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Optical parameters for characterization of thermal radiation in ceramic sponges – Experimental results and correlation

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ABSTRACT

Structured ceramic elements are often used in chemical engineering processes for optimization or increasing the efficiency of technical equipment. Knowledge of the thermal properties, including heat conduction and thermal radiation effects, of these elements is necessary for designing high temperature applications. Well-known elements are honeycombs or packed beds. These have recently been substituted by sponges (open-cell foams) due to several advantageous properties. Regarding this material, only a few, but not sufficient, investigations on radiative heat transfer exist in the literature to date.

In this publication, experimental results for the spectral transmittance and reflectance obtained by Fourier transform infrared spectrometry (FTIR) for different ceramic sponges (variations of material, porosity and cell density) are presented. Within these parameters, the total extinction coefficient (here: Rosseland extinction coefficient) and the total emissivity of the different sponges investigated are determined. The total extinction coefficient reveals a strong dependency on cell size and porosity while the total emissivity only depends on porosity. These optical parameters allow the estimation of radiative heat transfer in ceramic sponges. Furthermore, an empirical correlation for predicting the total extinction coefficient from the window diameter is proposed. The radiative part of the thermal conductivity of ceramic sponges can be estimated using the Rosseland extinction coefficients obtained.

1. Introduction

Open-cell foams are solid network structures with high porosities typically of about 75–95%. The notation "sponge" is used to differentiate between these and classic foams (solid phase with gas bubbles separated from each other). A photograph of a typical ceramic sponge made of Al_2O_3 is shown in Fig. 1. The light microscopy picture on the right-hand side gives an impression of the network structure and identifies some of the characteristic lengths of sponges (cell diameter, strut diameter, window diameter).

Sponges combine the advantages of conventional structures (packed beds and honeycombs) while the disadvantages of these structures are reduced. Advantages include high specific surface areas, low pressure drops and good radial mixing [1]. The continuous solid phase offers advantageous heat transfer properties. Sponges have a significantly higher thermal conductivity compared to packed beds of spherical particles. This fact is of special interest for chemical reactors in which high exothermic reactions are performed. Potential technical applications for sponges are porous burners, solar receivers, carriers for catalysts, heat insulation and heaters [2,3].

Reliable correlations for the two-phase heat transfer at high temperatures are necessary to describe the heat transfer inside these technical applications. Depending on the design of the technical equipment and on the level of resolution of the processes required, a heterogeneous or a homogeneous model can be used for heat transfer calculations. Using a heterogeneous model, the fluid and the solid phase are considered separately. The transport equations are coupled by a term describing the heat transfer from the fluid to the solid phase. This term contains the heat transfer coefficient, which is the key parameter in this model. Using the homogeneous model, the sponge is considered to be a quasi-continuous medium with superposed properties. Here, the key parameters are the axial and radial two-phase thermal conductivity (often called "effective thermal conductivity" in the literature). The transport equation for this model is given in Eq. (1). Knowing the two-phase thermal conductivity in both the radial and the axial direction, the heat transfer and the temperature field inside the sponge can be calculated.

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Nomenclature

Latin symbols

a_v	spectral absorption coefficient, m^{-1}
Al_2O_3	α-Alumina
c	light velocity, 3×10^8 ms^{-1}
C	constant
d_{cell}	cell size, m
d_{window}	window diameter, m
d_{strut}	strut diameter, m
E_R	Rosseland extinction coefficient, m^{-1}
E_v	spectral extinction coefficient, m^{-1}
h	Planck constant, 6.626×10^{-34} J s
I_v	spectral intensity of radiation, W m^{-2}
$I_{v,s}$	spectral intensity of black body radiation, W m^{-2}
k	Boltzmann constant, 1.38×10^{-23} J K^{-1}
L	sample length, m
OBSiC	Oxidic-Bonded Silicon Carbide
ppi	pores per inch
$\dot{q}$	heat flux density, W m^{-2}
R	total reflectance
R_v	spectral reflectance
s_v	spectral scattering coefficient, m^{-1}
T	temperature K
T_v	spectral transmittance
x	x-coordinate
z	z-coordinate

Greek symbols

Δ_{error}	mean error
ϵ	total emissivity
ϵ_v	spectral emissivity
Θ	angle
Λ_L	wavelength, μm
Λ_N	wavenumber
λ	thermal conductivity, W m^{-1} K^{-1}
v	frequency of radiation, s^{-1}
σ	Stefan–Boltzmann constant, 5.67×10^{-8} W m^{-2} K^{-4}
φ	angle
ψ	porosity

Subscripts

ax	axial
conduction	conduction
mono	monochromatic
net	net
r	radial
radiation	radiation
total	total
v	spectral
2ph	two-phase

$$\frac{\partial}{\partial t}((\psi \cdot \rho_f \cdot c_{p,f} + (1-\psi) \cdot \rho_s \cdot c_{p,s}) \cdot T) + u_z \cdot \frac{\partial}{\partial z}(\rho_f \cdot c_{p,f} \cdot T) = \frac{\partial}{\partial r}\left(\lambda_{2ph,r} \cdot \frac{\partial T}{\partial r}\right) + \frac{1}{r} \cdot \lambda_{2ph,r} \cdot \frac{\partial T}{\partial r} + \frac{\partial}{\partial z}\left(\lambda_{2ph,ax} \cdot \frac{\partial T}{\partial z}\right) \quad (1)$$

where ψ is the porosity, ρ the density, c_p the specific heat capacity, T the temperature, t the time, $\lambda_{2Ph,r}$ and $\lambda_{2Ph,ax}$ the two-phase thermal conductivity in radial and axial direction, u_0 the superficial air velocity, r the radial (perpendicular to the flow direction) co-ordinate and z the axial (in flow direction) co-ordinate. The index f denotes the fluid and s the solid phase. This contribution is focused on high temperature heat transfer without flow ($u_0 = 0$ ms^{-1}) using the homogeneous model for calculating temperature profiles. Under these conditions heat transport by thermal radiation is significant and cannot be neglected [4,5]. Two concepts exist in literature for considering both heat conduction and thermal radiation in the model stated in Eq. (1). In both concepts the two-phase thermal conductivities, $\lambda_{2Ph,r}$ and $\lambda_{2Ph,ax}$, are modeled. The first approach is based on the consideration of a unit cell of the porous medium and is called the Zehner–Bauer–Schlünder model. This kind of model was successfully applied on packed beds [6]. The second approach considers the two-phase thermal conductivities in that way that the two mechanisms, heat conduction and thermal radiation, can be treated separately. Thus, the two-phase thermal conductivities can be calculated by summing up the conductive and the radiative contributions as stated in Eq. (2). This is generally valid for optical thick samples with small free path of thermal radiation and small local temperature gradients in the sample due to the highly temperature dependence of thermal radiation [7,8]. In the past, some authors applied this approach also successfully on different kind of sponge types [4,5,8–13].

$$\lambda_{2ph,i} = \lambda_{2ph,conduction,i} + \lambda_{2ph,radiation} \quad \text{with} \quad i = r, ax \quad (2)$$

The two-phase thermal conductivity due to conduction ($\lambda_{2ph,conduction,i}$) was determined in previous experiments by Dietrich et al. [14]. The determination of the radiative two-phase thermal conductivity ($\lambda_{2ph,radiation}$) was realized in recent investigations. This publication reports on the experimental results as well as an

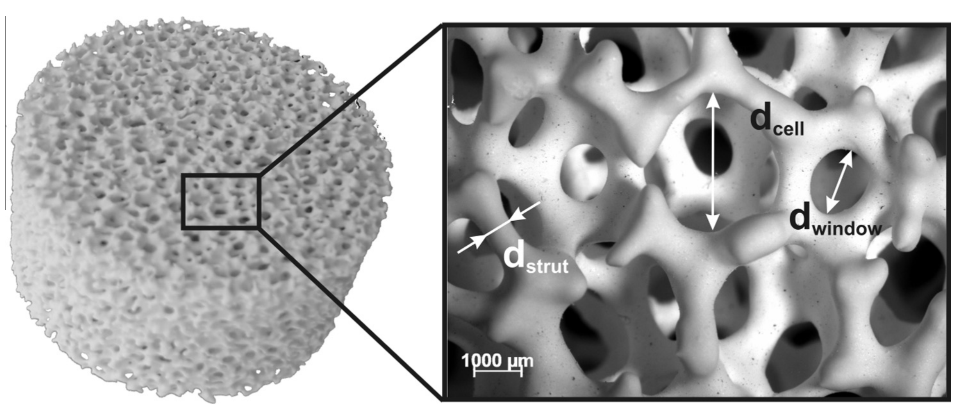

Fig. 1. Left: photograph of a typical ceramic sponge (made of Al_2O_3), right: light microscopy picture to illustrate the network structure.