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Virtual enclosure model for thermal radiation extinction inside porous materials with closed cell structure

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ABSTRACT

We present a virtual enclosure model for thermal radiation extinction in porous materials. The geometrical structure of the model is based on series of cuboid enclosures. The key conjecture of the model is that the mean free distance of photons emitted from the real cell can be applied for finding a virtual enclosure with opaque, isothermal and diffusive surfaces. This leads into the applicability of the view factor analysis of the virtual structure providing an efficient method for evaluation of the otherwise highly complex radiation interaction between large numbers of consecutive unit cells. The model is applied to analyzing how the cell configuration affects radiative extinction properties of materials with a wide range of complex refractive indices. It is shown, e.g., that an optimum cell configuration (size, wall thickness, aspect ratio) which minimizes radiative power can be detected for materials with sufficiently high ratio between the real and imaginary part of the refractive index. In addition, it is shown that for materials with high radiation extinction properties closed cell structures have superior radiation extinction properties as compared to open cell structures.

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1. Introduction

Thermal radiation through porous materials is an important part of overall heat transfer phenomena in many applications. Such materials include e.g. insulation, fluidized and packed beds, catalytic reactors, thermal protective, soot and fly-ash. Efficient optimization by modeling of the radiative properties is an important factor for predicting thermal radiation through porous materials, and for constructing new materials.

A starting point for a fundamental study of thermal radiation in porous materials is the Maxwell's equations for electromagnetics. However, the complex and often irregular nature of the physical structure of porous materials makes it difficult to use such an approach.

Several alternative methods for thermal radiation inside porous materials are presented in literature. Two basic approaches for the solution of radiative heat transfer in porous material are typically applied. In a continuum approach, the governing equations are derived by using the principle of energy conservation. Typically, methods based on the radiative transfer equation (RTE), which is an integro-differential equation, are applied [1].

In a discontinuous model the material is constructed of individual particles or cells. The radiative transfer in each cell can be computed by macroscopic methods, such as ray tracing or Monte Carlo simulation. These models consume much CPU time for the analysis of radiation in porous materials [2].

We present an alternative type of discontinuous closed cell model based on cuboid enclosures. We propose that by applying the mean free distance of photons, a virtual cuboid enclosure in which surfaces can be treated as diffusive, opaque and isothermal with uniform radiosity, can be found. This leads to an efficient computation method which is suitable for wide range of porous structures.

2. Model geometry

The porous material is assumed to be formed of cuboid enclosures (Fig. 1) with inner height b, inner length and width a, and thickness of the wall separating the adjacent cells s. The aspect ratio of the cuboid is

$$r = \frac{a}{b} \quad (1)$$

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Nomenclature

a	width of the cell, m
A	surface area, m^2; absorptance
b	height of the cell, m
E	emissive power, W/m^2
f	log-normal based fraction
F	view factor
i, j, k	number of xy-, xz- and yz-planes, respectively
I	radiation intensity, W/(m^2 sr)
J	radiosity, W/m^2
k	imaginary part of complex refractive index
k_R	radiative conductivity
n	real part of complex refractive index
N	number of cells
p	probability
q	radiative power, W
r	aspect ratio
s	thickness of the cell wall, m
S	thickness of a full dense material, m
T	temperature, K; transmittance
α	absorptivity
β	phase shift
Γ	radiative transmission efficiency
ε	emissivity
θ, φ, β	angles of incidence on xy-, xz-, and yz-planes, respectively
λ	wavelength, m
ρ	density of the porous material, kg/m^3; reflectivity
ρ_s	density of the full dense material, kg/m^3
σ	Stefan–Boltzmann constant, W/(m^{2}K^4)
τ	internal transmissivity
Φ	porosity
ω	solid angle

Superscripts

$'$	directional
$''$	per surface area
$\hat{}$	mean value
$\sim$	virtual

Subscripts

b	black body
$bead$	interbead
C	cold outer surface of material
H	hot outer surface of material
IM	intermediate
min	minimum
opt	optimal
λ	spectral

The porosity Φ of the porous material can be written as

$$\Phi = 1 - \rho/\rho_s = \frac{r^2 b^3}{(rb+s)^2(b+s)} \quad (2)$$

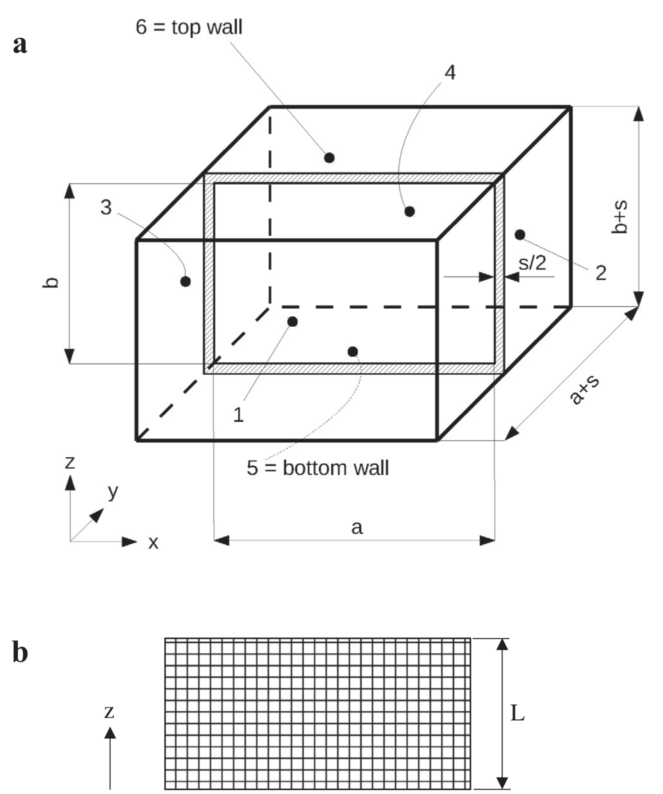

Fig. 1. Geometry of the closed cell porous structure model. (a) A single unit cell (a is the cell inner length and width, b is the cell inner height, s is the thickness of the wall separating the adjacent cells), (b) network of cells (L is the thickness of the material).

where ρ is the density of the porous material and ρ_s the density of the full dense solid material from which the porous material is composed of. For $r = 1$ we get the cell wall thickness from Eq. (2)

$$s = \frac{\left(1 - \Phi^{\frac{1}{3}}\right)b}{\Phi^{\frac{1}{3}}} \quad (3)$$

The total thickness L of the porous material is assumed to be small compared to its width and length. The material consists of N successive hollow cuboids in direction of the thickness:

$$N = \frac{L-s}{b+s} \approx \frac{L}{b+s} \quad (4)$$

3. Radiative power in cuboid based closed cell porous material

3.1. Opaque cell walls

First we derive the radiative power for a single cuboid enclosure in a network structure consisting of opaque walls. Temperature gradients exist only in the direction of the thickness of the material (direction of z-axis in Fig. 1). This means that radiative heat transfer through the network of porous cells can be considered as one-dimensional.

The walls are considered opaque, diffusive emitters and reflectors with constant spectral radiosity J_λ at each wall. According to these assumptions the standard view factor based analysis is valid for a single cuboid enclosure. For the surface i, the spectral radiative power $q_{\lambda i}$ for the cuboid enclosure of Fig. 1 can be determined from

$$q_{\lambda i} = \sum_{j=1}^{6} A_i F_{ij}(J_{\lambda i} - J_{\lambda j}) \quad (5)$$

where J is the radiosity, and F is the view factor. Surface areas of the side walls of the cuboid are $A_1 = A_2 = A_3 = A_4 = ab$ and for the bottom and top surfaces $A_5 = A_6 = a^2$. The spectral radiative power can be also given as

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