JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 16, No. 2, April–June 2002

Identification of Polyurethane Foam Radiative Properties—Influence of Transmittance Measurements Number

D. Baillis* and J. F. Sacadura†
Institut National des Sciences Appliquées de Lyon, 69621 Villeurbanne, France

Spectral radiative properties (absorption coefficient, scattering coefficient, and phase function) of open-cell polyurethane foam are identified using a combination of hemispherical and bidirectional spectral transmittance and reflectance measurements in the infrared wavelength region 2–15 μm. The influence of the number of transmittance measurements on identification results is analyzed. The Gauss linearization technique is used in the identification method, and discrete ordinates method is applied to solve the radiative transfer equation.

Nomenclature

g	=	spectral Henyey–Greenstein phase function parameter
I	=	intensity of radiation
I_0	=	intensity of the collimated incident beam
ly	=	sample thickness
P_λ	=	spectral phase function
T	=	transmittance or reflectance
β	=	volumetric extinction coefficient
β_R	=	Rosseland mean extinction coefficient
β^*	=	weighted extinction coefficient
θ	=	angle between the incident and scattered direction
κ	=	volumetric absorption coefficient
μ	=	cosine of the polar angle defined from the normal direction of the sample (for the normal direction $\mu = 1$)
σ	=	volumetric scattering coefficient
ω	=	volumetric scattering albedo coefficient

Subscripts

e	=	experimental
t	=	theoretical
λ	=	monochromatic wavelength

I. Introduction

INSULATING foam consists of a porous semitransparent medium, which absorbs, emits, and scatters radiation. Heat transfer in such media occurs by conduction through the solid material and through the gas filling the pores and by thermal radiation, which propagates through the structure. Even if analytical or numerical techniques are available to solve the coupled heat-transfer problem in semitransparent media, some difficulty remains to determine the radiative properties of these porous materials. In this work a special emphasis is put on the identification of radiative properties of open cell polyurethane (PU) rigid foam. The radiative properties of foam that are required for solving the radiative transfer equation are the spectral volumetric scattering and absorption coefficients and the spectral volumetric phase function. There are two main groups of methods to determine the radiative properties of porous media: 1) prediction models such as the well-known Mie theory and 2) experimental methods using parameter identification techniques. From a review of literature, the following comments can be made about the methodologies used:

1) Few works have been devoted to the foam radiative properties prediction model. The foam structure is complex, and the unit cell appears to closely resemble a pentagonal dodecahedron. Glicksman and Torpey[1] and Glicksman et al.[2] considered the foam as a set of randomly oriented blackbody struts of constant thickness with an assumed efficiency factor of one. They neglected scattering phenomena by the struts. Kuhn et al.[3] used infinitely long cylinders to describe the struts. The triangular cross sections were converted into circular ones with the same geometrical mean cross section. Then they used Mie scattering calculations to predict the radiative properties. Baillis et al.[4] have determined radiative properties from morphological data, such as porosity, particle sizes, and from solid hemispherical reflectivity. Struts with varying thickness and strut joints were considered. The particles were assumed to have a random orientation and were considered thick enough to be considered as opaque. These authors have taken into account scattering phenomena by applying to these particles a combination of geometric optics laws and diffraction theory.

2) In previous research about determination of radiative properties of porous media using inverse analysis techniques, two types of transmittance and reflectance measurements are usually used: directional–hemispherical or directional–directional. Many of works have been devoted to the identification of radiative properties using directional–hemispherical measurements assuming isotropic scattering. Among the more recent, the works of Skocypec et al.[5] and Hale and Bohn[6] on reticulated ceramics and those of Kuhn et al.[3] on polystyrene and polyurethane foam can be cited. In Hendricks and Howell[7] spectral radiative properties were recovered from spectral hemispherical reflectance and transmittance measurements. Two dual-parameter phase functions were investigated for the materials: one based on the physical structure of reticulated porous ceramics and the other based on a modified Henyey–Greenstein phase function. There were then a total of four variables to determine in the inverse radiative analysis: absorption coefficient, scattering coefficient, and two phase function parameters. This required multiple (four as minimum) independent measurements. Multiple sample thicknesses have been considered to provide enough information to retrieve the four variables simultaneously. Nicolau et al.[8] using directional–directional measurements have identified radiative properties (extinction coefficient, scattering albedo, and phase function parameters) of fiber insulating materials. They proposed a new phase function, which is a combination of two Henyey–Greenstein functions coupled with an isotropic component. Moura et al.[9] considered different angles of incidence onto the sample for directional–hemispherical measurements. The phase function used

Received 12 December 2000; accepted for publication 11 September 2001.

*Assistant Professor, Centre de Thermique de Lyon, UMR 5008; domino@cethil.insa-lyon.fr. Member AIAA.

†Professor, Centre de Thermique de Lyon, UMR 5008; cethil@insa-lyon.fr.

is the same as in Nicolau et al.[8] Numerical simulations have shown that the case of normally incident collimated beam onto the sample with bidirectional transmittance and reflectance measurements is more appropriate than the case of collimated beam with different angles of incidence onto the sample with hemispherical transmittance and reflectance measurements.

The two methods, directional–hemispherical or directional–directional measurements, with a normally incident collimated beam onto the sample present advantages and disadvantages. Indeed, directional–hemispherical measurements are easily and quickly acquired, but just the extinction and scattering coefficients can be identified for one sample thickness, assuming the phase function to be known. However, a number of researchers and engineers are interested in the determination of materials phase function. Directional–directional measurements, on the other hand, contain more information permitting identification of phase function if there are sufficiently measurement directions. But for most of measurement directions, except near the normal, the energy measured can be small, and the experimental data can be very noisy. In this paper a combination of directional–directional transmittance and directional–hemispherical transmittances and reflectances is used to identify radiative properties and, more particularly, the phase function.

First, the technique of parameter identification is presented. The discrete ordinates method is used to solve the radiative transfer equation. The two types of devices that permit measurement of either directional–hemispherical or directional–directional transmittance and reflectance are described. Then radiative properties including phase function obtained from this approach for PU foam are presented. The influence of the number of transmittance measurements on the identified results is analyzed. In addition, a study of sensitivity of radiative parameters to directional–directional transmittance and directional–hemispherical reflectance and transmittance is presented.

II. Parameter Identification

A. Method

The parameter identification method used in this work is based upon 1) experimental data of transmittances and reflectances T_{ei} obtained for several measurement directions i, for a given set of samples; and 2) theoretical transmittances and reflectances T_{ti} calculated for the same directions as the ones of the experimental data and for the same sample thickness.

For each wavelength the goal is to determine the radiative parameters (ω, β, g), which minimize the sum of squared relative differences F between the measured and calculated transmittances and reflectances over the N measurements:

$$F(\omega, \beta, g) = \sum_{i=1}^{N} \left[\frac{T_{ti}(\omega, \beta, g) - T_{ei}}{T_{ei}} \right]^2 \tag{1}$$

The method used in this work is the Gauss linearization method,[10] which minimises F by setting to zero the derivatives of F with respect to each of the unknown parameters.

In the case of hemispherical measurements, the number of measurements is $N = 2$: one for transmittance and one for reflectance. In the case of the combination of hemispherical and directional measurements, N is $(2 + N_{bd})$, where N_{bd} is the total number of bidirectional measurement directions.

B. Parameter Sensitivity Coefficient

The analysis of sensitivity coefficients is a powerful tool for understanding the physical behavior of the problem.[11] The sensitivity coefficients show the variation of the transmittance or reflectance with respect to the a variation of the parameters. Their comparison is not very easy when the parameters do not have the same units, which is often the case. Then, for comparison, it is preferable to study the normalized dimensionless sensitivity coefficients, defined in Eq. (2) as

$$X(i, p_j) = \frac{\partial T_i p_j}{\partial p_j T_i} \tag{2}$$

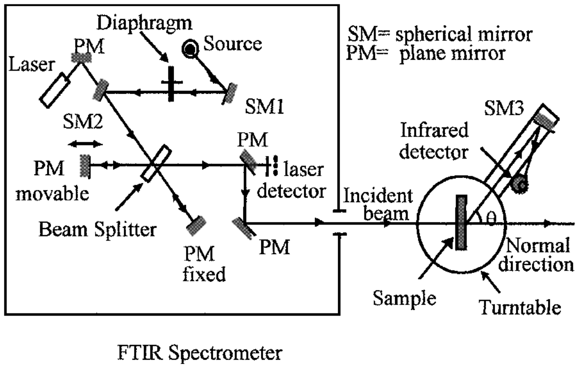


Fig. 1 Schematic of the experimental device using an FTIR spectrometer to measure bidirectional transmittance and reflectance.

where T_i ($i = 1, N$) represents hemispherical or directional transmittance or reflectance and p_j ($j = 1, 3$) represents the radiative parameters ($p_1 = \omega$, $p_2 = \beta$, $p_3 = g$).

C. Experimental Setup

In both cases of directional or hemispherical measurements, the sample is submitted to a collimated normal incidence beam. The radiation emitted by the source is modulated. A potassium bromide beamsplitter and a liquid-nitrogen-coded MCT (mercury cadmium telluride) detector are used.

Bidirectional Transmittance and Reflectance Measurements

The experimental directional–directional spectral transmittances data are obtained from an experimental device using a Fourier transform infrared (FTIR) spectrometer (FTS 60A Bio-Rad, Inc.). The schematic of the setup is shown in Fig. 1. The source of radiation, characterized by a blackbody emission spectrum at 1300°C, is a ceramic tube. The divergence half-angle of incident beam is $\theta_0 = 1.27$ deg. The detection system is composed of a spherical mirror collecting the beam and concentrating it on the MCT detector (2.2–15.3 μm). It is mounted on a rotating arm allowing the measurement of the radiation transmitted or reflected by the sample at several angles. The diameter of the beam incident on the sample is around 50 mm while the sample holder diameter is smaller, that is, 30 mm. Both the spectrometer and the detection system are purged with dry air. The transmittances or reflectances $T(\mu)$ for normal incidence are defined by the expression in Eq. (3):

$$T(\mu) = I(\mu)/I_0 d\omega_0 \tag{3}$$

where I_0 the intensity of the collimated beam normally incident onto the sample within a solid angle $d\omega_0$.

Remark: The transmittance or reflectance defined by Eq. (3) are different from the classical transmittance or reflectance measured by the spectrometer, which are the fraction M of the incident energy transmitted or reflected by the sample. The relation between the transmittance or reflectance T defined by the Eq. (3) and M is $T = M/\mu d\omega_0$. By definition, M is smaller than 1, but as $\mu d\omega_0$ is also smaller than 1, T can be larger than 1.

Hemispherical Transmittance and Reflectance Measurements

Hemispherical transmittance and reflectance measurements are performed with a 76-mm-diam, gold-coated integrating sphere from Labsphere and a Bruker FTIR spectrometer IFS 66v. The light source is a SiC globar. The sphere is mounted outside the spectrometer. The beam diameter is 1.3 cm, which is the same as the sample holder diameter.

The hemispherical transmittances and reflectances are defined by Eqs. (4a) and (4b).

Transmittance:

$$T = 2\pi \frac{\int_0^1 I(\mu)\mu d\mu}{I_0 d\omega_0} \tag{4a}$$

Reflectance:

$$T = -2\pi \frac{\int_{-1}^{0} I(\mu)\mu d\mu}{I_0 d\omega_0} \tag{4b}$$

D. Theoretical Model

Heat transfer in the experimental device sample is calculated numerically. The boundary conditions and the assumptions are 1) one-dimensional radiative transfer in the semitransparent medium (Thickness of samples used is less than 528 μm, and so the ratio of the sample holder diameter to the sample thickness is larger than 24.); 2) azimuthal isotropy; and 3) the self-emission term is not taken into account here because of the radiation modulation and phase sensitive detection.

With these conditions the radiative transfer equation (RTE) for the sample can be written in the following form [Eq. (5)]:

$$\mu \frac{\partial I_\lambda}{\partial y} + \beta_\lambda I_\lambda = \frac{\sigma_\lambda}{2} \int_{-1}^{1} I_\lambda(y, \mu') P_\lambda(\mu', \mu)\,\mathrm{d}\mu' \tag{5}$$

where μ' the cosine of polar angle of incident direction.

The Henyey–Greenstein phase function $P_\lambda(\theta) = (1 - g_\lambda^2)/(1 + g_\lambda^2 - 2g_\lambda \cos\theta)^{1.5}$ is investigated in this work. According to the value of the parameter g_λ, this function permits a representation of the phase function for the medium. More particularly, for g_λ nearly equal to one, the Henyey–Greenstein phase function permits a representation of the highly forward phase function, which is the case for fibrous and foam medium.

The boundary conditions are given by Eq. (6):

$$I_\lambda(0, \mu) = \begin{cases} I_{0\lambda} & \text{if} \quad \mu_0 \le \mu \le 1 \\ 0 & \text{elsewhere} \end{cases}$$

$$I_\lambda(l_y, \mu) = 0 \qquad \text{for} \qquad \mu < 0 \tag{6}$$

The discrete ordinates method with a quadrature over 24 directions is applied to solve the integro-differential radiative equation (5). This method is very precise. The quadrature used is a combination of two Gaussian quadratures, and it allows a concentration of ordinates in the neighborhood of the incident direction suitable for forward scattering materials. The spherical space is discretized into 12 directions for the positive range of μ and 12 other symmetric directions for the negative μ. More details about this quadrature can be found in Nicolau et al.[8] and Nicolau.[12] By writing the radiative transfer equation [Eq. (5)] for each direction μ of the quadrature and by replacing the integral term by a sum over the 24 directions of the quadrature, a system of partial differential equations is obtained. This system is solved analytically by separating collimated radiation and scattered radiation.

III. Rosseland Mean Extinction Coefficient and Radiative Conductivity Definition

For thickness sufficiently large foam insulation can be considered as optically thick. In this case the radiative flux can be approximated by the Rosseland equation introducing a radiative conductivity k_r.[2,3,13,14]

$$k_r = \frac{16 n^2 \bar{\sigma} \Theta^3}{3\beta_R} \tag{7}$$

where $\bar{\sigma}$ is the Stefan–Boltzmann constant, n is the effective index of refraction, and Θ is the temperature, and β_R is defined by Eq. (8):

$$\frac{1}{\beta_R} = \int_0^\infty \frac{1}{\beta_\lambda^*} \frac{\partial e_{b\lambda}}{\partial e_b}\,\mathrm{d}\lambda \tag{8}$$

where e_b is the blackbody radiative emissive power.

The Rosseland approximation is valid when the medium absorbs and scatters isotropically. To take into account the foam anisotropic scattering, a weighted spectral extinction coefficient β_λ^* is used [Eq. (9)][13,14]:

$$\beta_\lambda^* = \kappa_\lambda + \sigma_\lambda^* \qquad \text{with} \qquad \sigma_\lambda^* = \sigma_\lambda(1 - \langle\cos\theta\rangle_\lambda)$$

$$\langle\cos\theta\rangle_\lambda = 0.5 \int_{-1}^{1} P_\lambda(\theta)\cos\theta d(\cos\theta) \tag{9}$$

The integral in Eq. (9) is calculated from the quadrature over the 24 directions used to solve the RTE.

IV. Application to a Polyurethane Foam Sample

The data of PU foam samples studied are described. Then the influence of the number of transmittance measurements on the identification results using combination of bidirectional transmittances and hemispherical measurements is analyzed. Radiative properties obtained from this approach are shown, and sensitivity coefficients are analyzed.

A. Data

Three specimens of different thicknesses of the same rigid open cells PU foam are studied: sample 1 ($ly = 310$ μm), sample 2 ($ly = 427$ μm), sample 3 ($ly = 528$ μm). Particle dimensions (as defined by Baillis et al.[4]) obtained from a microscopical analysis are strut thickness minimum 12.5 μm and maximum 17.5 μm. The foam density is 44 kg/m^3. The cell dimensions are 110 μm for longitudinal size in normal direction of the sample and 78 μm for transversal size. The sample diameter/cell diameter ratio is larger than 115, and so variation in results caused by the face nonhomogeneity are avoided. The sample thickness-to-cell-size ratio is larger than 2.8. It will be verified that nonhomogeneity influence weakly results. These three sample thicknesses seem to us to be a good compromise. Indeed, for larger sample thickness, energy transmitted is too weak and too noisy. For thinner samples the number of cells in the thickness is smaller.

Energy measured in the backward directions and in some forward directions is very small and noisy. Hence, only the directional transmittances near the normal direction for which there is enough energy and hemispherical measurements are used for identification. As a result, eight measurements ($N = 8$) are considered for each wavelength: 1) six directional transmittance measurements, Nos. $1, 2, \ldots, 6$, in the directions nearest to the normal corresponding to $\mu = 1$, 0.99948, 0.99832, 0.99631, 0.99359, and 0.99036, respectively; and 2) two hemispherical measurements, Nos. 7 and 8, for hemispherical transmittance and hemispherical reflectance, respectively. Two-hundred-eighty-six spectral transmittance or reflectance data points have been selected in the wavelength range ($2.2\ \mu\text{m} \le \lambda \le 15.3\ \mu\text{m}$).

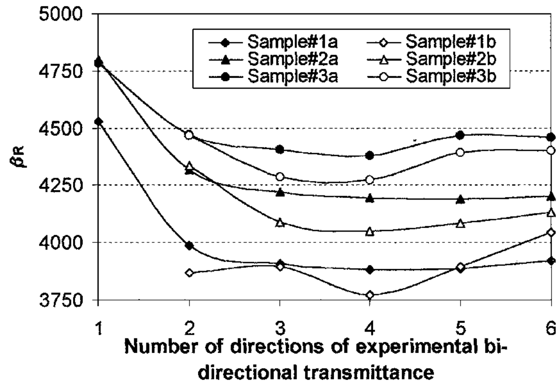
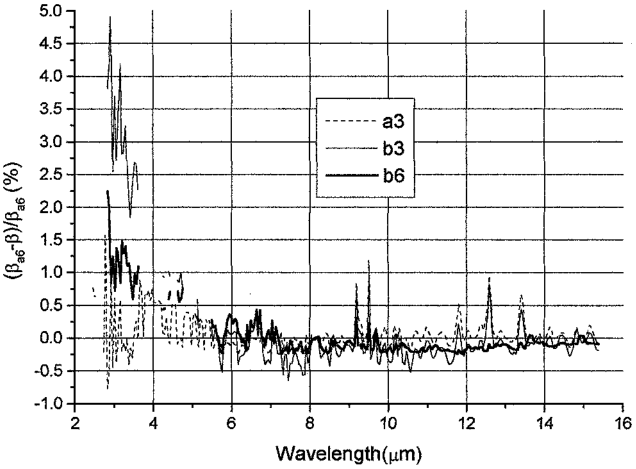


Fig. 2 Rosseland mean extinction coefficient calculated from identification results as function of the number of directions of experimental bidirectional transmittance for the three different sample thicknesses. Case a: bidirectional transmittance and hemispherical transmittance and reflectance are used for identification. Case b: bidirectional transmittance and only hemispherical transmittance are used. These cases are identified by suffix a and b for sample numbers.

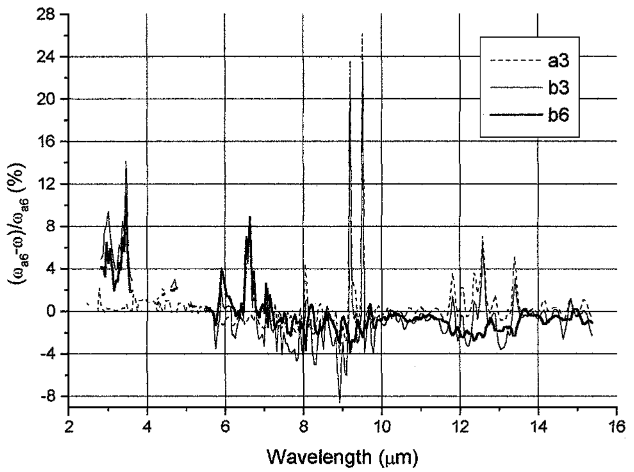
B. Influence of the Number of Transmittance Data Used on the Identification Results

If the model is correct and if there are no measurement errors, the identified values tend to converge to the same value as the number of directions of transmittance measurement used in the identification technique increases. In Fig. 2 Rosseland mean extinction coefficient β_R at 500 K obtained from identified values [Eq. (8)] for the three foam samples is shown as a function of the number of directions of experimental bidirectional transmittance used in the identification. Two cases with different measurements are considered: case a, bidirectional transmittance and hemispherical transmittance and reflectance; case b, bidirectional transmittance and only hemispherical reflectance. For each case (a or b), from a number of directions of bidirectional transmittance larger than two the percentage difference in values of Rosseland mean extinction coefficient is less than 6.7%. The difference between results obtained from case a or b with the same bidirectional measurements is less than 3.5%. As a result, only two directions of bidirectional transmittance and hemispherical reflectance seem to be necessary to identify radiative properties and to calculate Rosseland mean extinction coefficient. These results confirm the good behavior of the model.

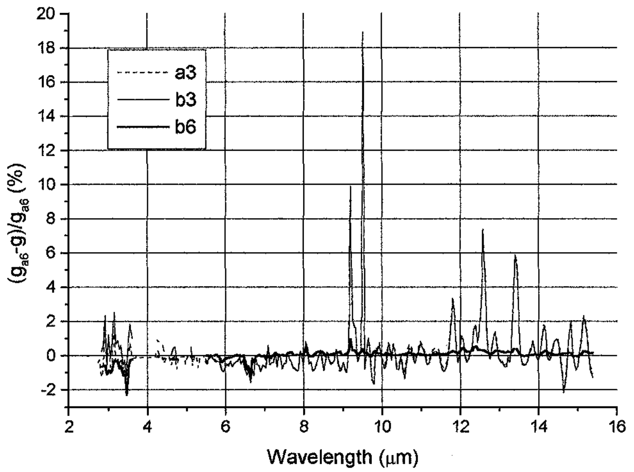
Moreover, the identified radiative properties corresponding to the cases a and b with three and six measurements of bidirectional transmittance are also compared. The case a3, a6 means case a with three and six measurements of bidirectional transmittance, respectively. In the same way case b3, b6 means case b with three and six measurements of bidirectional transmittance, respectively. The relative deviation between the identified results obtained from the case a for six measurements of bidirectional transmittance (case a6) and the other cases is shown for the sample 2 of 427 μm in Fig. 3. The relative deviation in the extinction coefficient is less than 5% and less than 1% for wavelengths larger than 3.6 μm. The relative deviations in the albedo coefficient and Henyey–Greenstein coefficient g are small except for only two wavelengths (9.2 μm, 9.5 μm) for cases



Extinction coefficient β

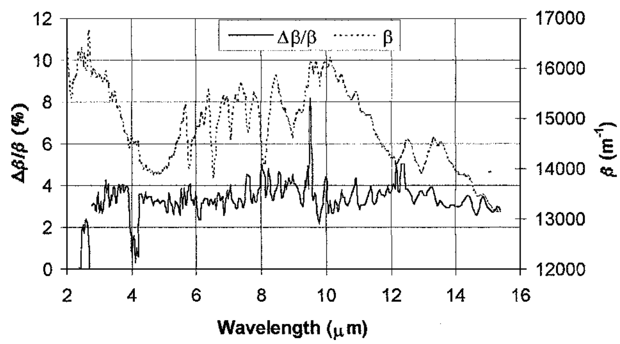


Albedo coefficient ω

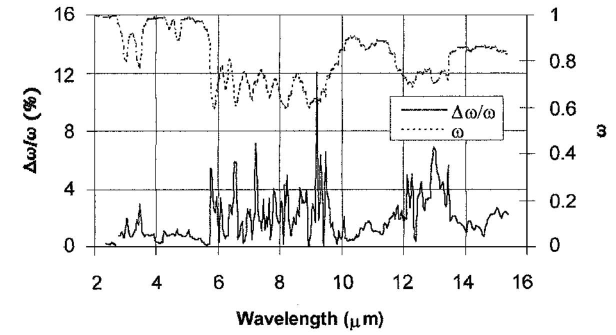


Henyey–Greenstein coefficient g

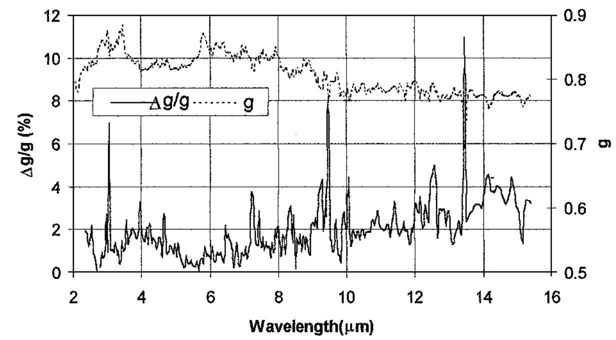
Fig. 3 Relative deviation between the identified parameters obtained from case a for six directions of bidirectional transmittance (case a6) and other cases a and b for three or six directions of bidirectional transmittance used in the identification (cases a3, b3, b6). Sample 2 of 427 μm.



Extinction coefficient



Scattering albedo



Henyey–Greenstein coefficient

Fig. 4 Radiative properties (average values and relative mean square deviation) calculated over the three different sample thicknesses obtained for case a6 (six bidirectional transmittance and hemispherical measurements) as function of wavelength.

a3 and b3. These deviations are accounted for by measurement errors for the direction six for these two wavelengths for this sample. This can be caused by the weak transmittances for directions other than $\mu = 1$ in the range of wavelengths (8–10 μm). As there are 286 measurement wavelengths, the deviations are generally small as is confirmed by the Rosseland mean extinction coefficient analysis. The good agreement observed between the two cases (a, b) tends to show that errors caused by the two types of measurement (bidirectional transmittance and hemispherical transmittance) influence little identified radiative properties. Though the different cases give nearly the same results, the case a6, with more measurements, seems to be preferable because for the other cases there is no convergence for some wavelengths smaller than 5 μm. As a result, the comparison of the identified results obtained for the different cases (case a or b with different numbers of bidirectional transmittances) have permitted verification of the good behavior of the model and also a confirmation of the fact that experimental errors influence identification results very little.

C. Radiative Properties—Average Values and Mean Square Deviation

For each specimen k ($k = 1, 3$) of different thickness $(ly)_{k=1,3} = (310, 427, 528\ \mu\text{m})$, the radiative coefficients are identified from six bidirectional transmittances and hemispherical transmittances and reflectances, by using the parameter identification method described in Sec. II. Then from these results $(\beta_\lambda)_{k=1,3}$, $(\omega_\lambda)_{k=1,3}$, $(g_\lambda)_{k=1,3}$, obtained for the three thicknesses, the average value of each parameter over the three specimens of different thicknesses is calculated. The three specimens coming from the same PU foam, these average values, correspond to radiative properties $\beta_\lambda, \omega_\lambda, g_\lambda$, of the PU foam studied. The relative mean square deviation Δp_j is also calculated.

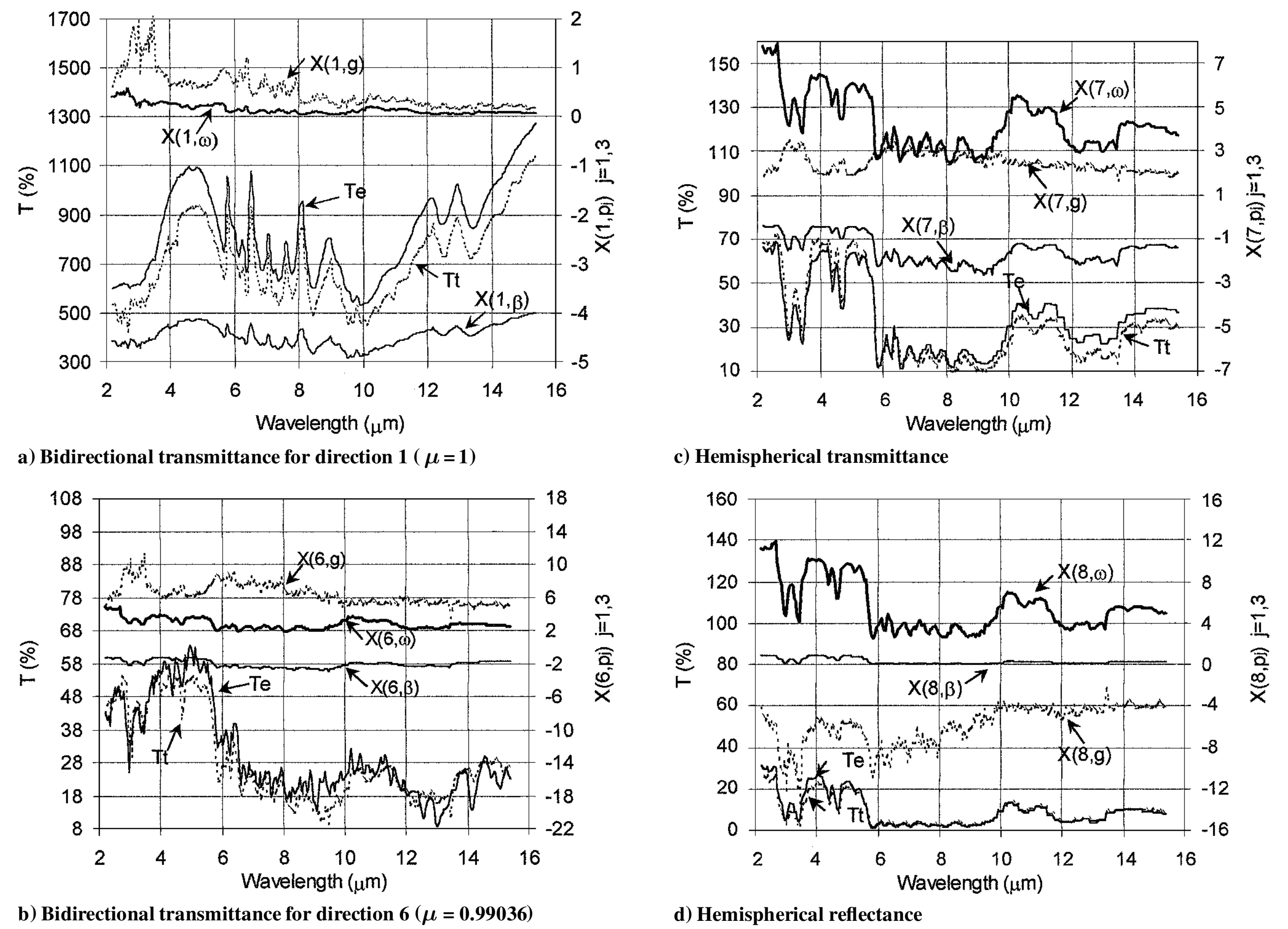
$$\overline{p_j} = \frac{1}{3}\sum_{k=1}^{3} p_{jk}, \qquad p_1 = \omega_\lambda,\ p_2 = \beta_\lambda,\ p_3 = g_\lambda \tag{10}$$

$$\Delta p_j = \frac{1}{\overline{p_j}}\sqrt{\frac{1}{2}\sum_{k=1}^{3}(p_{jk} - \overline{p_j})^2} \tag{11}$$

Radiative coefficients and relative mean square deviation are shown in Fig. 4. The extinction coefficients remain between 13,000 and 17,000 m^{-1}. The albedo varies between 0.6 and 1. The Henyey–Greenstein phase function parameter varies between 0.75 and 0.9. The relative mean square deviation calculated over the three different thicknesses is smaller than 5% except for very few wavelengths for which it still remains smaller than 12%. These few peaks are caused by experimental measurement errors, transmittances other than for direction $\mu = 1$ being weak in the range of wavelengths 6–10 and 12–14 μm (Figs. 5 and 6). More particularly, peaks at 9.2 and 9.5 μm, which are observed again, are as a result of the measurement error for the sample 2, for the direction six as discussed before. The generally small relative mean square deviation over the three different thicknesses confirms the validity of results and shows that the influence of the nonhomogeneous distribution of material remains weak. The mean square deviation is not calculated around 2.7 μm, because identification has converged only for one sample thickness for this wavelength.

D. Sensitivity Coefficient–Comparison Between Experimental and Theoretical Transmittances and Reflectances

From the average identified radiative properties introduced in the radiative transfer model described in Sec. II.D., theoretical



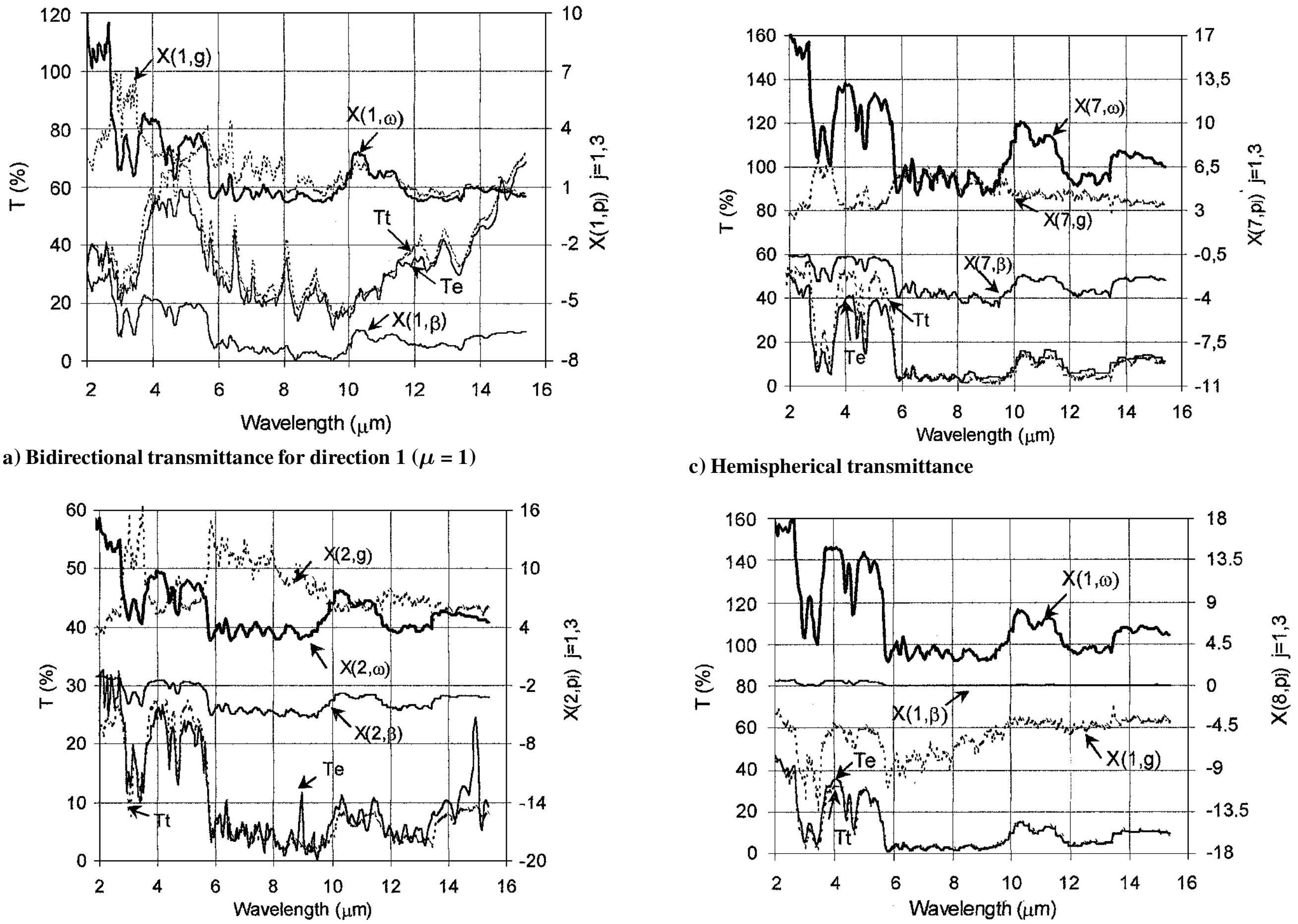
a) Bidirectional transmittance for direction 1 ($\mu = 1$)

c) Hemispherical transmittance

b) Bidirectional transmittance for direction 6 ($\mu = 0.99036$)

d) Hemispherical reflectance

Fig. 5 Theoretical and experimental results of transmittance or reflectance (Te, Tt) and normalized sensitivity coefficients (X) as function of wavelength for sample thickness 310 μm.



a) Bidirectional transmittance for direction 1 (μ = 1)

c) Hemispherical transmittance

b) Bidirectional transmittance for direction 2 (μ = 0.99948)

d) Hemispherical reflectance

Fig. 6 Theoretical and experimental results of transmittance or reflectance (*Te*, *Tt*) and normalized sensitivity coefficients (X) as function of wavelength for sample thickness 528 μm.

transmittances and reflectances and sensitivity coefficients are calculated for the three different thicknesses. To limit the number of graphs, results are only shown for the thinnest and thickest sample thickness of 310 and 528 μm (Figs. 5 and 6). A good agreement can be observed between experimental and theoretical results. This is not an independent check because theoretical results are obtained from the identification method using the same experimental results. Bidirectional transmittances can reach values larger than 100% as a result of the definition Eq. (3).

For the three different thicknesses the plots have the same general shape, and the following observations can be made. For normal direction the β sensitivity is the larger. It can be deduced that direction 1 plays an important role in determining β (Figs. 5a and 6a). For directions two to six, sensitivity coefficient and transmittances are nearly the same; also only results for directions two or six are shown (Figs. 5b and 6b). For these directions, compared to direction 1, β sensitivity decreases, and the sensitivity of ω and g increases. The g sensitivity is the larger. For hemispherical transmittance ω sensitivity coefficient is the larger (Figs. 5c and 6c). For hemispherical reflectance the β sensitivity is nearly zero, and g and ω sensitivity coefficients are large (Figs. 5d and 6d).

Moreover, as the thickness increases sensitivity coefficients increase slightly, and as expected transmittances decrease (especially for direction 1), and reflectance increases.

V. Conclusions

In this work radiative properties (β_λ, ω_λ, g_λ) of open cells PU foam are determined using a combination of hemispherical transmittances and reflectances and bidirectional measurements in the wavelength range 2–15 μm. As there is insufficient energy in the other directions, only six bidirectional transmittances near the normal direction can be taken into account. The following conclusions can be drawn from these measurements and identification:

1) Analysis of the influence of the number of transmittance measurements on the identification results permits the verification of the good behavior of the model and the quantification of some experimental errors for some measurement directions and some wavelengths. For the number of bidirectional transmittance directions larger than two, results converge nearly to the same value of Rosseland mean extinction coefficient β_R. The relative deviation in radiative properties obtained for three directions and six directions, with or without hemispherical transmittance, remains small except for very few wavelengths. For these wavelengths measurement errors are caused by the weak and noisy transmittances for some directions. In spite of this, globally these deviations remain small. The good agreement observed between the two cases, one with hemispherical transmittance and the other without it, tends to show that errors caused by the two different types of measurement (bidirectional transmittance and hemispherical transmittance), or caused by measurement errors for some directions, have little influence on identification results. Though the different cases give nearly the same results, the case a6 having more measurements seems to be preferable because for the other cases there is no convergence for some wavelengths smaller than 5 μm.

2) Radiative properties average over the three sample thicknesses and mean square deviations of these properties are calculated from identifications. The case (a6) with six bidirectional transmittances and hemispherical measurements is considered. The small relative mean square deviations over the three different thicknesses confirm the validity of results. The influence of the nonhomogeneous

distributions of materials appears to be weak. It can be observed that an Henyey–Greenstein phase function parameter g of around 0.8 seems representative for the PU foam samples.

3) Sensitivity coefficients show that the combination of hemispherical measurements and bidirectional transmittances provides complementary information useful in the identification process. Bidirectional transmittance in direction 1 plays a major role in identifying β, the sensitivity of β being largest for this direction. Directions two to six are useful to identify g parameter, the sensitivity of g being the larger for these directions. For hemispherical transmittance and reflectance it is the sensitivity of ω, which is the largest.

Acknowledgments

The authors thank J. Kuhn, who initiated the collaboration between ZAE Bayern and INSA Lyon, and M. Arduini Schuster for conducting hemispherical transmittance and reflectance measurement. They also acknowledge Imperial Chemical Industries Polyurethane of Belgium who provided the samples for testing.

References

[1]Glicksman, L. R., and Torpey, M. R., "A Study of Radiative Heat Transfer Through Foam Insulation," Massachusetts Inst. of Technology, Subcontract 19X-09099C, Cambridge, MA, Oct. 1988.

[2]Glicksman, L. R., Marge, A. L., and Moreno, J. D., "Radiation Heat Transfer in Cellular Foam Insulation," *Developments in Radiative Heat Transfer ASME*, edited by S. T. Thynell, Vol. 203, American Society of Mechanical Engineers, New York, 1992, pp. 45–54.

[3]Kuhn, J., Ebert, H. P., Arduini-Chuster, M. C., Büttner, D., and Fricke, J., "Thermal Transport in Polystyrene and Polyurethane Foam Insulations," *International Journal of Heat and Mass Transfer*, Vol. 35, No. 7, 1992, pp. 1795–1801.

[4]Baillis, D., Raynaud, M., and Sacadura, J. F., "Spectral Radiative Properties of Open Cell Foam Insulation," *Journal of Thermophysics and Heat Transfer*, Vol. 13, No. 3, 1999, pp. 292–298.

[5]Skocypec, R. D., Hogan, R. E., Jr., and Muir, J. F., "Solar Reforming of Methane in a Direct Absorption Catalytic Reactor on a Parabolic Dish: II-Modeling and Analysis," *Proceedings of the American Society of Mechanical Engineers–ASME 2nd International Solar Energy Conference*, edited by T. R. Mancini, K. Watanabe, and D. E. Klett, American Society of Mechanical Engineers, New York, 1991, pp. 303–310.

[6]Hale, M. J., and Bohn, M. S., "Measurements of the Radiative Transport Properties of Reticulated Alumina Foams," *Proceedings of the American Society of Mechanical Engineers/American Solar Energy Society Joint Solar Energy Conference*, edited by A. Kirkpatrick and W. Worek, American Society of Mechanical Engineers, New York, 1993, pp. 507–515.

[7]Hendricks, T. J., and Howell, J. R., "Absorption/Scattering Coefficients and Scattering Phase Functions in Reticulated Porous Ceramics," *Journal of Heat Transfer*, Vol. 118, No. 1, 1996, pp. 79–87.

[8]Nicolau, V. P., Raynaud, M., and Sacadura, J. F., "Spectral Radiative Properties Identification of Fiber Insulating Materials," *International Journal of Heat and Mass Transfer*, Vol. 37, Suppl. 1, 1994, pp. 311–324.

[9]Moura, L. M., Baillis, D., and Sacadura, J. F., "Identification of Thermal Radiation Properties of Dispersed Media: Comparison of Different Strategies," *Heat Transfer, Proceedings of 11th IHTC*, edited by J. S. Lee, Vol. 7, Seoul, Republic of Korea, 1998, pp. 409–414.

[10]Beck, J. V., and Arnold, K. J., *Parameter Estimation in Engineering and Science*, Wiley, New York, 1977, Chap. 7, pp. 334–418.

[11]Raynaud, M., "Strategy for Experimental Design and Estimation of Parameters," *High Temperatures-High Pressures*, Vol. 31, No. 1, 1999, pp. 1–15.

[12]Nicolau, V. P., "Identification des Propriétés Radiatives des Matériaux Semi-Transparents Diffusants," Ph.D. Dissertation 94 ISAL. 0001, Dept. of Thermal Energetics, Inst. National des Sciences Appliquées de Lyon, France, Jan. 1994.

[13]Doermann, D., and Sacadura, J. F., "Heat Transfer in Open Cell Foam Insulation," *Journal of Heat Transfer*, Vol. 118, No. 1, 1996, pp. 88–93.

[14]Baillis, D., Raynaud, M., Sacadura, J. F., "Determination of Spectral Radiative Properties of Open Cell Foam. Model Validation," *Journal of Thermophysics and Heat Transfer*, Vol. 14, No. 2, 2000, pp. 137–143.