

Analysis of the volumetric phenomenon in porous beds subject to irradiation

P. Wang^{a,b}, K. Vafai^b, and D. Y. Liu^a

^aCollege of Energy and Electrical Engineering, Hohai University, Nanjing, China; ^bBourns College of Engineering, University of California, Riverside, California, USA

ABSTRACT

This work examines the volumetric effect of convection within a packed bed in the presence of collimated irradiation. Using a modified P-1 approximation incorporating a local thermal nonequilibrium (LTNE) model, the energy transportation through convection and thermal conduction, and collimated and diffuse radiative transfer are investigated. The impact of pertinent parameters such as porosity ϕ , pore diameter d_p , and optical thickness τ on the volumetric effect are analyzed. In addition, the mechanisms of how the volumetric effect impacts LTNE and radiative heat loss are revealed. The effect of the volumetric heat transfer coefficient h_v , the fluid flow velocity u , and the ratio of solid to fluid thermal conductivities ζ versus the volumetric effect are systematically analyzed and displayed through a number of contour maps to assess the efficiency η . Our analysis shows that enhancing the volumetric effect and extending the thickness of the porous medium improves the efficiency η .

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1. Introduction

The “*volumetric effect*” phenomenon can occur in a porous medium as the radiative energy is converted to the energy of the fluid. A unique feature of the heat transfer process occurring under a volumetric effect in porous media is that both the inlet fluid flow and the incoming radiation are located at the irradiated side. In addition, the direction of the fluid flow is parallel rather than perpendicular to the radiative flux in the porous media. Due to the structural characteristics of porous media [1], the incoming radiation and the heat transfer process is extended from “surface” to “volume.” Therefore, the outlet fluid temperature should be higher than that of the solid matrix on the irradiated surface (see Figure 1). Consequently, higher radiative flux (without reaching the temperature limit of the material), less thermal radiative loss, and an increased thermal efficiency can be achieved, which is termed the *volumetric effect*.

Convective heat transfer processes in porous media as well as local thermal nonequilibrium (LTNE) models incorporating the temperature difference between solid and fluid phases have been discussed in the literature [2–4]. Variants of this model were offered by Alazmi and Vafai [5] who considered the effects of non-Darcy, dispersion, nonequilibrium, and variable porosities. The effect of different boundary conditions under LTNE conditions was studied by Yang and Vafai [6]. Thermal radiation behavior plays an important role in packed and fluidized beds where the temperatures are extreme [7]. Flamant et al. [8] investigated the radiation transfer process in a double-layer structure (glass bed and SiC porous layer) by experimentally using a two-flux approximation to obtain the temperature distribution. Using the same method, Skocypec et al. [9] analyzed the model for use in the oxidized wires in an air receiver; their results compared quite well with the experimental results of Chavez and Chaza [10]. Wang et al. [11] proposed a detailed dimensionless LTNE model under a

Nomenclature

c_p	specific heat of fluid at constant pressure (J kg ⁻¹ K ⁻¹)	β	extinction coefficient (m ⁻¹)
F	inertial coefficient	σ	Stefan–Boltzmann constant
d_p	pore diameter (m)	σ_s	scattering coefficient
G	incident radiation	θ	dimensionless temperature
h_{sf}	fluid-to-solid heat transfer coefficient (W m ⁻² K)	ζ	ratio of solid to fluid thermal conductivities
K	permeability (m ²)	ρ	density (kg m ⁻³)
L	thickness of a absorber (m)	τ	optical thickness
Nu	Nusselt number	ω	single scattering albedo
P	pressure (Pa)	Ψ	dimensionless heat flux
Pr	Prandtl number	Subscripts	
q_0	initial heat flux (W m ⁻²)	a	average
q	heat flux	c	collimated
$\hat{s}$	unit vector in the direction of fluid flow	d	diffuse
T	temperature (K)	e	effective/environment
u	velocity (m s ⁻¹)	f	fluid phase
V	velocity vector (m s ⁻¹)	l	heat loss
α_{sf}	specific surface area of the porous medium (m ⁻¹)	r	radiative
ϵ	emissivity	s	solid phase
ϕ	porosity	t	total
λ	thermal conductivity (W m ⁻¹ K ⁻¹)	v	void
μ	dynamic viscosity (kg m ⁻¹ s ⁻¹)	w	wall

Rosseland approximation for an air receiver. Wang et al. [12] have analyzed the transport of radiative energy, under collimated irradiation perpendicular to a packed bed. Some works have focused on applications such as solar dish receivers using different numerical methods [13].

Little attention has been devoted to the effect of collimated irradiation on a porous bed, and volumetric effect revealed from this heat transfer process has not been reported. The purpose of this study is to understand the volumetric effect phenomenon under collimated irradiation based on an LTNE model in a porous bed. The effect of geometric parameters such as the porosity ϕ , the pore diameter d_p , and the optical thickness τ on the volumetric effect of porous media will be examined. Furthermore, energy transportation incorporating thermal conduction, convection, radiative heat transfer, and also heat loss will be analyzed from the perspective of the volumetric effect. Finally, the thermal efficiency η for a wide range of variations in the geometric parameters, that is, porosity ϕ and pore diameter d_p , will be systematically analyzed within a number of contour maps.

2. Model

A fundamental configuration composed of a parallel plate channel filled with a porous medium is considered and shown in Figure 1. The computational area has a thickness L , and the height H in the y direction is assumed to be sufficiently long so that a one-dimensional approximation in the direction of the incoming irradiation can be invoked. We also assume that the solid matrix is homogeneous and isotropic so that any variations in the solid and fluid phase thermal properties can be disregarded. Furthermore, the flow is considered to be steady and fully developed.

2.1. LTNE model

Continuum equation:

$$\nabla \langle V \rangle = 0 \quad (1)$$

Momentum equation [2,3]:

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

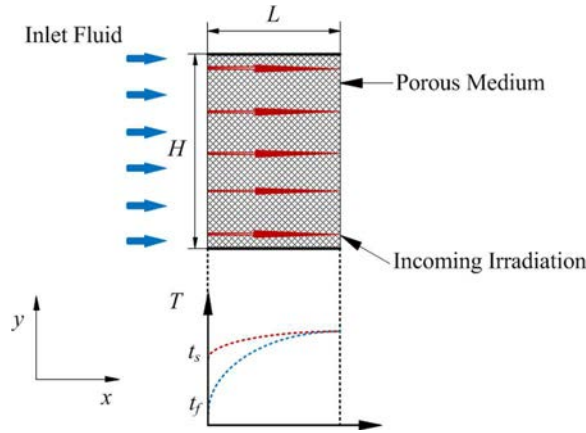


Figure 1. Schematic diagram of the volumetric effect phenomenon.

where $\langle P \rangle^f$ is the gauge pressure, and the local volume average of a quantity Φ can be defined as $\langle \Phi \rangle \equiv \frac{1}{V_f} \int_{V_f} \Phi dV$; $\mathbf{J}$ is a unit vector oriented along the velocity vector where the permeability K and empirical function F which depends primarily on the microstructure of the porous medium can be represented as in Vafai [2]:

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

$$F = \frac{1.75}{\sqrt{150\phi^{3/2}}} \quad (4)$$

Energy equations:

Fluid phase:

$$(\rho c_p)_f \langle \mathbf{V} \rangle \cdot \nabla \langle T_f \rangle = \nabla (\lambda_{fe} \cdot \nabla \langle T_f \rangle) + h_{sf} a_{sf} (\langle T_s \rangle - \langle T_f \rangle) \quad (5)$$

Solid phase:

$$0 = \nabla \cdot (\lambda_{se} \cdot \nabla \langle T_s \rangle - q_r) - h_{sf} a_{sf} (\langle T_s \rangle - \langle T_f \rangle) \quad (6)$$

where the effective thermal conductivity for the fluid and solid phase are expressed as follows:

$$\lambda_{fe} = \phi \lambda_{fe} \quad (7)$$

$$\lambda_{se} = (1 - \phi) \lambda_{se} \quad (8)$$

A detailed comparison of the correlations for the volumetric heat transfer coefficient h_v for the porous medium was performed by Wang [14]. As for the large porosity and pore diameter used in this study, the empirical correlation established by Younis and Viskanta [15] is selected and can be presented as follows:

$$h_v = 0.819 (1 - 733(d_p/L)) \text{Re}_d^{0.36 [1 + 155(d_p/L)]} \quad (9)$$

2.2. Radiation transfer

Due to the collimated irradiation assumption, a modified differential approximation (P-1 model) is applied to address the problem. When incident collimated irradiation is removed from the intensity field, the remnant intensity can deviate only slightly from the isotropic condition. Similar to the classic P-1 model, we treat the remnant portion as fairly diffuse, which is the result of emission from the boundary and within the medium, and also the radiation scattered away from the

collimated irradiation. We thus express the diffuse radiative flux q_d and the incident radiation G_d as follows:

$$\nabla q_d = \kappa(4\sigma\langle T_s \rangle^4 - G_d) + \sigma_s G_c \quad (10)$$

$$q_d = -\frac{1}{3\beta} \nabla G_d \quad (11)$$

Combining the expression of q_d and G_d from Eqs. (10) and (11), the differential equation for G_d is obtained as

$$0 = \frac{1}{3\beta} \nabla G_d^2 + \kappa(4\sigma\langle T_s \rangle^4 - G_d) + \sigma_s G_c \quad (12)$$

Meanwhile, q_c , the remnant collimated radiative flux after partial extinction through absorption and scattering along its path in a direction perpendicular to the boundary, is given by the exact solution:

$$\mathbf{q}_c = \hat{\mathbf{s}} G_c = q_0 e^{-\tau} \quad (13)$$

where the optical thickness τ is given by $\tau = \beta/x$, the extinction coefficient β is the sum of the absorption κ and the scattering coefficients σ_s , and the initial incoming irradiation $q_c = 1$ MW. Hsu and Howell [16] presented a method of simultaneously inverting the conductivity and extinction coefficient from the experimental data. The trend of the change of extinction coefficient shows a good agreement with the geometric optics limit prediction [17] in the proper range of geometric parameters:

$$\beta = \frac{\Psi}{d_p} (1 - \phi) \quad (14)$$

where the value of Ψ is constant based on the properties of reticulated porous ceramic (RPC) [18]. Other experimental test results show that the thermal radiative properties of RPC material are almost independent of the solid matrix temperature [19]. The detailed expressions are given as follows:

$$\kappa = (2 - \varepsilon) \frac{3}{2d_p} (1 - \phi) \quad (15)$$

$$\sigma_s = \varepsilon \frac{3}{2d_p} (1 - \phi) \quad (16)$$

2.3. Boundary conditions

Boundary Condition 1: Irradiated surface

The inlet of the fluid flow is the irradiated surface and the only source of radiative heat loss. In the model, we disregard the effect of the porous structure on inlet fluid flow and irradiation at the boundary wall. The wall is treated as a transparent virtual surface; that is homogeneous and diffusely gray with emissivity ε . Under this assumption, the total incoming irradiation εq_0 entering the porous medium is constant with the change of its geometric parameters. The remnant part of the incoming irradiation after absorption and scattering is treated as a volume phenomenon; its distribution in the incident direction can be expressed as $q_c = \varepsilon q_0 e^{-\tau}$.

As for the solid phase, convection on the boundary surface is included in the boundary control volume. However, the thermal radiative loss from the solid phase point to the ambient is considered to be a surface phenomenon; the energy balance equation is given as follows:

$$-\lambda_{se} \frac{d\langle T_s \rangle}{dx} \Big|_{x=0} + \phi \sigma \varepsilon \left(\langle T_s \rangle^4 \Big|_{x=0} - T_e^4 \right) = 0 \quad (17)$$

As for the fluid phase, the temperature of the inlet air is given by

$$T_f \Big|_{x=0} = T_e \quad (18)$$

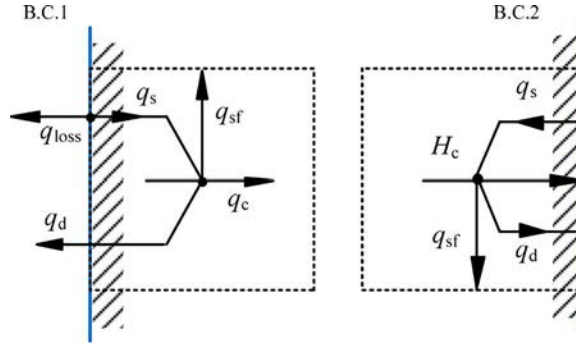


Figure 2. Boundary condition for the irradiated surface and back wall of the porous medium.

The diffusive radiative heat loss emits directly from the void of the pore structure to the ambient environment. The emissivity is considered as a unit, and the blackbody emissive power E_b is zero when the Mashak boundary condition is applied on the virtual wall of the irradiated surface as follows:

$$-\frac{1}{3\beta} \frac{dG_d}{dy} \Big|_{x=0} = -\varphi \frac{G_d|_{x=0}}{2} \quad (19)$$

Boundary Condition 2: Back wall

For simplicity, we assume that the radiative flux emitting from the porous medium is perfectly reflected by the back wall; consequently, the solid phase of the back wall can be considered adiabatic (see Figure 2). In this manner, energy conservation is obtained by simultaneously considering the actual heat and fluid flow processes in the porous medium. The boundary condition for the radiative heat transfer under the assumption above is given as follows [12]:

$$-\frac{1}{3\beta} \frac{dG_d}{dx} \Big|_{x=L} = \frac{\varepsilon_1 \left(4\sigma_s \langle T_s \rangle^4 \Big|_{x=L} - G_d \Big|_{x=L} \right) + 4(1 - \varepsilon_1) H_c \Big|_{x=L}}{2(2 - \varepsilon_1)} \quad (20)$$

where H_c is the collimated radiative flux arriving at the back wall. As for the solid phase, the energy balance of heat conduction and diffusive radiation under the impinging collimated irradiation can be coupled by the boundary condition as follows:

$$-\lambda_{se} \frac{d\langle T_s \rangle}{dx} \Big|_{x=L} - \frac{1}{3\beta} \frac{dG_d}{dx} \Big|_{x=L} + H_c = 0 \quad (21)$$

The related dimensionless parameters can be defined as follows:

$$X = \frac{x}{L} \quad (22)$$

$$\theta_f = \frac{T_f}{T_e} \quad (23)$$

$$\theta_s = \frac{T_s}{T_e} \quad (24)$$

where the L is the thickness of the porous medium, and $T_e = 300$ K is the ambient temperature. The conductive heat flux for the solid phase Ψ_s can be represented as

$$\Psi_s = -\frac{\lambda_{se}}{q_0} \frac{\partial T_s}{\partial y} \quad (25)$$

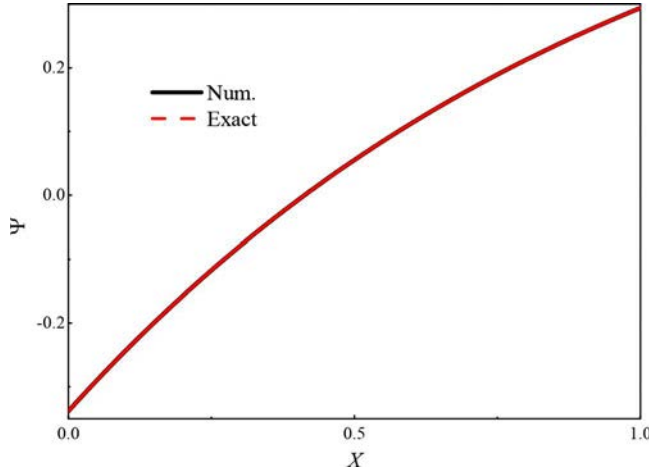


Figure 3. Comparison of the numerical result and the exact solution.

and the diffuse radiative flux Ψ_d and the collimated radiative flux Ψ_c can be represented as follows:

$$\Psi_d = -\frac{1}{3\beta q_0} \frac{\partial G_d}{\partial y} \quad (26)$$

$$\Psi_c = \frac{G_c}{q_0} \quad (27)$$

2.4. Numerical procedure and validation

Governing equations are discretized using a SIMPLE algorithm by applying the finite volume method [20]. An upwind differencing method is employed to discretize the convective terms. Convergence is considered to have been reached when the relative variation of temperature between consecutive iterations is smaller than 10^{-8} for all grid points in the computational domain after the grid independent test.

To further validate our results, particularly the radiation transfer using the P-1 approximation, we compared them with the exact solution that considered a plane-parallel slab of an absorbing and isotropically scattering medium with a black cold bottom surface that has no effect of convection, as shown in Figure 1. For simplicity, the single scattering albedo ω is set as the unit. Figure 3 compares our numerical result with the exact solution for the diffusive radiative flux, which can be presented as

$$q_d = \left(\frac{5 - e^{-\tau_H}}{4 + 3e^{-\tau_H}} - e^{-\tau} \right) \quad (28)$$

where the τ_H is the optical thickness at the position back wall ($y = 0$). It can be seen in Figure 3 that good agreement has been achieved.

3. Results and discussion

3.1. Effect of porosity ϕ and pore size d_p

Figure 4a shows the effect of the porosity ϕ on the dimensionless temperature distribution of the fluid phase θ_f in the incident direction (X direction). It can be seen that θ_f increases along the incident direction. Increasing the porosity ϕ increases the gradient of θ_f in the X direction. At low porosity ($\phi = 0.85$), the dimensionless temperature of the fluid phase θ_f initially increases and then decreases, leading to the creation of a maximum. With the increase of ϕ , this maximum generally decreases until

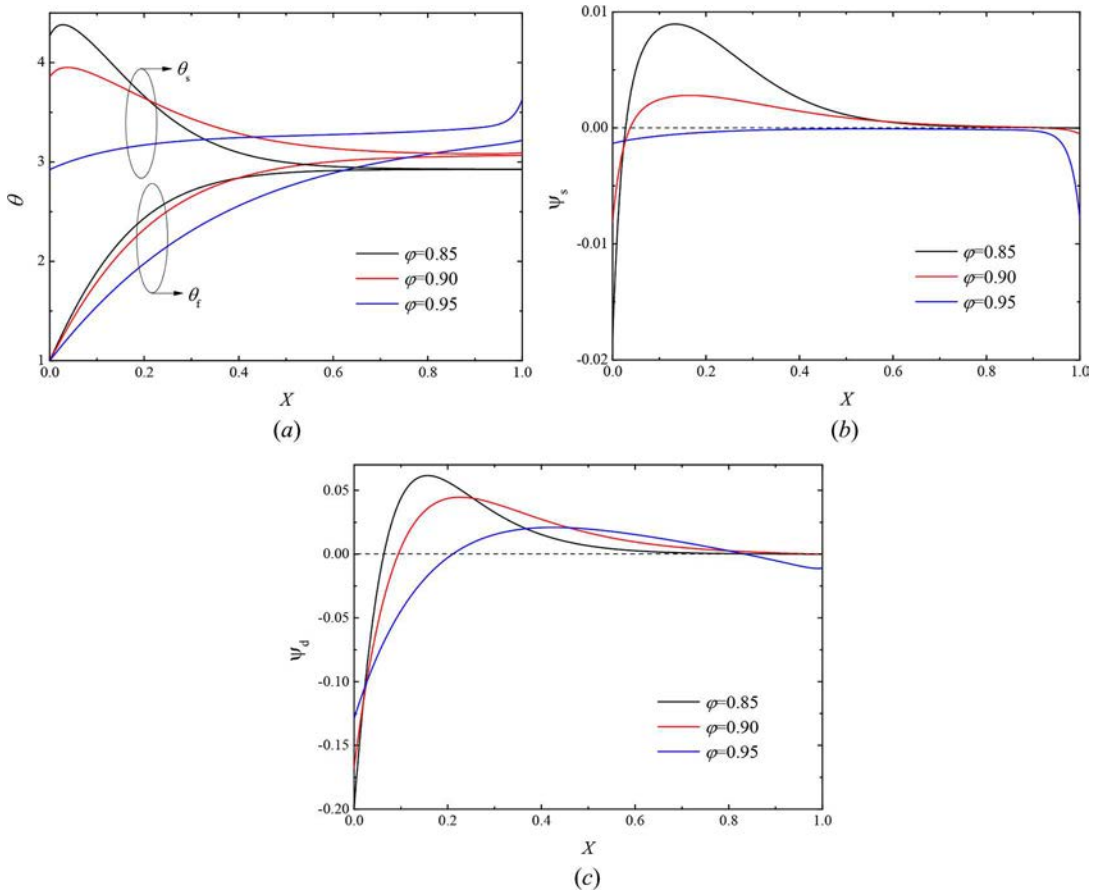


Figure 4. Effect of porosity ϕ on temperature θ and heat flux Ψ distributions along the flow direction: (a) θ_t and θ_s , (b) Ψ_s , (c) Ψ_d .

the dimensionless temperature distribution of the solid phase θ_s monotonically increases in the X direction, clearly displaying the volumetric effect. The dimensionless temperature of the solid phase θ_s at the back wall of the porous medium is more sensitive to the increase of porosity ϕ compared with that of the fluid phase, thus resulting in greater temperature differences between the solid and fluid phases.

Figure 4b and 4c depicts the distribution of the conductive heat flux Ψ_c and the diffuse radiative flux Ψ_d in the solid phases. As shown in Figure 4b, when the porosity is relatively low ($\phi = 0.85$), the solid phase conductive heat flux Ψ_s is negative (pointing from the back wall to the irradiated surface). Its absolute value in the X direction gradually reduces to zero and then increases, leading to the creation of a zero value point that clearly corresponds to the maximum temperature point located inside rather than on the irradiated surface, that is, the volumetric effect moves the solid phase maximum temperature inside the porous medium.

When the porosity is relatively high ($\phi = 0.95$), the incoming irradiation can fully enter the porous medium, most of which can even reach the back wall. This portion of energy, termed H_c in Eq. (20), returns back through conduction of the solid phase; consequently, the direction of Ψ_s is always negative, with an extremely significant volumetric effect. This result is consistent with the assumption of the boundary condition of the back wall, that is, the back wall of the porous medium is opaque and adiabatic to collimated radiative flux q_c . Thus, in the negative X direction, as the porosity ϕ increases, the conductive heat flux Ψ_s sharply decreases at the irradiated surface but gradually increases at the back wall; the volumetric effect is enhanced.

Similar to the distribution of the conductive heat flux Ψ_s (see Figure 4c), the diffuse radiative flux Ψ_d at the irradiated surface is also negative. Its absolute value sharply decreases to zero, that is, it continually increases to a maximum value inside the porous medium, and then gradually decreases. The essence of this maximum is that the incident radiation G_d initially increases and then decreases in the X direction, leading to the creation of a maximum value point of Ψ_d . Within this variation, there exists a zero value point where the directions of the diffuse radiative flux are changed that we call the “separation point” of the Ψ_d . There is actually a separation point for the conductive heat flux Ψ_s that corresponds to the maximum temperature point. In comparing Figure 4b and 4c, it can be seen that the diffuse radiative flux Ψ_d is significantly greater than the conductive heat flux Ψ_s , which indicates that along with interphase convection, radiative heat transfer is the primary means of energy transportation. In addition, the separation point of the diffuse radiative flux Ψ_d coincides with that of the conductive heat flux Ψ_s , which means that the heat conduction and thermal radiation are coupled but not totally synchronous.

Figure 5a shows the effect of pore diameter d_p on the distribution of the dimensionless temperature for the fluid and solid phases (θ_f and θ_s), the conductive heat flux Ψ_s , and the diffuse radiative flux Ψ_d in the X direction. As seen in Figure 5a–5c, the impact of the variation of the pore diameter d_p on θ_f , θ_s , Ψ_s , and Ψ_d is similar to that of the porosity ϕ . An increase in both porosity and pore diameter results in sparse pore structure, which allows the incoming irradiation to more deeply penetrate

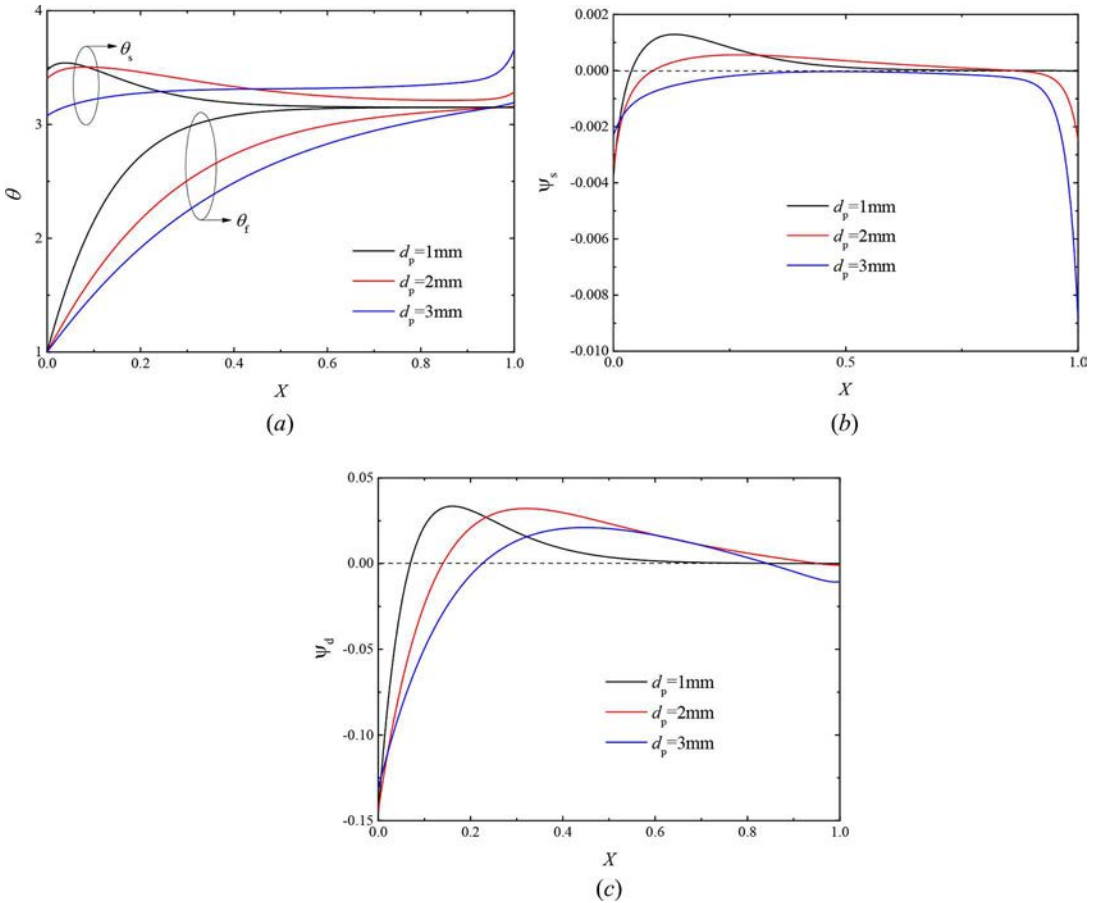


Figure 5. Effect of pore diameter d_p on temperature θ and heat flux Ψ distributions along the flow direction: (a) θ_f and θ_s , (b) Ψ_s , (c) Ψ_d .

the porous medium, that is, moving the primary heat transfer process inside the porous medium; therefore, a significant volumetric effect is obtained.

3.2. Effect of optical thickness τ

The key feature behind the influence of porosity φ and pore diameter d_p on the heat transfer process is that the change in pore structure reconstructs the distribution of the incident radiative flux in the porous medium. The combined influence of the pore structure can be primarily represented by the optical thickness τ . To analyze the radiative transfer process by considering the actual properties of the porous medium, the optical thickness τ is chosen as a parameter from 1 to 10, which can be defined as follows:

$$\tau = \beta H \quad (29)$$

$$\beta = \kappa + \sigma_s \quad (30)$$

Figure 6 shows the effect of the optical thickness τ on the dimensionless temperature and heat flux distributions in the X direction. We selected three different parameters pertaining to the pore structure: $d_p = 0.003$, $\varphi = 0.98$ for $\tau = 1$; $d_p = 0.0024$, $\varphi = 0.92$ for $\tau = 5$; and $d_p = 0.003$, $\varphi = 0.8$ for $\tau = 10$.

It can be seen in Figure 6a that when the optical thickness τ decreases, the convection between the solid and fluid phases is weakened, leading to an increase of the solid phase temperature. However, the scattering and absorption process of the incoming irradiation simultaneously moves forward in the X

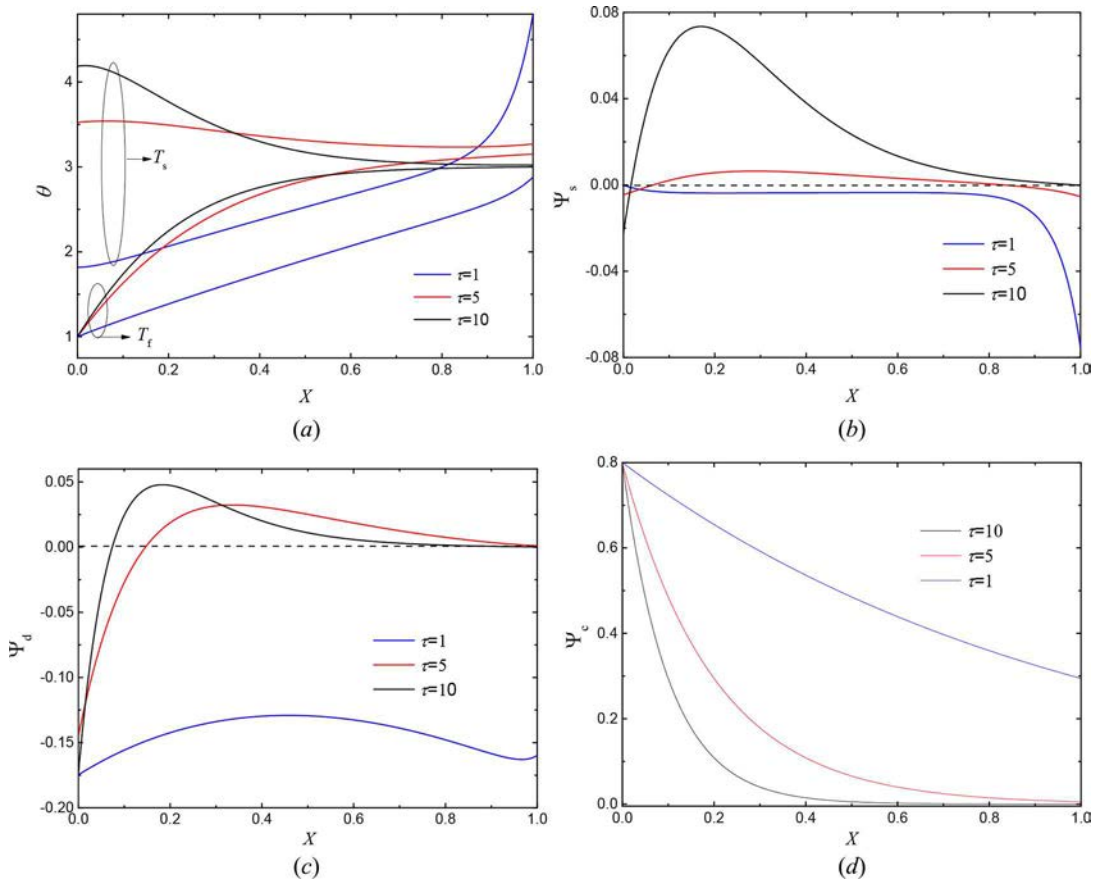


Figure 6. Effect of optic thickness τ on temperature θ and heat flux Ψ distributions along the flow direction: (a) θ_f and θ_s , (b) Ψ_s , (c) Ψ_d , (d) Ψ_c .

direction; consequently, the combined effect of these two mechanisms decreases the solid phase temperature at the irradiated surface. Therefore, a smaller optical thickness τ enhances the LTNE between the fluid and solid phases at the back wall but weakens it at the irradiated surface, indicating that the heat exchange within the given thickness of the porous medium is insufficient.

Figure 6b shows the distribution of conductive heat flux Ψ_s in the solid phase. It can be seen that when the optical thickness τ is large ($\tau = 10$), the separation point is close to the irradiated surface. The location of this point corresponds to that of the maximum temperature, which is consistent with Figure 6a. Moreover, with the decrease in the optical thickness τ , the separation point for the conductive heat flux Ψ_s gradually moves forward in the flow direction. When the optical thickness τ is small ($\tau = 1$), a “reflux” phenomenon of the conductive heat flux Ψ_s eventually occurs, that is, the direction of Ψ_s from the back wall completely points to the irradiated surface.

With the sharp decays of the collimated radiative flux Ψ_c close to the irradiated surface, as seen in Figure 6d, the corresponding incident radiation G_d rapidly increases to the maximum point where $\Psi_d = 0$, as seen in Figure 6c, resulting in a separation point of the diffusive radiative flux. When $\tau = 10$, the separation point locates at $X = 0.1$ and advances in the X direction as the optical thickness τ increases (located at $X = 0.2$ when $\tau = 5$). When $\tau = 1$, the separation point disappears and the direction of Ψ_d is completely negative in the X direction.

It can be seen in Figure 6d that the collimated radiative flux Ψ_c sharply decreases with the increase of the optical thickness τ . When the optical thickness is low ($\tau = 1$), only half of the extinction for the incoming irradiation has finished through the entire thickness of the porous medium; the remaining portion will radiate from the back wall of the porous medium in practical applications. Therefore, one can select a smaller optical thickness and a larger thickness that can reduce the surface heat loss but increase the absorption of the incoming irradiation.

3.3. Heat loss

The heat loss due to radiative heat transfer between the irradiated surface and the ambient space is the only method of heat loss for the porous medium in our model. This radiative heat loss can be divided into two components. One part is the conductive heat flux Ψ_{ls} that transfers from the inside to the irradiated surface and then radiates into the ambient space through thermal conduction of the solid matrix. The other part is the diffuse radiative flux Ψ_{ld} that directly radiates into the environment through the pore structure at the irradiated surface.

Figure 7 shows the effect of porosity ϕ and pore diameter d_p on the radiative heat loss Ψ_{ls} and the diffuse radiative heat loss Ψ_{ld} at the irradiated surface. It can be seen from Figure 8a that for a constant porosity ϕ , Ψ_{ld} initially increases as d_p increases and then decreases. When the pore diameter d_p is constant, Ψ_{ld} initially increases and then decreases; there is still a maximum point.

However, the conductive heat loss Ψ_{ls} significantly decreases as the porosity ϕ increases (see Figure 7b) due to a decrease in the cross-sectional area of the solid phase exposed to the environment. With a constant porosity ϕ , Ψ_{ls} decreases after an initial increase as the pore diameter d_p increases. With a relatively larger porosity ($\phi = 0.9$), a variation in d_p essentially has no effect on Ψ_{ls} due to the very small solid phase cross-sectional area. Thus, with a larger porosity, a larger pore diameter d_p increases the thermal performance of the porous medium. Upon comparing the two figures, one can see that the conductive heat loss Ψ_{ls} is one order of magnitude lower than the diffuse radiative heat loss Ψ_{ld} , which is the primary source of the total heat loss.

3.4. Efficiency

Geometric parameters such as porosity ϕ and pore diameter d_p are the fundamental parameters that characterize the intrinsic properties of porous media. Maps for the efficiency η using porosity and pore diameter as fundamental variables are presented in Figure 8a–8f. It can be clearly seen that an increase in both porosity and pore diameter (in the direction of the *dashed line*) enhances the

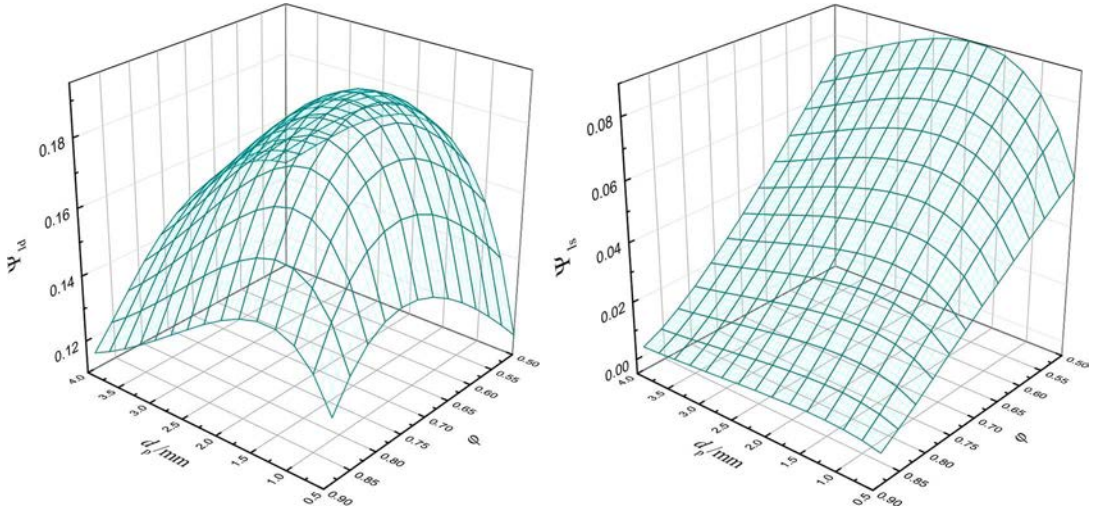


Figure 7. Effect of porosity ϕ and pore diameter d_p on the surface radiative heat loss Ψ_{is} and the diffusive radiative heat loss Ψ_{id} .

volumetric effect. On this basis, the influence of the ratio of solid to fluid thermal conductivities ζ , the flow velocity u , and the volumetric heat transfer coefficient h_v on the efficiency η are analyzed. We use the efficiency η to evaluate the thermal performance of the porous medium as a heat exchanger, which can be defined as the ratio of enthalpy rise of fluid to the total incoming radiation q_0 on the unit irradiated area:

$$\eta = \frac{\dot{m}c_p(T_o - T_i)}{q_0} \quad (31)$$

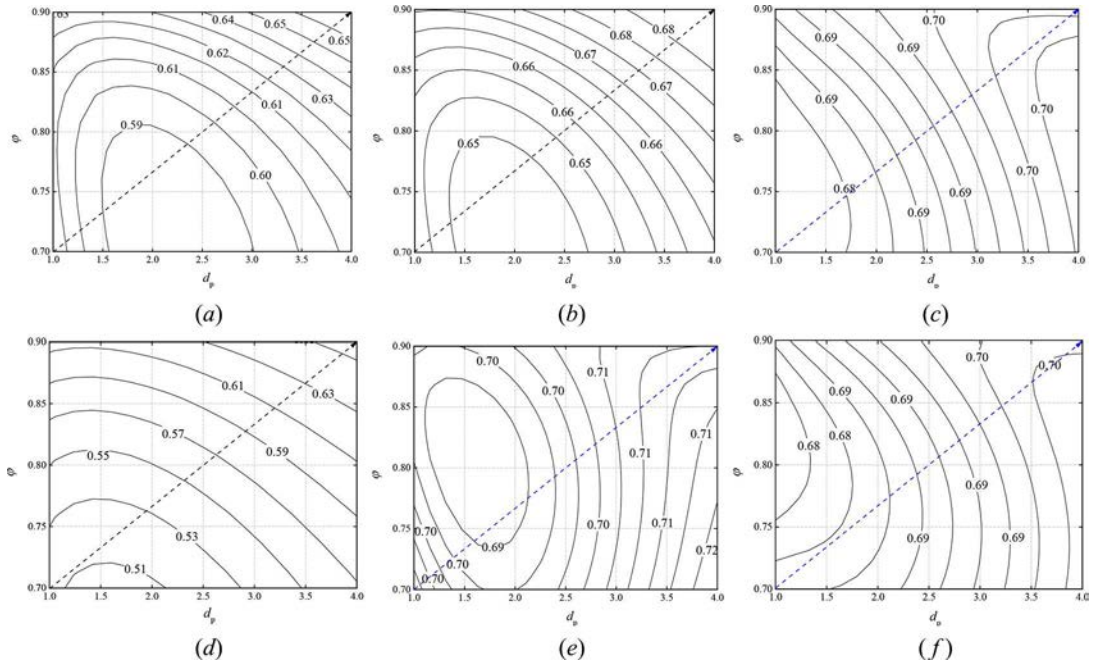


Figure 8. Effect of variation in porosity ϕ and pore diameter d_p on efficiency η for (a) $u=1$, $X_h=1$, $\zeta=1,000$, (b) $u=1$, $X_h=2$, $\zeta=1,000$, (c) $u=1$, $X_h=5$, $\zeta=1,000$, (d) $u=1$, $X_h=1$, $\zeta=100$, (e) $u=3$, $X_h=1$, $\zeta=1,000$, (f) $u=1$, $X_h=5$, $\zeta=2,000$.

3.4.1. Effect of volumetric heat transfer coefficient h_v

The volumetric heat transfer coefficient between the solid and fluid phases h_v significantly influences the heat transfer process in the porous medium. For the sake of simplicity, we directly multiply h_v by an enhancement factor X_h under the premise of unchanging porous structure parameters φ and d_p ; through this approach, we can analyze the effect of the local interphase heat transfer on the efficiency.

It can be seen from comparing Figure 8a, 8b, and 8c that an increase of the volumetric heat transfer coefficient ($X_h = 1, 2$, and 5) significantly increases the efficiency η (from 0.65 to 0.68, then to 0.7) within the entire range of geometric parameters. It is worth noting that when $X_h = 1$, the efficiency η has a minimum value point when $d_p \sim 0.5$ mm, $\varphi \sim 0.8$; the value of η initially decreases and then increases along the direction of the *dashed arrow line*, eventually reaching the maximum value within the parameter ranges. As X_h increases, the minimum point of η gradually moves to the left side; when $X_h = 5$, the impact of porosity φ and pore diameter d_p on η is monotonic within the given range of the geometric parameters. Thus, it can be seen that an increase in the volumetric heat transfer coefficient h_v is conducive to enhancing the volumetric effect by decreasing the solid phase temperature close to the irradiated surface.

3.4.2. Effect of fluid velocity u

Increasing the fluid phase velocity u can improve the efficiency η of the porous medium by increasing the volumetric heat transfer coefficient h_v . It can be seen on comparing Figure 8a and 8e that when the velocity u increases from 3 to 1 m s⁻¹, the efficiency η is significantly decreased throughout the entire range of the parameter. However, the efficiency η becomes more sensitive to the change of the geometric parameters, which means that the increased velocity of the fluid phase decreases the volumetric effect.

3.4.3. Effect of the ratio of solid to fluid thermal conductivities ζ

The effect of the ratio of solid to fluid thermal conductivities ζ on the efficiency η is dependent on interphase convection. On comparing Figure 8a and 8d, we can clearly see that the efficiency increases with an increase of the ratio of solid to fluid thermal conductivities ζ in most ranges of the parameter. However, for a sparse pore structure ($\varphi = 0.9$, $d_p = 4.0$ mm), the efficiency η increases slightly with an increase of ζ (from 100 to 1,000).

When the interphase convection is enhanced, this trend becomes more significant. It can be seen in Figure 8c and 8f (increase of X_h from 1 to 5) that the efficiency η with a sparse pore structure ($\varphi \sim 0.8$, $d_p \sim 3$ mm) significantly decreases by increasing ζ (from 1,000 to 2,000), whereas for the compact pore structure, a reversed trend is indicated. Therefore, when the volumetric effect is significant, decreasing the heat conductivity of the solid phase increases the efficiency; a weak volumetric effect provides the opposite result.

4. Conclusions

In this work we have analyzed the volumetric effect in a porous medium in the presence of collimated irradiation. The mechanisms of convective and radiative transport under this effect were revealed. A modified P-1 approximation with collimated irradiation was introduced to incorporate the radiative transfer. A boundary condition model incorporating the LTNE condition was developed. The following conclusions can be drawn based on our analysis:

1. The volumetric effect can be enhanced by increasing the porosity φ and pore diameter d_p or decreasing the optical thickness τ . In this manner, the sparse pore structure moves the main heat transfer process inside the porous medium by allowing more incoming irradiation to enter the porous medium, consequently obtaining a more significant volumetric effect.
2. The volumetric effect attenuates the LTNE between the solid and fluid phases at the irradiated surface but intensifies it at the back wall. Enhancing the volumetric effect and simultaneously

increasing the medium thickness can improve the thermal performance of the porous medium in practical applications.

3. Under the impact of the volumetric effect, both the conductive heat flux Ψ_c and the diffuse radiative flux Ψ_d reverse the flow direction at the irradiated surface, that is, pointing from the inside of the porous medium toward the outside. In terms of energy transportation, a separation point exists where the direction of the heat flux for both the conductive and radiative energy changes due to the volumetric effect.
4. An increase in the volumetric heat transfer coefficient h_v enhances convection in the high-temperature region close to the irradiated surface, consequently making the volumetric effect more significant. However, a high flow velocity u of the fluid phase decreases the volumetric effect. With a significant volumetric effect, decreasing the ratio of solid to fluid thermal conductivities ζ improves the efficiency η , whereas under a weak volumetric effect, the result is the opposite.
5. The separation point of the diffuse radiative flux Ψ_d always lags behind the conductive heat flux Ψ_c , which shows that the energy transportation by heat conduction and thermal radiation is coupled and restricted. Radiative heat transfer dominates the energy transportation in the porous medium when comparing the diffuse radiative flux Ψ_d with the conductive heat flux Ψ_s . However, the conductive heat loss Ψ_{ls} at the irradiated surface is also an order of magnitude lower relative to the diffusive radiative heat loss Ψ_{ld} ; thus, diffuse radiative heat loss is the primary heat loss within the porous medium.

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