms obtained assuming purely conductive materials poorly fit with the measured thermograms. The experimental/numerical agreement characterized by $\langle \Delta T^* \rangle$ is much better when the coupled radiation–conduction model is taken into account (see Table 3).

These observations seem quite logical given that, when the temperature rises, the relative contribution of radiation heat transfer increases rapidly leading to the obsolescence of the purely conductive hypothesis underlying the classical FLASH method. Therefore, the classical FLASH experiment could not be considered as an accurate method of measurement of the equivalent conductivity of low-density polymer foams at elevated temperatures.

5 Conclusions

Measuring the thermal performances, i.e., the equivalent thermal conductivity of low-density thermal insulators is, at present, very time-consuming due to the slowness of the standard methods of measurement. Therefore, the use of a fast and accurate measuring method is of primary importance for manufacturers who are interested in reducing the duration of the production process. The classical "FLASH" or photo-thermal method offers the advantages of simplicity and quickness but is, at present, very little used for the characterization of thermal insulators. It is mostly due to the fact that it is theoretically restricted to purely conductive materials. Therefore, we have investigated the possibility to extend the field of application of the classical FLASH method to low-density.

For this purpose, we have conducted FLASH experiments on three different polymer foam samples at ambient and elevated temperatures. At the same time, spectrometric measurements have been performed on slabs of the corresponding foam samples in order to characterize the radiative behaviors, i.e., to identify the equivalent spectral radiative properties of the samples. Thereafter, the phonic conductivities of the foam samples have been identified by applying a least-square fit-method associated with a numerical simulation of the 1D transient heat transfer to the experimental thermograms. The direct heat transfer model used for the identification solves the radiation–conduction coupling and has recourse to the radiative properties identified for each foam sample.

Subsequently, the phonic conductivities and radiative properties identified for each foam samples allowed us to compute their equivalent conductivities which clearly show that the contributions of radiative transfer are quite significant even at ambient temperature. These equivalent conductivities are then compared with the conductivities obtained by the classical FLASH treatments of the thermograms. It appears that the errors made on the equivalent conductivities when using the classical FLASH method are quite negligible at ambient temperatures. These results definitely demonstrate the possible extension of the classical FLASH method to the accurate measurement of the equivalent conductivity of low-density polymer foams at ambient temperature. This conclusion may be of primary interest in view of reducing the time required to measure the equivalent conductivity of this kind of materials.

On the other hand, the results obtained at relatively elevated temperatures indicate that the classical FLASH approach consistently overestimate the equivalent conductivities of the samples tested. Indeed, the radiative transfer contribution is then

Downloaded From: http://heattransfer.asmedigitalcollection.asme.org/ on 04/01/2015 Terms of Use: http://asme.org/terms

sufficiently important to lead to noticeable errors around 5% for the lightest samples. This failure is confirmed by the poor agreement between the thermograms measured at elevated temperature and the ones obtained from the classical FLASH method.

Acknowledgment

This study is a contribution to the ANR MatetPro 2008 project entitled "THOMMI" (Project Number ANR-08-34-5476 from 01/01/2009 to 31/12/2011). The authors acknowledge the partners of this project: the CETHIL and MATEIS laboratories of INSA Lyon, the EC2MS company, the CRYOSPACE company, and the SIMAP Laboratory of the Joseph FOURIER University (Grenoble). The authors also gratefully acknowledge the Centre Scientifique et Technique du Bâtiment (CSTB) of Grenoble (France) for making available its FTIR spectrometer and its foam cutting facilities which have been used for the radiative characterisation of the foam samples.

Nomenclature

C = specific heat (J/kg/K)
D = diameter of the FLASH sample (m)
e = thickness of the black coating (m)
g_λ = spectral asymmetry factor of the phase function
h = heat transfer coefficient ($W/m^2/K$)
H = thickness of the foam slab (m)
I_z^λ = spectral radiant intensity at the point of coordinates (z) in the direction $\vec{\Delta}$ ($W/m^2/Sr$)
I_j^m = radiant intensity at the discrete point of coordinate z_j in the discrete direction m ($W/m^2/Sr$)
$I_0^\lambda(T)$ = spectral radiant intensity of the black body at temperature T ($W/m^2/Sr$)
k = thermal conductivity of the foam sample (W/m/K)
k_{rad} = "radiative" conductivity of the foam sample (W/m/K)
L = thickness of the foam sample used for the FLASH experiment (m)
M = mass of the sample (kg)
nZ = number of spatial discretization of the sample along the axial axis
nZ_{coat} = number of spatial discretization of the interface coating along the axial axis
$\dot{q}$ = heat flux (W/m^2)
Rh_λ = spectral hemispherical reflectance of the foam slab
t = time (s)
t^* = dimensionless time $= t/\Delta t$
T = temperature (K)
T^* = scaled temperature
T_m = mean temperature (K)
T_{coat} = temperature of the interface coating (K)
T_{ext} = external temperature (K)
T_h and T_c = temperature of the hot and cold plates (K)
Td_λ = spectral directional transmittance of the foam slab
Th_λ = spectral hemispherical transmittance of the foam slab
V = volume of the sample (m^3)
w_m = weighting factor for the mth direction of the angular discretization
z = axial coordinate

Greek Symbols

β_λ, σ_λ, and κ_λ = spectral extinction, scattering, and absorption coefficients (m^{-1})
β^* = scaled extinction coefficient
$\omega_\lambda = \sigma_\lambda/\beta_\lambda$ = spectral scattering albedo
ε = porosity of the foam sample
ρ = density (kg/m^3)
λ = radiation wavelength (μm)
Ω = solid angle
Ω_{detect} = solid angle of the infrared detector
σ_{SB} = Stefan–Boltzmann constant ($\approx 5.67 \times 10^{-8}$ $W/m^2/K^4$)
μ_m = directing cosine of the mth discrete directions of the quadrature
$\Phi_\lambda(\theta)$ = spectral scattering phase function
τ = duration of the pulse irradiation (s)
Δt = FLASH measurement duration (s)
Δz_j = dimension of the discretized volume along the axial axis (m)

Subscripts

air = of air
c = conductive
coat = coating
equ = equivalent
exp = experimental
FLASH = from FLASH experiment
j = at the point of coordinates z_j
ident = identified
min = underestimating value
mean = mean value
max = overestimating value
num = numerical
PVC = PVC
PS = polystyrene
rad = radiative
s = of the sample
solid = solid phase
t = total
th = theoretical

Superscripts

z = along the axial axis
l = at the lth iteration
m = mth direction of the quadrature
0 = initial

References

[1] Degiovanni, A., 1977, "Diffusivité et Méthode Flash," Rev. Gén. Therm., **185**, pp. 420–441 (English Abstract).
[2] Degiovanni, A., and Laurent, M., 1986, "Nouvelle Technique d'identification de la diffusivité thermique pour la méthode FLASH," Revue de Physique Appliquée, **21**(3), pp. 229–237 (English Abstract).
[3] André, S., and Degiovanni, A., 1995, "A Theoretical Study of the Transient Coupled Conduction and Radiation Heat Transfer in Glass. Phonic Conductivity Measurements by the Flash Technique," Int. J. Heat Mass Transfer, **38**(18), pp. 3401–3412.
[4] André, S., and Degiovanni, A., 1998, "A New Way of Solving Transient Radiative–Conductive Heat Transfer Problems," J. Heat Transfer, **120**, pp. 943–955.
[5] Tan, H. P., Maestre, B., and Lallemand, M., 1992, "Transient and Steady-State Combined Heat Transfer in Semi-Transparent Materials Subjected to a Step Irradiation," ASME J. Heat Transfer, **113**, pp. 166–173.
[6] Hahn, O., Raether, F., Arduini-Schuster, M. C., Fricke, J., and Degiovanni, A., 1997, "Transient Coupled Conductive/Radiative Heat Transfer in Absorbing, Emitting and Scattering Media: Application to Laser-Flash Measurements on Ceramic Materials," Int. J. Heat Mass Transfer, **40**(3), pp. 689–698.
[7] Lazard, M., André, S., and Maillet, D., 2004, "Diffusivity Measurement of Semi-Transparent Media: Model of the Coupled Transient Heat Transfer and Experiments on Glass, Silica Glass and Zinc selenide," Int. J. Heat Mass Transfer, **47**, pp. 477–487.
[8] Lazard, M., Andre, S., and Maillet, D., 2003, "Thermal Characterization of Semi-Transparent Media: Measurement of Phononic Diffusivity of Glass and Silica," Eur. Phys. J. Appl. Phys., **23**, pp. 207–211.
[9] Coquard, R., Baillis, D., and Rochais, D., 2009, "Experimental Investigations of the Coupled Conductive and Radiative Heat Transfer in Metallic/Ceramic Foams," Int. J. Heat Mass Transfer, **52**(21–22), pp. 4907–4918.
[10] Cheheb, Z., Albouchi, F., and Nasrallah, S. B., 2008, "Measurement of Thermal Radiative and Conductive Properties of Semitransparent Materials Using a Photothermal Crenel Method," J. Quant. Spectrosc. Radiat. Transf., **109**, pp. 620–635.
[11] Brandrup, J., Immergut, E. H., and Grulke, E. A., eds., 1999, *Polymer Handbook*, 4th ed., Wiley-Interscience, New York.
[12] Glicksmann, L. R., and Schuetz, M. A., 1994, *Low Density Cellular Plastics*, N. C. Hilyard and A. Cunningham, eds., Chapman and Hall, London, pp. 104–152.

Downloaded From: http://heattransfer.asmedigitalcollection.asme.org/ on 04/01/2015 Terms of Use: http://asme.org/terms