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 method (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...
transfer is significant. They used an inverse identification method associated with a semi-analytical model of coupled conductive–radiative transient heat transfer in a 1D slab. The inverse method allowed them to identify the phononic conductivity of the materials and some radiative parameters from the FLASH experiment. They show that their new approach allows an accurate estimation of the phononic 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, Cograph 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 quadruple 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 interest 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 obtain accurately the equivalent radiative properties of the foams. Using these properties, we manage to evaluate 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 evaluate 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 (m³):

\[ \varepsilon = \frac{\rho_{\text{solid}} - M/V}{\rho_{\text{solid}} - \rho_{\text{air}}} \]

The specific heat C of each foam samples is estimated by

\[ C_i = \frac{\varepsilon \rho_{\text{air}} C_{\text{air}} + (1 - \varepsilon) \rho_{\text{solid}} C_{\text{solid}}}{\rho_i} \]

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

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Table 1 Properties of the polymer foam samples characterized experimentally

<table>
<thead>
<tr>
<th>Sample</th>
<th>Solid phase</th>
<th>ρ (kg/m³)</th>
<th>ε</th>
<th>Δε/ε</th>
<th>L (mm)</th>
<th>ε'</th>
<th>ε''</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC 75</td>
<td>0.946</td>
<td>0.008</td>
<td>4.83</td>
<td>0.045</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVC 130</td>
<td>0.906</td>
<td>0.008</td>
<td>5.15</td>
<td>0.045</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS 33</td>
<td>0.970</td>
<td>0.01</td>
<td>4.58</td>
<td>0.045</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

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: \( \tau = 0.5 \text{ ms} \), \( E_{\text{max}} = 600 \text{ J} \), and \( D_{\text{las}} = 40 \text{ mm} \).

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.
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/phonon 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 \( T_{\text{exp}}(t) \) 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

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

The evolution of the temperature calculated by our theoretical model is influenced by the following parameters: \( L, \rho_{\text{coat}}, C_{\text{coat}}, k_{\text{coat}}, h, \rho, C, \) and \( k_e \) and the radiative properties \( \beta_j, \kappa_j, \sigma_j, \) and \( \Phi_j(0) \) 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

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

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

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

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

for \( k = 1,N \).

The partial derivatives \( \frac{\partial T_{\text{num}}(t_n)}{\partial P_k} \) are called the sensitivity 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

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

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

\[
T_{\text{num}}(t_n, [P_k]_{k=1,N}^{l-1}) = T_{\text{num}}(t_n, [P_k]_{k=1,N}^{l-1}) + \sum_{k=1}^{N_t} \left( T_{\text{exp}}(t_n) - T_{\text{num}}(t_n) \right) \frac{\partial T_{\text{num}}(t_n)}{\partial P_k} \cdot \Delta P_k^{l-1}
\]

We finally have to solve the following matrix system, where the superscript \( l \) refers to the entire matrices

\[
[A]_l = [B]_l \text{ with } A_{l,j} = \sum_{n=1}^{N_t} \left( T_{\text{exp}}(t_n) - T_{\text{num}}(t_n) \right) \frac{\partial T_{\text{num}}(t_n)}{\partial P_k} \cdot \Delta P_k^{l-1};
\]

\[
[B]_l = \sum_{n=1}^{N_t} \left( T_{\text{exp}}(t_n) - T_{\text{num}}(t_n) \right) \frac{\partial T_{\text{num}}(t_n)}{\partial P_k}
\]

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

In the present study, the unknown parameters which have to be identified are the effective/phonon conductivity \( k_e \) of the foam sample and the coefficient of thermal exchange \( h \). \( N = 2; P_1 = k_e; P_2 = h \).
3.2 Identification of the Radiative Properties of the Foam Samples From Spectrometric Measurements. Measurements of the directional $T_d$ and hemispherical $Th_i$ transmittance and of the hemispherical reflectance $Rh_j$ 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

$$\mu \frac{\delta I_{z,\mu}^l}{\delta z} = -\beta_{z,\mu} I_{z,\mu}^l + \frac{\sigma_z}{4\pi} \int \Phi_i(\theta) I_{\pi,\mu}^l d\Omega$$

(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

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

(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

$$T_d = \frac{1}{\mu_{\text{detec}}} \int_{\mu=0}^{\mu_{\text{source}}} I_{z=0,\mu}^l d\mu; \quad Th_i = \frac{1}{\mu_{\text{source}}} \int_{\mu=0}^{\mu_{\text{source}}} I_{z=0,\mu}^l d\mu; \quad Rh_j = \frac{1}{\mu_{\text{source}}} \int_{\mu=0}^{\mu_{\text{source}}} I_{z=0,\mu}^l d\mu$$

(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 Heney–Greenstein phase functions. These phase functions can be expressed using only one parameter noted $g_z$:

$$\Phi_{H-G_z}(\theta) = \frac{1 - g_z^2}{(1 + g_z^2 - 2g_z \cos \theta)^2}$$

(12)

The radiative behavior of the samples could then be characterized by three radiative properties: $\beta_j$, $\omega_j$, and $g_z$.

These spectral properties are identified for each wavelength by minimizing the functions $F_j$, expressing the discrepancies between the measured and computed values of $T_d$, $Th_i$, and $Rh_j$.

$$F_j(\beta_j, \omega_j, g_z) = \left[ \begin{array}{c} (T_d)_\exp - (T_d)_\text{num} \\ (Th_i)_\exp - (Th_i)_\text{num} \\ (Rh_j)_\exp - (Rh_j)_\text{num} \end{array} \right]$$

(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

$$(T_d)_\exp = (T_d)_\text{num}; \quad (Th_i)_\exp = (Th_i)_\text{num}; \quad (Rh_j)_\exp = (Rh_j)_\text{num}$$

In order to minimize $F_j$, 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 $\Delta \beta_j$, $\Delta \omega_j$, and $\Delta g_z$ by solving the following system:

$$\left[ \begin{array}{c} \frac{\partial T_d}{\partial \beta_j} \frac{\partial T_d}{\partial \omega_j} \frac{\partial T_d}{\partial g_z} \\ \frac{\partial Th_i}{\partial \beta_j} \frac{\partial Th_i}{\partial \omega_j} \frac{\partial Th_i}{\partial g_z} \\ \frac{\partial Rh_j}{\partial \beta_j} \frac{\partial Rh_j}{\partial \omega_j} \frac{\partial Rh_j}{\partial g_z} \end{array} \right] \left[ \begin{array}{c} \Delta \beta_j \\ \Delta \omega_j \\ \Delta g_z \end{array} \right] = 0$$

(14)

This system is solved successively for each iteration level $l$ to calculate the parameter values $(\beta_j)^{l+1} = (\beta_j)^{l} + \Delta \beta_j$, $(\omega_j)^{l+1} = (\omega_j)^{l} + \Delta \omega_j$, and $(g_z)^{l+1} = (g_z)^{l} + \Delta g_z$ until the discrepancy ratios $\frac{|(T_d)_\exp - (T_d)_\text{num}|}{|T_d|\text{exp}}$, $\frac{|(Th_i)_\exp - (Th_i)_\text{num}|}{|Th_i|\text{exp}}$, and $\frac{|(Rh_j)_\exp - (Rh_j)_\text{num}|}{|Rh_j|\text{exp}}$ 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 $\beta_j^* = \kappa_z + \sigma_z (1 - g_z)$ 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 foam.
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 $\langle \Delta T^* \rangle = \frac{\int |T_{exp}(t) - T_{num}(t)| dt}{t_f}$. 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 $\Delta T^* = T_{exp}(t) - T_{num}(t)$.

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:

$$k_c = \varepsilon \times k_{air} + (1 - \varepsilon) \times \frac{(2 - f_d)}{3} \times k_{solid}$$

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

$$\varepsilon \times k_{air} + \frac{2}{3} \times k_{solid} > k_c > \varepsilon \times k_{air} + \frac{1}{3} \times k_{solid}$$

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

- At ambient temperature ($k_{air} = 0.0257$ W/m/K, $k_{PVC} = k_{PS} = 0.16$ 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 $k_{air} = 0.0314$ W/m/K, $k_{PS} = 0.16$ W/m/K at $T = 373$ K; and $k_{air} = 0.0328$ W/m/K, $k_{PVC} = 0.165$ 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 $f_d$ 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.

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

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>$T$ (K)</th>
<th>$k_c$ ident. (mW/m/K)</th>
<th>$h$ ident. (W/m²/K)</th>
<th>$\langle \Delta T^* \rangle$</th>
<th>$k_{eq}$ comp. (mW/m/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>293</td>
<td>29.39</td>
<td>9.04</td>
<td>0.00405</td>
<td>35.69</td>
</tr>
<tr>
<td>2</td>
<td>293</td>
<td>31.25</td>
<td>10.61</td>
<td>0.00336</td>
<td>33.63</td>
</tr>
<tr>
<td>3</td>
<td>293</td>
<td>28.00</td>
<td>7.38</td>
<td>0.00493</td>
<td>32.6</td>
</tr>
<tr>
<td>1</td>
<td>403</td>
<td>36.50</td>
<td>27.06</td>
<td>0.00837</td>
<td>50.70</td>
</tr>
<tr>
<td>2</td>
<td>403</td>
<td>37.48</td>
<td>32.49</td>
<td>0.00666</td>
<td>43.76</td>
</tr>
<tr>
<td>3</td>
<td>373</td>
<td>34.60</td>
<td>11.06</td>
<td>0.00499</td>
<td>43.75</td>
</tr>
</tbody>
</table>
The identified values of $k_e$ 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

$$k_{eq} = \left( q_{e}^+ + q_{e}^- \right) \times H \quad (T_e - T_h)$$

The computations of the equivalent conductivities have been conducted for a mean temperature $T_m = (T_e + T_h)/2$ 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

- 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 $k_{rad} = k_{eq} - k_e$. These contributions are, respectively, $k_{rad} = 6.3 \, \text{mW/m/K}$, $k_{rad} = 2.38 \, \text{mW/m/K}$, and $k_{rad} = 4.6 \, \text{mW/m/K}$ for sample nos. 1, 2, and 3 at $T = 293$ K, and $k_{rad} = 14.2 \, \text{mW/m/K}$, $k_{rad} = 6.28 \, \text{mW/m/K}$ for sample nos. 1 and 2 at $T = 403$ K, and $k_{rad} = 9.15 \, \text{mW/m/K}$ 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...
The experimental error is computed simply by the contribution. As an example, for sample No. 1 at low-density polymer foams.

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

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>T (K)</th>
<th>$k_{\text{eq}}$ ident. (mW/mK)</th>
<th>$H$ ident. (W/m$^2$/K)</th>
<th>$(\Delta T^*)$</th>
<th>% error $k_{\text{eq}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>293</td>
<td>35.64</td>
<td>8.31</td>
<td>0.00456</td>
<td>-0.14</td>
</tr>
<tr>
<td>2</td>
<td>293</td>
<td>33.75</td>
<td>10.41</td>
<td>0.00377</td>
<td>+0.3</td>
</tr>
<tr>
<td>3</td>
<td>293</td>
<td>32.59</td>
<td>7.22</td>
<td>0.00538</td>
<td>-0.03</td>
</tr>
<tr>
<td>1</td>
<td>403</td>
<td>54.41</td>
<td>13.04</td>
<td>0.0116</td>
<td>+4.4</td>
</tr>
<tr>
<td>2</td>
<td>403</td>
<td>45.30</td>
<td>13.04</td>
<td>0.0104</td>
<td>+3.5</td>
</tr>
<tr>
<td>3</td>
<td>373</td>
<td>45.70</td>
<td>9.60</td>
<td>0.0116</td>
<td>+4.4</td>
</tr>
</tbody>
</table>

conductivity $k_{\text{FLASH}}$ 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 $k_c$, $\beta_1$, $\omega_1$, and $g_j$ in Sec. 4.2. This relative error is computed simply by $(k_{\text{FLASH}} - k_{\text{eq}})/(k_{\text{eq}})$. In Figs. 3–8, we have also computed 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 $\Delta T^*$ 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 overestimate 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 $(\Delta T^*)$ 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 definitively 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
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.

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Nomenclature

\( C = \) specific heat (J/kg/K)  
\( D = \) diameter of the FLASH sample (m)  
\( e = \) thickness of the black coating (m)  
\( g_s = \) spectral asymmetry factor of the phase function  
\( h = \) heat transfer coefficient (W/m²/K)  
\( H = \) thickness of the foam slab (m)  
\( I' = \) spectral radiant intensity at the point of coordinates \((z)\) in the direction \( \Delta \) (W/m²/Sr)  
\( I'_m = \) radiant intensity at the discrete point of coordinates \( z_j \) in the discrete direction \( m \) (W/m²/Sr)  
\( I_0(T) = \) spectral radiant intensity of the black body at temperature \( T \) (W/m²/Sr)  
\( k = \) thermal conductivity of the foam sample (W/m/K)  
\( k_{\text{rad}} = \) "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)  
\( n_Z = \) number of spatial discretization of the sample along the axial axis  
\( n_{Z_{\text{coat}}} = \) number of spatial discretization of the interface coating along the axial axis  
\( q = \) heat flux (W/m²)  
\( R_h = \) spectral hemispherical reflectance of the foam slab  
\( t = \) time (s)  
\( t^* = \) dimensionless time \( = t/\Delta t \)  
\( T = \) temperature (K)  
\( T_s = \) mean temperature (K)  
\( T_{\text{coat}} = \) temperature of the interface coating (K)  
\( T_{\text{ext}} = \) external temperature (K)  
\( T_h \) and \( T_c = \) temperature of the hot and cold plates (K)  
\( T_{d_{\text{rad}}} = \) spectral directional transmittance of the foam slab  
\( T_{d_{\text{rad}}} = \) spectral hemispherical transmittance of the foam slab  
\( V = \) volume of the sample (m³)  
\( w_m = \) weighting factor for the \( m \)-th direction of the angular discretization  
\( z = \) axial coordinate

Greek Symbols

\( \beta, \sigma, \) and \( \kappa = \) spectral extinction, scattering, and absorption coefficients (m⁻¹)  
\( \beta^k = \) scaled extinction coefficient  
\( \omega_s = \sigma_s/\beta_s = \) spectral scattering coefficient  
\( \varepsilon = \) porosity of the foam sample

\( \rho = \) density (kg/m³)  
\( \lambda = \) radiation wavelength (µm)  
\( \Omega = \) solid angle  
\( \Omega_{\text{detect}} = \) solid angle of the infrared detector  
\( \sigma_{\text{SB}} = \) Stefan–Boltzmann constant \((\approx 5.67 \times 10^{-8} \) W/m²/K⁴)  
\( \mu_m = \) directing cosine of the \( m \)-th discrete directions of the quadrature  
\( \Phi_j(l) = \) spectral scattered phase function  
\( \tau = \) duration of the pulse irradiation (s)  
\( \Delta = \) FLASH measurement duration (s)  
\( \Delta_z = \) dimension of the discretized volume along the axial axis (m)

Subscripts

\( a = \) of air  
\( c = \) conductive  
\( \text{coat} = \) coating  
\( \text{equ} = \) equivalent  
\( \text{exp} = \) experimental  
\( \text{FLASH} = \) from FLASH experiment  
\( j = \) at the point of coordinates \( z_j \)  
\( \text{id} = \) identified  
\( \text{min} = \) underestimating value  
\( \text{max} = \) overestimating value  
\( \text{num} = \) numerical  
\( \text{PVC} = \) PVC  
\( \text{PS} = \) polystyrene  
\( \text{rad} = \) radiative  
\( \text{s} = \) of the sample  
\( \text{solid} = \) solid phase  
\( \text{th} = \) theoretical

Superscripts

\( z = \) along the axial axis  
\( l = \) at the \( l \)-th iteration  
\( m = \) \( m \)-th direction of the quadrature  
\( 0 = \) initial

References