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Radiative properties effects on unsteady natural convection inside a saturated porous medium. Application for porous heat exchangers

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ABSTRACT

The present article deals with a numerical study of coupled fluid flow and heat transfer by transient natural convection and thermal radiation in a porous bed confined between two-vertical hot plates and saturated by a homogeneous and isotropic fluid phase.

The main objective is to study the effects of radiative properties on fluid flow and heat transfer behavior inside the porous material. The numerical results show that the temperature, the axial velocity, the volumetric flow rate and the convective heat flux exchanged at the channel's exit are found to be increased when the particle emissivity (ε) and/or the absorption coefficient (κ) increase or when the scattering coefficient (σ_s) and/or the single scattering albedo (ω) decrease. Furthermore, the amount of heat (Q_c) transferred to fluid and the energetic efficiency E_c are found to be increased when there is a raise in the particle emissivity values.

In order to improve the performance of heat exchanger, we proposed the model of a porous heat exchanger which includes a porous bed of large spherical particles with high emissivity as a practical application of the current study.

1. Introduction

Fluid flow and heat transfer by natural convection coupled with thermal radiation in porous media have been motivated by numerous applications such as thermal insulation technology, material processing, and storage of radioactive nuclear waste materials to name just a few industrial applications like packed-bed heat exchangers.

The knowledge of equivalent radiative properties of the porous medium is necessary for all work of modeling taking account heat transfer by radiation in the presence of a granular materials. Generally, there are four distinct approaches to determine the equivalent radiative properties of a porous medium. The first approach is called the independent scattering theory. It is based on the knowledge of radiative properties of individual particles (Kerker [1], Bohren and Huffman [2]). The equivalent radiative properties of the homogeneous medium are obtained by summing the radiative properties of each individual particle and radiative properties of the surrounding medium. This theory requires a good knowledge of the radiative properties of particles. The second approach is called the theory of multiple scattering (Tsang et al. [3]). It is based on the resolution of the equation governing the propagation of electromagnetic fields, also called diffusion equation. This approach is accurate because it takes into account the effect of dependent scattering and multiple scattering between particles. However, its development is restricted to the case of medium containing small particles for which analytical solutions can be obtained (Foldy [4]). When the particles are large size and opaque, correction factors for radiative properties (from the independent theory) have been proposed in the literature (Kamuito [5] and Kamuito et al. [6], Singh and Kaviany [7]). The third approach is the inverse method of parameter identification (Nicolau [8], Baillis and Sacadura [9]). This is an experimental approach used to determine the radiative parameters aiming to minimize the difference between experimental and the same theoretical variables. The experimental variables are obtained by radiometric measurements of radiative properties while the theoretical variables are obtained by solving the radiative transfer equation. The fourth approach is the statistical method of Monte Carlo (Tancrez and Taine [10], Coquard and Baillis [11]). It is a probabilistic method which simulates the propagation of a photon flux through a representative sample of the medium to be analyzed. This approach is rather similar to the theory of multiple scattering except that the wave aspect of radiation is ignored.

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Nomenclature

A	aspect ratio of the channel ($=H/D$)
$Bi_{i,o}$	modified inlet (respectively, outlet) Biot numbers ($=h_{i,o}D/\lambda$)
c_p	specific heat capacity at constant pressure, J/kg K
D	channel width, m
D^{ℓ}	direction cosine integrated over $\Delta\Omega_{\ell}$
D_p	particle diameter, m
E_c	energetic efficiency
g	gravitational acceleration, m s^{-2}
$h_{i,o}$	heat transfer coefficient, W m^{-2} K^{-1}
H	channel height, m
I	dimensionless intensity
I'	intensity, W m^{-2} sr^{-1}
k	permeability of the porous medium, m^2
n	refractive index
N	Planck number ($=\lambda\beta\Delta T/4n^2\sigma T^4$)
Nu	Nusselt number
$\overline{Nu}$	average Nusselt number
P	dimensionless motorize pressure
P'	pressure, kg m^{-1} s^{-2}
P_∞	ambient pressure, kg m^{-1} s^{-2}
q_r	dimensionless heat flux density
q_r'	heat flux density, W m^{-2}
Q	dimensionless heat flux
Q_c	amount of heat transferred to fluid, J
q_v	dimensionless volumetric flow rate
R	temperature ratio ($=T_\infty/T_h$)
Ra	modified Rayleigh number ($=kg\beta_f D\Delta T/\alpha\nu_f$)
s	dimensionless distance traveled by a beam
S	radiative source function, W m^{-3} sr^{-1}
S_r	scaling factor for radiative transfer
t	dimensionless time
t'	time, s
T	dimensionless temperature
T'	temperature, K
T_h	hot temperature, K
T_∞	ambient temperature, K
u	outward unit normal vector of control volume face
v_x, v_z	dimensionless transverse and axial velocity
v_x', v_z'	transverse and axial velocity, m s^{-1}
x, z	dimensionless coordinates
x', z'	coordinates, m

Greek letters

α	thermal diffusivity, [$=\lambda/(\rho c_p)_f$], m^2 s^{-1}
β	extinction coefficient, m^{-1}
β_f	coefficient of volumetric expansion, K^{-1}
γ	volumetric specific heat ratio [$=(\rho c_p)_{eff}/(\rho c_p)_f$]
δ	average porosity
ΔA	area of control-volume face
ΔV	control volume
$\Delta\Omega$	control angle
ε	emissivity of the solid particles
κ	absorbing coefficient, m^{-1}
λ	thermal conductivity, W m^{-1} K^{-1}
μ_f	fluid dynamic viscosity, kg m^{-1} s^{-1}
ν_f	fluid kinematic viscosity, m^2 s^{-1}
ξ	Walls emissivity
ρ	Walls reflectivity
σ	Stefan–Boltzmann constant
σ_s	scattering coefficient, m^{-1}
τ_D	optical thickness
ω	single scattering albedo
Ω, Ω'	solid angles, sr

In this study, we are interested in opaque and homogenous medium with particles of size greater than the radiation wavelength. Therefore, the multiple scattering approach is best suited to predict the equivalent radiative properties. The main purpose is to study the effects of equivalent radiative properties on fluid flow and heat transfer behavior inside the porous material. Interesting effects of the governing parameters, namely ε, κ, σ_s, and ω on the evolutions of dynamic and thermal fields, as well as on the evolutions of volumetric flow rate, convective heat flux, the amount of heat transferred to fluid and the energetic efficiency are also presented and discussed. A practical application of the current study is to enhance the performance of porous heat exchangers.

2. Mathematical formulation

A schematic representation of the physical model and the coordinate system is given in Fig. 1. The vertical channel is filled with a fluid-saturated porous medium, and subjected to a uniform hot temperature. The porous medium, at local thermal equilibrium assumption, is considered as a homogeneous, isotropic, and participating medium that can emit, absorb, and scatter isotropically radiative energy. The bounding walls of the channel, with constant emissivity ξ and reflectivity ρ, are assumed to be gray-diffuse surfaces. The fluid is Newtonian and assumed to be a Boussinesq one. The Darcy flow model is assumed to be valid because it is generally employed to model slow flows in porous media. Moreover, we are concerned with a heat exchanger including a porous bed. To maximize the amount of heat transferred to fluid it is better to increase the residence time in the heat exchanger and for this raison the flow is considered to be low speed.

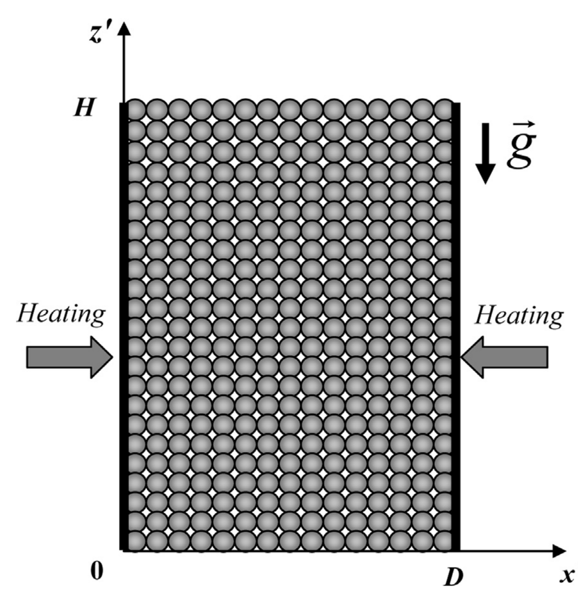

Fig. 1. Physical model and coordinate system.