International Journal of Heat and Mass Transfer 112 (2017) 387–400

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Numerical quantification of coupling effects for radiation-conduction heat transfer in participating macroporous media: Investigation of a model geometry

David Y.S. Perraudin, Sophia Haussener *

Laboratory of Renewable Energy Science and Engineering, EPFL, Station 9, 1015 Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 31 October 2016
Received in revised form 21 March 2017
Accepted 22 March 2017

Keywords:
Semitransparent porous media
Coupled radiative-conductive heat transfer
Monte Carlo ray tracing
Finite volumes

ABSTRACT

Radiative-conductive heat transfer in porous media is usually investigated by decoupling the heat transfer modes and solving the volume-averaged continuum equations using effective transport properties. However, both modes are naturally coupled and coupling effects might significantly affect the results. We aim at providing quantitative understanding of the coupling effects occurring in a model geometry. This is an important first step towards improving the accuracy of heat transfer predictions in engineering applications.

We developed a numerical method using a structured mesh, cell centered finite volumes and Monte Carlo ray tracing techniques in order to simulate the 3-dimensional and unsteady coupled radiative-conductive heat transfer in semitransparent macroporous media. We have optimized the numerical method with regards to memory and computational requirements leading to optimal performance and allowing to perform a parameter variation study for various steady state cases.

We conducted a parameter study considering different optical and thermal material properties and boundary conditions in order to quantify the coupling effect between conduction and radiation, and to demonstrate its dependencies. In terms of thermal properties, it was found that the ratio of bulk thermal conductivities is governing the coupling effect. A distinct peak at a given conductivity ratio was found. The influence of optical properties is discussed in details. It was found that a significant coupling effect exists, reaching up to 15% of the total thermal heat flux.

The verified modeling framework in conjunction with our non-dimensionalization offers a tool to investigate the importance of radiation-conduction coupling in a quantitative manner. It is an important step towards understanding the detailed mechanisms of radiation and conduction coupling and provides engineering guidelines on the importance of these effects.

1. Introduction

Semitransparent porous media are of interest in a variety of applications, including solar energy conversion, space and medical technologies, or chemical processing. The multiple scales present in such applications remain a challenge for engineering. At high temperatures, radiative heat transfer can dominate the heat transfer and certain ceramics that are opaque at room temperatures become transparent. Conversely, at room temperature, without external irradiation, radiative heat transfer is negligible. In the absence of fluid flow, heat transfer occurs by conduction and radiation simultaneously. The term *coupled* is used to highlight the naturally occurring interaction between radiative and conductive heat transfer. The unsteady heat transfer equation in a homogeneous media accounting for radiation and conduction incorporates, in addition to the divergence of the conductive heat fluxes, also the divergence of the radiative fluxes as a non-linear source term, resulting in the complex interdependence. Additionally in porous media, this equation has to be solved for each homogeneous phase.

The multiscale nature of applications incorporating porous materials makes it often impossible to run direct numerical simulations for heat transfer. Instead, effective radiative and conductive properties of porous media are used in order to allow for efficient simulation. The approach is based on the assumption that the porous media can be approximated by an analogous media consisting of two homogeneous and continuous phases. The properties of these analogous phases, also called effective transport properties,

---

* Corresponding author.
E-mail address: sophia.haussener@epfl.ch (S. Haussener).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.03.079
0017-9310/

Nomenclature

A	surface
c_p	specific heat capacity
e	normalized error
$\mathbf{G}$, $\mathbf{H}$	discrete version of $\mathbf{g}$, $\mathbf{h}$
$\mathbf{g}$, $\mathbf{h}$	tensors defined in analogy to view factors
$\mathrm{i} = \sqrt{-1}$	imaginary unit
I	radiative intensity
I_b	blackbody intensity ($n^2\sigma_\mathrm{B}T^4/\pi$)
k	thermal conductivity
L	sample dimension
$m = n - \mathrm{i}\cdot\tilde{k}$	complex index of refraction
$\hat{\mathbf{n}}$	normal vector (normal to boundary or interface)
N	conduction-to-radiation parameter
N_c	number of control volumes
N_b	number of boundary faces
$\mathbf{q}$	heat flux
$\mathbf{r}$	position vector
$\hat{\mathbf{s}}$	direction of radiative intensity
T	temperature
t	time
V	volume
$\beta = \kappa + \sigma_\mathrm{s}$	extinction coefficient
θ	polar angles
κ	absorption coefficient
λ	wavelength
ξ	modified radiation-to-conduction parameter
ζ	coupling effect
ρ	density
σ_s	scattering coefficient
σ_B	Stefan Boltzmann constant
φ	azimuthal angle
Φ	scattering phase function
ϕ	porosity
Ω	solid angle

Subscripts

s	solid phase
f	fluid phase
r	radiative
e	emitted
b	boundary
i, j	iteration parameters

are determined such that the solution of the homogenized problem results in the same temperature or intensity fields as the solution to the original, discrete-scale problem. This approach allows for efficient computations. Details of volume averaging theory applied to problems relevant in heat and mass transfer are described in [1]. Effective properties can be determined experimentally [2,3] or through simulations. As the effective properties significantly depend on the geometry of the porous media, accurate computational approaches directly incorporate the exact morphology using, for example, computed tomography of the materials of interest [4–8]. There have been attempts to summarize effects of conduction and radiation into one single parameter sometimes referred to as "phononic diffusivity" [9,10] or "equivalent conductivity" [11]. This parameter must, by definition, heavily depend on temperature.

The interest in understanding the radiative-conductive coupling in semitransparent porous media comes from the fact that various models have been developed for the separate determination of the effective radiative [12] and effective conductive [13] properties but their application in the coupled case is ambiguous. Superimposing the effect of radiation and conduction in order to obtain a solution to a coupled problem seems convenient but not necessarily accurate. The aim of this work is to study, whether the superposition of conductive and radiative heat fluxes computed separately is a valid procedure, or whether coupling effects exist, and to quantify their sensitivity to bulk material properties. In case superposition is justified, existing models can easily be combined. In case coupling effects exist, their quantification will allow using existing models, improved with a well investigated and quantified coupling effect.

Theoretical work has predicted the existence of coupling effects [14]. This work is based on the derivation of the volume-averaged energy equations for porous media and shows that in the volume-averaged equations additional coupling terms for radiation and conduction exist. However, no quantification is given for a realistic case and the importance of the different terms under various conditions is not given in [14]. Coquard et al. [11] stated that in the case of "metal or ceramic open cell foams" they have "checked from numerous results obtained on different cellular structures with various optical properties that this coupling is relatively weak". Their findings suggest that for some setups the superposition of the results obtained for the two modes separately is justified without giving more details.

We aim at quantifying these coupling effects, at predicting their dependence on boundary conditions and geometrical and material properties. We therefore developed a numerical method which is capable of pore-scale simulations with coupled radiative-conductive heat transfer in macroporous media. Such a method must be significantly more powerful than commonly used methods in single phase setups in one or two dimensions, such as discrete ordinate methods [15], finite elements [16] or spherical harmonics methods ($\mathrm{P_N}$ method) [17,18]. It must be capable of capturing three dimensions, different phases, resolving porous structures, while remaining computationally efficient and accurate. We present results obtained for a model geometry. Structured, lattice-type porous media are of interest in a wide variety of applications (porous burners, heat exchangers, or lightweight structures), provide interesting test media with well-defined structures, and can easiest be implemented as materials by design [19].

2. Governing equations

2.1. Assumptions

The steady state case of a macroporous media consisting of two phases (for example one fluid and one solid) is considered. Both phases are assumed at rest, such that heat is transferred either by conduction or by radiation. Macroporous implies that the radiative heat transfer occurs in the geometric optics regime such that $\pi L/\lambda \gg 1$ holds if L is a characteristic length scale and λ the wavelength. The fluid phase is transparent and the solid phase semitransparent, thus participating in the radiative heat exchange through absorption and internal emission. Internal scattering in the bulk material of the participating phase is neglected ($\sigma_\mathrm{s} = 0$). The participating medium and the domain boundaries are grey, such that wavelength dependencies can be dropped. The partici-