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Experimental characterization and theoretical modeling of the infrared-optical properties and the thermal conductivity of foams

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ABSTRACT

In order to understand and improve the thermal insulation performance of cellular polymeric foams, two different polymers and corresponding foams, extruded polystyrene foam (XPS) and Polyurethane foam (PUR) were selected and thoroughly characterized at ZAE Bayern. At first radiative properties, cell morphology and thermal conductivity were characterized. The measured results were then compared to the theoretical model developed at ZAE Bayern. The validated model allows then the prediction of the insulation performance of an arbitrary XPS or PUR foam with given density and geometrical structure. It also allows defining the optimal structure (resin, cell morphology, density) to achieve the desired thermal conductivity.

1. Introduction

Buildings are at the core of the European Union's prosperity, and they represent about 40% of all energy consumption in Europe and generate about 33% of Green House Gases. Among all the energy measures, building insulation appears to be the most efficient way to improve and reduce the carbon foot print. It is therefore important to develop an insulation material that can be effectively implemented in energy efficient buildings: efficient isolation, compliance with standards, environmental and safety regulations, cost-effectiveness and easiness of installation and high durability.

Conventional insulating materials such as polystyrene foam and polyurethane foam were developed and commercialized for decades. The characterization of the product performance and the thermal insulation modeling were comprehensively reported for instance in Ref. [1].

In this report, the goals are to understand the impact of the resin architecture and the cell morphology which determine the conductive and radiative heat transfer. The measured properties will then be used to develop and validate the thermal conductivity model. The understanding of the impacts of resin properties, cellular structure and mass transport will help to design the insulating foam product that offers the highest thermal performance at the optimum cost.

2. Material selection

Two foams of different polymers (polystyrene and polyurethane) were selected for this study. The foams were obtained at two different foaming technologies. The polystyrene foam (XPS) from DOW is obtained through the extrusion foaming process, using carbon dioxide as the main blowing agents. The polyurethane foam (PU), a product of Efisol – Soprema, is obtained from a reactive foaming process, with MDI and polyol using isopentane as blowing agent. Basic foam properties can be seen in Table 1.

The infrared-optical properties of the XPS-foam specimen and of the PUR-foam specimen are investigated in detail. At first, infrared-optical measurements of both foams are performed. From the spectral effective specific extinction coefficient e^*_Λ in the wavelength range between 1.4 μm and 35 μm the total effective specific extinction coefficient at ambient temperature and the radiative thermal conductivity are derived. Moreover a calculated specific extinction coefficient by using Mie-theory is compared with the experimental one in order to validate the model. The total thermal

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Nomenclature

a_Λ	spectral specific absorption coefficient
D	thickness of the sample
d_{wall}	thickness of the walls
e^*_Λ	spectral effective specific extinction coefficient
$e^*(T)$	total effective specific extinction coefficient
e^*_{strut}	spectral effective specific extinction coefficient of the struts
e^*_{wall}	spectral effective specific extinction coefficient of the walls
$\mathrm{f}_{\mathrm{R}}(\Lambda,T)$	Rosseland weight function
f_{strut}	volume fraction of the struts
$i_{\mathrm{B}}(\Lambda,T)$	spectral intensity emitted by a black body at a given wavelength Λ and temperature T
$i_{\mathrm{B,t}}(T)$	total intensity emitted by a black body at a given temperature T
k	imaginary part of the complex refractive index of the bulk material
K_{n}	Knudsen number
L_Λ	mean free path of thermal radiation in the medium
m	mass of the foam-sample
n	real part of the complex refractive index of the bulk material
q_{c}	heat flux caused by solid and gaseous thermal conduction
q_{gas}	heat flux caused by gaseous thermal conduction
q_{rad}	heat flux caused by radiation
q_{sol}	heat flux caused by solid thermal conduction
s^*_Λ	spectral effective specific scattering coefficient
T	temperature
T_{rad}	radiative temperature (approx. mean temperature)
V_{cell}	volume occupied by a cell
V_{strut}	cell struts volume
V_{wall}	cell walls volume
x	geometrical coordinate
β	coefficient which depends on the gas and the Knudsen number K_{n}
δ_{m}	gas mean free path
ε	emittance of the surrounding
Φ_{strut}	diameter of the struts
Φ_{wall}	diameter of the walls
λ_{bulk}	solid thermal conductivity of the bulk material
λ_{c}	thermal conductivity due to solid and gaseous thermal conduction
λ_{gas}	thermal conductivity due to gaseous thermal conduction
$\lambda_{\mathrm{gas,0}}$	initial gaseous thermal conductivity
λ_{rad}	radiative thermal conductivity
λ_{sol}	thermal conductivity due to solid thermal conduction
Π	porosity of the foam
ρ	density of the foam
ρ_{bulk}	bulk density
σ	Stefan–Boltzmann-constant ($5.67 \cdot 10^{-8}$ W/(m$^2 \cdot$K^4))
$\omega^*_{0,\Lambda}$	spectral effective albedo

conductivity was also measured by using a guarded hot plate apparatus.

3. Experimental determination of the infrared optical properties

The experimental characterization of thermal radiation properties of dispersed media is also well discussed for instance in Ref. [2]. In this work the foams were measured at ZAE Bayern using a Fourier Transform Infrared (FTIR) spectrometer Bruker Vertex 70v in the wavelength range from 1.4 μm to 35 μm, which is decisive for the radiative thermal transport at ambient temperature [3].

For the infrared measurements several thin platelets were cut from each foam, perpendicular to the specimen thickness and to the thermal radiation flow (S direction). The dimensions of the platelets are about 20 mm × 20 mm with different thicknesses. The samples are then placed in the opening of an integrating sphere, which is coupled to the FTIR-spectrometer, for measuring transmittance and reflectance. The sample is irradiated normal to the surface and the radiation reflected into the front side hemisphere or transmitted into the rear side hemisphere is measured for the transmittance or reflectance spectra, respectively. Several samples with different thicknesses were measured in order to consider eventual inhomogeneities in the foam and to guarantee a sufficiently good average measurement value. For calculating the spectral effective specific extinction coefficient e^*_Λ, the mass per area m'' of each sample was also determined.

Table 1
Description of the samples.

Sample number	Foam material	Density (kg/m^3)	Compressive strength (kPa)
1	XPS	32.5 ± 0.5	401 ± 27
2	PU	38.5 ± 0.5	422 ± 6

From the measured spectral directional-hemispherical transmittance T_{dh} and reflectance R_{dh}, the spectral effective specific extinction coefficient e^*_Λ and the spectral effective albedo ω^*_Λ of each specimen were calculated, using a certain solution of the equation of radiative transfer, the so called three-flux solution [4]. The three-flux solution allows to quantify the radiative transfer through scattering and absorbing media as well as to determine the spectral scattering and absorption coefficients of the investigated specimens.

3.1. Definition terms of the radiative heat transfer

3.1.1. Spectral extinction coefficient

The spectral specific extinction coefficient e_Λ is a measure for the attenuation of radiation within the samples. It includes scattering and absorption processes within the material. The influence of anisotropic scattering on radiative transfer can be enclosed by scaling to the so called effective quantities, marked with a star (s^*_Λ, e^*_Λ und $\omega^*_{0,\Lambda}$) [4,5]. The spectral effective specific extinction coefficient e^*_Λ is given by the sum of the spectral effective specific scattering coefficient s^*_Λ and spectral specific absorption coefficient a_Λ [6]:

$$e^*_\Lambda = s^*_\Lambda + a_\Lambda \quad \left[\frac{\mathrm{m}^2}{\mathrm{kg}}\right]. \tag{1}$$

The reciprocal of the product of the spectral effective specific extinction coefficient e^*_Λ and the density ρ of the foam is the mean free path L_Λ of thermal radiation in the medium, i.e. the path before scattering or absorption takes place: