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Statistical characterization of near-wall radiative properties of a statistically non-homogeneous and anisotropic porous medium

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ABSTRACT

The radiative properties statistical characterization method of Tancrez and Taine has been extended to statistically anisotropic and *non-homogeneous* porous media. When a homogenized phase of such a medium does not follow Beer's law on extinction, extinction and scattering coefficients have no physical meaning: the phase is completely characterised by an extinction cumulative distribution function, a scattering cumulative probability, a general phase function and an effective optical index. A simple expression of the emission source term, in local thermal equilibrium conditions, is given for any non-homogeneous and anisotropic porous medium. The radiative transfer can be modelled by a Generalized Radiative Transfer Equation that is also extended to non-homogeneous porous media. This characterization method has been applied to the radiative properties of a packed bed of opaque and diffuse spherical particles bounded by a wall: the local porosity strongly varies near the wall and the homogenized phase is non Beerian. In the bulk of the medium, Beer's law becomes valid and extinction, absorption and scattering coefficients have been determined.

1. Introduction

Nowadays, porous media play an important role in many industrial fields such as catalytic combustion, chemical processes, nuclear reactors, insulating materials (foams, fibres or reticulated ceramics) [1,2]. Therefore, many investigations of heat and mass transfer in porous media have been carried out and many models for prediction and optimization of the involved industrial processes have been developed [3]. Since many processes involve high temperatures, a particular interest has been given to radiative transfer.

The limitation of today models of prediction of the radiative fluxes near the boundaries of spherical packed beds has been reported [4]. The authors suggest that either the characterization of the radiative properties or the radiative model are not valid. The specificity of the near-wall morphology and its consequences in terms of heat transfer have been reviewed [5] and a characterization of the morphology of a packed bed and its radiative conductivity has been developed [6]. However, the radiative Fourier law is not valid in the vicinity of a wall for strong temperature gradient [7]. Moreover this model, as most of the radiative models developed so far, postulates the Beer's law validity, *i.e.* that the transmittivity decays exponentially when the optical thickness increases. But the Beer's law is generally not valid in a statistically anisotropic medium [8].

Most of the authors have considered a Beerian behavior of the homogenised continuous medium associated with the porous medium or a phase of this medium. A review of the prediction of such effective radiative properties can be found in Ref. [9]. Early works have sought to determine the radiative properties of a packed bed by adding up the effect of each particle. Since the independent scattering theory fails to predict experimental and direct Monte Carlo simulation results of packed beds [10], scaling coefficients have been introduced [11–13]. Dependent scattering is however difficult to model for particles of complex shape and more advanced methods have thus been required. More generally, a common approach for determining the radiative properties of homogenised porous media, arbitrary assumed Beerian, is based on the parameter identification method: It consists of comparing the results of a given radiative model with reference data. The reference data can be either issued from experiments [14–16] or from simulation results [17]. The main issues of the parameter identification method are that: (i) A certain type of phase function is assumed (Henyey and Greenstein type or isotropic for instance); (ii) The determination of the radiative properties depends on chosen radiative transfer model, often based on Beer's law; (iii) The experimental uncertainty adds up to the limits of the identification technique.

Two general approaches have been developed in parallel in the last decade for non Beerian media: A spatial averaging method and a statistical one. The spatial averaging method applied to the

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Nomenclature

Latin symbols

A	specific area per unit volume of the whole porous medium
B	generalized extinction coefficient
D	particle diameter
d	spatial resolution
G	cumulated distribution function
g	asymmetry factor
I	extinction point
I_ν°	equilibrium intensity
K	generalized absorption coefficient
k^R	radiative conductivity
M	initial point in the fluid phase
n	optical index
$\mathbf{n}$	normal unit vector
P	cumulative probability
p	phase function
R	particle radius
s	curvilinear spatial coordinate
S	source term
T	temperature
$\mathbf{u}$	unit vector
v	pseudo-optical thickness
x	Cartesian spatial coordinate

Greek symbols

α	particle absorptivity
β	extinction coefficient
ε	validity criterion
δ	size of a voxel
$\mathbf{\Omega}$	solid angle
Π	porosity
θ, φ	Euler angle
μ	cosine of the angle θ
ν	frequency
η	generalized scattering coefficient

Indexes

a	absorption
b	at the boundaries
e	emission
eff	effective
ext	extinction
i	incident
l	leaving
r	reflected
sc	scattering
$'$	current point
1	related to the scattered ray
$^+$	non dimensional

radiative transfer equation has been introduced by Consalvi et al. [18]: For a transparent gas phase and several opaque particle phases, the authors have introduced the notions of local mean temperature and intensity and have developed a multiphase radiative transfer equation. More recently, the spatial averaging method has been extended to two-phase media [1], multi-phase media [19], packed beds and reticulated media [20].

A statistical method has been proposed by Tancrez et Taine for characterizing the radiative properties of a priori non-Beerian porous medium [8]. A semi-transparent homogenised phase associated with the opaque interfaces of a porous medium is completely characterized by statistical functions [8,21], *i.e.*:

(i) A cumulative distribution function of extinction $G_{ext}(M,\mathbf{u},v)$ which represents the probability for a ray issued from a point M within the homogenized medium in the direction $\mathbf{u}$ to be extinguished before travelling the distance v. It is the complementary to one to the transmitivity from M to M'. Its values are therefore in the range of [0,1]. It can be calculated from the chord length distribution function of the propagation phase [8] using the morphology of the porous medium (tomography obtained experimentally [22–27] or analytical description [8,28]). In the case of Beerian medium, G_{ext} is an exponential function that is completely determined by an extinction coefficient β.

(ii) A cumulative probability of absorption $P_a(M,\mathbf{u},v)$ or a cumulative probability of scattering $P_{sc}(M,\mathbf{u},v)$;

(iii) A phase function $p(\mathbf{u}_i,\mathbf{u}_r)$. It is worth to note that for Dispersed radius Overlapping Opaque Spheres (DOOS) it has been proven that the phase function depends only on the scattering angle $\mu_s = \mathbf{u}_i \cdot \mathbf{u}_r$ and that the distribution function of μ_i is linear, where $\mu_i = \mathbf{u}_i \cdot \mathbf{n}$ and $\mathbf{n}$ is the normal unit vector towards the fluid phase at the impact point of a ray with an opaque sphere [8];

(iv) An effective refractive index $n_{eff_\nu}(\theta,\varphi)$ depending on the propagating direction which has been introduced for anisotropic media [28].

This method presents numerous advantages: (i) In the porous medium, the validity of the Beer's law is often questionable. The radiative properties are determined without using this assumption, and a criterion has been introduced to quantify the error made when assuming Beer's law validity in the Radiative Distribution Function Identification approach [22]; (ii) The issues related to dependent scattering are avoided. The rays are tracked until the first extinction (by absorption, scattering or reflection in the case of opaque wall). Multiple scattering phenomena are taken into account only in the radiative transfer model; (iii) The characterization of the radiative properties does not use any radiative transfer model. (iv) The method can be applied to many type of porous media. The morphology can be analytically described or obtained for real porous media from tomography measurements (foam [24,27], non-spherical particle packed beds [25,26], etc.). The approach has even been extended to statistically anisotropic media [22,28,29] and validated with physical measurements [23]. (v) Finally, the model has been coupled to other heat transfer modes [30].

The present paper deals with the characterization of near wall radiative properties of a statistically non-homogeneous and anisotropic homogenized medium associated with a porous medium with opaque and solid phases. A general model is developed. It is applied to the determination of the near-wall radiative properties of packed beds composed of spherical particles, in the perspective of radiation transfer modeling coupled to other heat transfer modes within reactors. In reactors used in chemical industry, the geometry of the packing is disturbed in the near wall region. Important porosity variations extend over a thickness of a few particle diameters; The medium becomes then non-homogeneous. The complex features of the medium near the wall affect the thermal properties of the medium in particular the radiative ones.

The general near-wall characterization model is developed in Section 2 and the numerical approaches in use are presented in Section 3. Finally, the radiative properties related to a numerically generated packed bed, bounded by a wall, are completely characterized in Section 4.