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Analysis of collimated irradiation under local thermal non-equilibrium condition in a packed bed

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ABSTRACT

Forced convective heat transfer in a packed bed in the presence of collimated irradiation and under local thermal non-equilibrium is analyzed in this work. Both the collimated and diffusive radiative transfer processes are accounted for using the modified P-1 approximation. Two boundary condition models considering different limiting conditions at the wall which couple radiation and convection under LTNE were constructed. The effect of pertinent parameters such as the porosity φ, pore diameter d_p, ratio of the solid to fluid thermal conductivities ζ; radiative properties including optical thickness τ, scattering albedo ω, and the wall emittance ε_w were analyzed. Also, their effects on the temperature and heat flux distributions in the incident direction were analyzed systematically and the limiting interactions between thermal radiation and conduction were revealed. The differences between the two boundary models with the effects of the cited parameters were analyzed. Our analysis demonstrated that an increase in either φ or d_p enhances the transfer of radiative energy into the channel.

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1. Introduction

Porous media is widely used in many modern industrial applications due to its excellent attributes, such as high thermal conductivity, large specific area and high resistant to heat shock. Many research works have been carried out investigating the use of porous media in various applications such as solar thermal energy, nuclear waste storage, heat pipes and heat transfer enhancement [1]. The local thermal non-equilibrium (LTNE) model describes the heat transfer process in a porous medium [2,3]. Variants of this model was given by B. Alazmi and K. Vafai [4] considering the effect of non-Darcy, dispersion, non-equilibrium and variable porosity. The effect of different boundary conditions under LTNE conditions was given by Yang and Vafai [5,6]. For high temperature cases, thermal radiation behavior cannot be neglected [7–9]. Its impact on conductive heat transfer in a packed bed has been analyzed by Singh and Kaviany [10,11]. For an open-cell structure porous medium, Zhao et al. [12,13] investigated the radiation properties of an ideal structure analytically. The radiative properties such as spectral volumetric absorption and scattering coefficients of porous structures have been obtained experimentally by Hendricks and Howell [14,15] and Baillis et al. [16,17]. Wang et al. [18] have studied the influence of the radiation transfer on coupled heat transfer process with conduction and convection in a porous medium for a typical industrial device. Flamant and Olalde [19] have investigated the radiation transfer process in a double layer structure (glass bed and SiC porous layer) experimentally using a two-flux approximation to obtain the temperature distribution. Using the same method, Skocypec et al. [20] analyzed the model for oxidized wires in an air receiver; which compared quite well with the experimental result of Chavez and Chaza [21]. The heat transfer characteristics of this type of a porous medium was also numerically analyzed by Bai [22] and Xu et al. [23] and later validated by Wu et al. [24] considering different operational conditions.

Not much attention has been devoted to the effect of the collimated incident radiation in a two dimensional channel. For such a situation, the distribution of radiative energy changes in the incident direction and should be taken into account simultaneously with the convective processes. The purpose of the current study is to understand the role of the collimated incident radiation on the convective heat transfer in a porous channel under LTNE conditions. In this work, the temperature fields for the solid matrix and fluid phases will be analyzed while incorporating the local thermal non-equilibrium along with the modified differential approximation (P-1 model). The corresponding boundary conditions coupling radiation with conduction under LTNE condition will be established and the effect of intrinsic properties including

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Nomenclature

c_p	specific heat of fluid at constant pressure ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
d_p	pore diameter (m)
F	empirical function
G	incident radiation
H	height of the porous channel
H_c	the remnant collimated radiative flux arriving at the bottom wall
h_{sf}	fluid-to-solid heat transfer coefficient ($\mathrm{W\,m^{-2}\,K}$)
K	permeability ($\mathrm{m^2}$)
L	length of a porous channel
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
q_0	initial impinging heat flux at the upper wall
q_{in}	initial heat flux ($\mathrm{W/m^{-2}}$)
q	heat flux
Re_d	pore Reynolds number
T	temperature (K)
u	velocity (m/s)
$\boldsymbol{V}$	velocity vector ($\mathrm{m\,s^{-1}}$)
$\boldsymbol{x}$	spatial coordinate, horizontal
$\boldsymbol{X}$	dimensionless x
$\boldsymbol{y}$	spatial coordinate, vertical
$\boldsymbol{Y}$	dimensionless y

Greek symbols

α_{sf}	specific surface area of a porous medium ($\mathrm{m^{-1}}$)
β	extinction coefficient ($\mathrm{m^{-1}}$)
ε	emissivity
φ	porosity
Φ	example quantity
κ	absorption coefficient
λ	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
μ	dynamic viscosity ($\mathrm{kg\,m^{-1}\,s^{-1}}$)
σ	Stefan–Boltzmann constant
σ_s	scattering coefficient
γ	heat flux distribution parameter
θ	dimensionless temperature
ζ	ratio of solid to fluid thermal conductivities
ρ	density ($\mathrm{kg\,m^{-3}}$)
τ	optical thickness
τ_H	optical thickness at the position $y = 0$
ω	single scattering albedo
Ψ	dimensionless radiative flux

Subscripts

a	average
c	collimated
d	Diffuse
e	effective/environment
f	fluid phase
m	mean value
r	radiative
s	solid phase
t	total
w	wall

some key optic parameters will be discussed. In addition the difference between the two boundary condition models will be discussed. Finally, the effect a wide range of variations in the governing parameters such as the porosity, φ, and the pore diameter, d_p on the heat transfer process will be systematically analyzed.

2. Model description

2.1. Physical model and assumptions

A fundamental configuration composed of a parallel plate channel filled with a porous medium as shown in Fig. 1 is considered. The computational area has the height H and the length L. The extension in the z direction is assumed to be long enough so that the problem will be essentially a two dimensional configuration. The inlet velocity at the entrance is uniform and the imposed constant heat flux is considered to be the collimated irradiation impinging perpendicularly on the upper wall. The heat transfer process in the incident direction will be analyzed based on the following assumptions:

1. The upper wall of channel is treated as transparent to the collimated irradiation but opaque and adiabatic for the inner radiation.
2. The upper and bottom walls are taken to be diffuse-gray surfaces with a negligible thickness.
3. The radiation transfer between the entrance and outlet surface and the upper and bottom walls is negligible.
4. The flow is steady and incompressible.
5. The thermophysical properties including the radiative properties of the fluid and the porous matrix are assumed to be isotropic, homogeneous and constant.

2.2. Mathematical model

2.2.1. Governing equations [2–9]

Conservation of mass:

$$\nabla \cdot \langle \boldsymbol{V} \rangle = 0 \tag{1}$$

Momentum equation:

$$\frac{\rho_f}{\varphi}\langle(\boldsymbol{V}\cdot\nabla)\boldsymbol{V}\rangle = \frac{\mu_f}{\varphi}\nabla^2\langle\boldsymbol{V}\rangle - \nabla\langle P\rangle^f - \frac{\mu_f}{K}\langle\boldsymbol{V}\rangle - \frac{\rho_f F\varphi}{\sqrt{K}}[\langle\boldsymbol{V}\rangle\cdot\langle\boldsymbol{V}\rangle]\boldsymbol{J} \tag{2}$$

where K is the permeability and the empirical function F depends primarily on the microstructure of the porous medium and can be represented as:

$$K = \frac{\varphi^3 d_p^2}{150(1-\varphi)^2} \tag{3}$$

$$F = \frac{1.75}{\sqrt{150\varphi^{3/2}}} \tag{4}$$

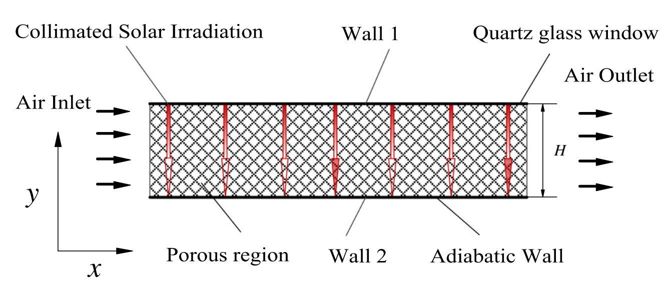

Fig. 1. Schematic diagram of the problem and the corresponding coordinate system.

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