Buoyancy-Driven Channelling Flow in Vertical Porous Layer*

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The porosity of the near-wall region is higher than that of the core region in a porous insulating layer. Then the buoyancy-driven flow will be channelled along the wall of the layer. Considering such an inhomogeneous porous multilayer consisting of a thin fluid layer and a homogeneous porous layer, and proposing an extension of the Beavers-Joseph condition, a theoretical analysis is made on the buoyant channelling flow to clarify the effect of flow and thermal resistance near the wall on heat transfer characteristics. It is shown that heat transfer is generally enhanced by enthalpy transport due to the channelling flow; however, in the weak convection region it is reduced by the thermal resistance near the wall. Discussion is also focused on the critical thickness of the effective fluid layer to eliminate the effect of the enthalpy transport.

Key Words: Porous Media, Natural Convection, Boundary Condition, Channelling Flow, Effective Thermal Conductivity

1. Introduction

In a porous insulating layer, there often arises a high-porosity region near a bounding wall due to inhomogeneous packing or the difference of thermal expansion between the wall and the packing material. The increase of porosity will produce an additional thermal resistance in the vicinity of the wall since the thermal conductivity of interstitial gas is generally lower than that of packing material, while it yields the decrease of flow resistance. The channelling flow causes the deterioration of the insulating performance, and it may cause hot spots, especially in the high-temperature insulating system. Keeping step with the recent tendency toward high-performance insulation, it is of importance to elucidate the fundamental characteristics of heat transfer of the inhomogeneous system.

For vertical natural convection through the porous insulating layer, Masuoka et al.⁽¹⁾ studied the

effects of additional thermal resistance near the wall by using the concept of wall thermal resistance⁽²⁾. The numerical simulations considering the variation of porosity or permeability in the vicinity of the wall were performed by Poulikakos and Bejan⁽³⁾, Nishimura et al.⁽⁴⁾ and Cheng⁽⁵⁾. Furthermore, Masuoka et al.⁽⁶⁾ considered the inhomogeneous porous layer as a multilayer consisting of an effective fluid layer and a homogeneous porous layer, and gave the analytical solutions for the heat transfer of the vertical insulating layer. The boundary conditions at the interface between the porous layer and the fluid layer, however, have been the subject of controversy.

In the present study, we discuss the effect of inhomogeneity of porous media on heat transfer through a vertical insulating layer heated from the side. In particular, we focus our discussion on the relative effects of channelling flow and near-wall thermal resistance on heat transfer. First, we examine the boundary condition on the shear stress at the porous interface for the duct flow along the permeable wall, and modify the Beavers-Joseph condition⁽⁷⁾. Then a simple analytical solution for heat transfer of buoyant channel flow by using the extended boundary condition is derived, and our solution is compared with the previous experimental results. Finally we estimate the critical thickness of the effective fluid

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layer to eliminate the effect of channelling flow.

Nomenclature

- B : nondimensional gap width $[\equiv b^3/(ks)]$
 b : gap width
 d_p : particle diameter
 c_p : specific heat at constant pressure
 Da : Darcy number $[\equiv k/l^2]$
 g : gravitational acceleration
 h : heat transfer coefficient
 h_m : average heat transfer coefficient [Eq.(21)]
 h_p : average heat transfer coefficient in porous layer [Eq.(16)]
 h_w : average heat transfer coefficient in fluid layer [Eq.(16)]
 k : permeability
 l : height of porous layer [Fig. 6]
 Nu : average Nusselt number $[\equiv h_m s / \lambda_p]$
 Ra_s : Rayleigh number based on s
 $[\equiv g \beta (T_h - T_c) s^3 / (\nu \chi)]$
 T : temperature
 T_r : reference temperature $[\equiv (T_h + T_c) / 2]$
 u : streamwise velocity
 u_{loc} : local velocity
 s : width of porous layer [Fig. 6]
 α : slip coefficient [Eq.(3)]
 β : coefficient of thermal expansion
 γ : effective viscosity ratio [Eq.(2)]
 δ : thermal boundary layer thickness
 ε : porosity
 θ : nondimensional interface temperature
 $[\equiv (T_h - T_{ha}) / (T_h - T_r)]$
 χ : thermal diffusivity $[\equiv \lambda_p / (\rho c_p)]$
 λ : thermal conductivity
 μ : viscosity
 ν : kinematic viscosity
 ρ : density
 Subscript
 c : cooled surface
 f : fluid layer
 h : heated surface
 p : porous layer
 w : wall

2. Boundary Conditions at Permeable Surfaces

2.1 Effective shear stress

For porous media such as packed spheres, bundles of capillary tubes or textile materials, the exact position of the boundary or the interface between the porous medium and the surrounding fluid becomes indistinct in the order of magnitude of the effective pore diameter, and further, the definition of overall shear stress requires discussion. As shown in Fig. 1, we consider the parallel plates used by Taylor⁽⁸⁾ and

Richardson⁽⁹⁾ as a model for porous media to consider the flow along the permeable porous boundary. The local velocity is continuous at the interface between the porous medium and the fluid layer such that the average (Darcian) velocity is also continuous. However, it should be emphasized that a part of the shear stress on the fluid side is supported by the solid wall at the interface and this shear stress is not uniform over the x - z plane in general, so the apparent shear stress defined by using the gradient of the average velocity is not continuous at the porous interface. We examine thoroughly the boundary condition at the porous interface by applying the Navier-Stokes equation directly to the duct flow along the permeable parallel plates and dealing with the flow field microscopically.

We pay attention to the interface between the inner and outer fluid flowing along the permeable boundary of the porous medium consisting of parallel plates (see Fig. 2), assuming that the flow is fully developed in the x direction. Thus the dimensionless momentum equation becomes

$$\frac{\partial^2 U}{\partial Y^2} + \frac{\partial^2 U}{\partial Z^2} + \frac{1}{Da} = 0, \quad (1)$$

where velocity component u , pressure gradient dp/dx and independent variables y, z have been nondimensionalized as follows:

$$Y = \frac{y}{l}, \quad Z = \frac{z}{l}, \quad l = \frac{t+a}{2}$$

$$U = \frac{u_{loc}}{Q}, \quad Q = -\frac{k}{\mu} \frac{dp}{dx}, \quad Da = \frac{k}{l^2}$$

$$k = \frac{\varepsilon t^2}{12}, \quad \varepsilon = \frac{t}{t+a}, \quad \eta = \frac{b}{t}.$$

The calculation is made for the region surrounded by the dashed lines in Fig. 2 according to the symmetry of geometry $(-\infty \leq y \leq b, 0 \leq z \leq (t+a)/2)$, and the boundary conditions are given by

$$Y = -200; \quad \frac{\partial U}{\partial Y} = 0$$

$$Z = 0, 1; \quad \frac{\partial U}{\partial Z} = 0.$$

Equation (1) is transformed into the finite-difference

Fig. 1 Model of porous layer

equation by using the control volume formulation, and it is solved iteratively.

The results of the numerical analysis are shown in Figs. 3 and 4, where the effective viscosity ratio γ and slip coefficient α in the Beavers-Joseph condition are defined as follows:

$$\frac{du_f}{dy} = \gamma \frac{du_p}{dy} \quad (2)$$

$$\frac{du_f}{dy} = \alpha \frac{u_f - Q}{\sqrt{k}} \quad (3)$$

The numerical results for the effective viscosity ratio γ tend to approach the curve of $\gamma=1/\varepsilon$ asymptotically as the nondimensional duct width η

Fig. 2 Coordinate system of duct flow along the permeable boundary

Fig. 3 Effective viscosity ratio

Fig. 4 Slip coefficient

increases. It is noted that numerical results are always larger than the curve of $\gamma=1/\varepsilon$. This shows that the shear stress on the fluid side is not fundamentally uniform and that the shear stress on the fluid side in the pore region is less than that in the solid region at the permeable interface. However, it can be said that the boundary condition for shear stress at the interface between a porous medium and a fluid layer is substantially approximated by the following equation⁽⁶⁾:

$$\mu \frac{du_f}{dy} = \frac{\mu}{\varepsilon} \frac{du_p}{dy} \quad (4)$$

The porous viscosity μ/ε obtained from the above equation may agree with the apparent viscosity evaluated from Slattery's momentum equation⁽¹⁰⁾; i.e., the continuity of the apparent shear stress in the form of Eq. (2) seems to be approximately valid.

The numerical results for the slip coefficient α are shown in Fig. 4 with the analytical result by Richardson⁽⁹⁾

$$\alpha \sim \frac{2\pi\sqrt{k}}{a \log a + (a+2t) \log (a+2t) - 2(a+t) \log (a+t)}$$

and the result of scale analysis by Masuoka et al.⁽⁶⁾

$$\alpha \sim \frac{1}{\varepsilon}$$

Although the present results show a similar tendency with Richardson's result, they agree rather quantitatively with the curve of $\alpha=1/\sqrt{\varepsilon}$ which is obtained by combining the analytical result by Neale and Nader⁽¹¹⁾ ($\alpha=\sqrt{\gamma}$) and the foregoing result ($\gamma=1/\varepsilon$). Thus the Beavers-Joseph condition is approximately expressed by

$$\mu \frac{du_f}{dy} = \frac{\mu}{\varepsilon} \frac{u_f - Q}{\sqrt{k/\varepsilon}} \quad (5)$$

2.2 Extension of Beavers-Joseph condition

The foregoing discussion basically assumes uniform velocity in the porous region. We focus on the boundary condition at the interface between a porous medium and a fluid layer under the condition that the velocity field through the porous layer is not uniform. In this condition the velocity change in Q within the thickness of $\sqrt{k/\varepsilon}$ may become comparable with the velocity slip ($u_f - Q$) at the interface. As shown in Fig. 5, the problem under consideration is two-dimensional natural convection through porous media along the isothermal vertical wall at T_w . The vertical wall is covered with a thin fluid layer of thickness b . The fundamental equations for momentum are expressed by the Navier-Stokes equation in a fluid layer and Slattery's equation⁽¹⁰⁾ in a porous layer. Neglecting the inertial terms and assuming the boundary layer approximation and Boussinesq's approximation, the momentum equations in each layer become

Fluid Layer ($0 \leq y \leq b$):

$$\mu \frac{d^2 u_f}{dy^2} + \rho g \beta (T_f - T_r) = 0 \quad (6)$$

Porous Layer 1 ($b \leq y \leq \delta$):

$$\frac{\mu}{\varepsilon} \frac{d^2 u_{p,1}}{dy^2} - \frac{\mu}{k} u_{p,1} + \rho g \beta (T_{p,1} - T_r) = 0 \quad (7)$$

Porous Layer 2 ($\delta \leq y$):

$$\frac{\mu}{\varepsilon} \frac{d^2 u_{p,2}}{dy^2} - \frac{\mu}{k} u_{p,2} = 0. \quad (8)$$

If the temperature profiles in porous and fluid layers are assumed as parabolic, the temperature profiles may be obtained by

$$\frac{T_f - T_r}{T_w - T_r} = \left(1 - GE \frac{y}{\delta}\right)^2 \quad (9)$$

$$\frac{T_{p,1} - T_r}{T_w - T_r} = G^2 \left(1 - \frac{y}{\delta}\right)^2, \quad (10)$$

where

$$G = \frac{W}{W - 1 + E}, \quad W = \frac{\delta}{b}, \quad E = \frac{\lambda_p}{\lambda_f}.$$

Substituting the above temperature profiles into Eqs. (6)~(8) and integrating Eqs. (6)~(8) with the boundary condition at the porous-fluid interface (Eq. (4)), the velocity profile in the porous layer 1 may be obtained as follows:

$$u_{p,1} = D_1 \exp\left(\frac{y}{\sqrt{\gamma k}}\right) + D_2 \exp\left(-\frac{y}{\sqrt{\gamma k}}\right) + u_{ps}, \quad (11)$$

where D_1, D_2 are integral constants and the particular solution u_{ps} becomes

$$u_{ps} = \frac{g \beta (T_w - T_r) k}{\nu} G^2 \left[\left(1 - \frac{y}{\delta}\right)^2 + \frac{2 \gamma k}{\delta^2} \right]. \quad (12)$$

Combining Eqs. (4) and (11) gives the velocity gradient on the fluid side at the permeable interface,

$$-\frac{du_f}{dy} = \sqrt{\frac{\gamma}{k}} \left[u_f - \left\{ u_{ps} + \sqrt{\gamma k} \frac{du_{ps}}{dy} \right. \right. \\ \left. \left. \times \left(1 + \frac{\exp(-\xi)}{\xi}\right) \right\} \right] \quad (13)$$

$$\xi = \frac{\delta - b}{\sqrt{\gamma k}}.$$

Fig. 5 Natural convection in porous layer with fluid gap

Here, ξ is sufficiently great in general and u_{ps} is approximated by $u_{p,d}$ which is obtained by applying Darcy's equation to the momentum equation for the porous layer,

$$u_{p,d} = \frac{g \beta (T_w - T_r) k}{\nu} G^2 \left(1 - \frac{y}{\delta}\right)^2, \quad (14)$$

so Eq. (13) reduces to

$$-\mu \frac{du_f}{dy} = \frac{\mu}{\varepsilon \sqrt{k/\varepsilon}} \left[u_f - \left\{ u_{p,d} + \sqrt{k/\varepsilon} \frac{du_{p,d}}{dy} \right\} \right]. \quad (15)$$

The above equation can be regarded as the extension of the Beavers-Joseph condition, which shows that the velocity Q in Eq. (5) should be estimated by the velocity at the location of $\sqrt{k/\varepsilon}$ apart from the interface between the fluid and porous layers.

3. Analysis

In this section the foregoing extended Beavers-Joseph condition is incorporated into the analysis of buoyant channel flow to clarify the effects of hydraulic and thermal resistances near the wall on heat transfer. We consider the natural convection through porous media in a vertical cavity with adiabatic horizontal walls and isothermal vertical walls at T_h and T_c as shown in Fig. 6. The vertical pressure walls are separated by a distance s and the horizontal ones by a height l . The walls are covered with a thin fluid layer of thickness b , where channelling flow arises.

The existence of the fluid layer will cause the additional thermal resistance near the wall; therefore the apparent average heat transfer coefficient $h_w (\equiv \lambda_f/b)$ in the fluid layer and the average heat transfer coefficient h_p in the porous layer are introduced as follows:

$$q_p = h_w (T_h - T_{ha}) = h_p (T_{ha} - T_r), \quad (16)$$

where q_p is the average heat flux and T_{ha} is the average temperature at the interface between the

Fig. 6 Model of porous insulating layer

porous layer and the fluid layer. Combining Eq.(16) and the analytical result by Masuoka et al.⁽¹⁾,

$$\frac{h_p l}{\lambda_p} = 1.52 \left\{ \frac{g\beta(T_{ha} - T_r)kl}{\nu\kappa} \right\}^{1/2}, \quad (17)$$

we obtain the relationship for nondimensional average interface temperature

$$\frac{h_w s}{2\lambda_p} \theta = \frac{1.52}{2\sqrt{2}} \left(Ra_s \frac{k}{sl} \right)^{1/2} (1 - \theta)^{3/2} \quad (18)$$

under the following condition:

$$\theta \geq \frac{2}{(h_w s / \lambda_p)} \left[\frac{1}{1 - 2(b/s) + 2/(h_w s / \lambda_p)} \right].$$

Next we estimate the enthalpy transport in the fluid layer. We can carry out the same analysis as one in the previous section under the following assumptions: 1) the momentum equation in the porous layer is Darcy's equation, 2) temperature profiles are linear and parabolic respectively in the fluid layer and in the porous layer, 3) Eq.(15) is used as the boundary condition at the permeable interface. Then we obtain the velocity profile in the fluid layer as

$$u_f = \frac{g\beta(T_h - T_r)k}{12\nu} A W Y \{ 2\theta A W^2 Y^2 - 6A W Y + 12R \}, \quad (19)$$

where

$$R = \frac{1}{6(1 + \alpha A)} \left[\alpha \{ (3 - \theta)A^2 + 6(1 - \theta) \} + 3(2 - \theta)A - \frac{24\alpha^2 E \theta}{A} \right].$$

The average heat flux due to enthalpy transport in the fluid layer is approximated by the equation

$$q_e = \frac{\rho C_p}{2l} \left(\frac{T_h + T_{ha}}{2} - T_r \right) \int_0^b u_f dy. \quad (20)$$

Defining the average heat transfer coefficient as

$$q = q_p + q_e = h_m (T_h - T_c), \quad (21)$$

we have the average Nusselt number in the form

$$Nu = \frac{1.52}{2\sqrt{2}} \left(Ra_s \frac{k}{sl} \right)^{1/2} (1 - \theta)^{3/2} + \frac{1}{24} Ra_s \frac{k}{sl} B \times \left\{ \frac{12(R/A) - (4 - \theta)}{4} \right\} \left(\frac{2 - \theta}{4} \right), \quad (22)$$

$$B = \frac{b^3}{ks},$$

where the second term on the right-hand side expresses the enhancement of heat transfer due to channeling flow.

In the actual calculation procedure, we seek the nondimensional interface temperature θ from Eq.(18) with the bisection method, and then obtain the average Nusselt number from Eq.(22).

4. Analytical Results and Discussion

Figure 7 shows the variation of average Nusselt number Nu given by Eq.(22) with porous Rayleigh number $Ra_s k/(sl)$, which is utilized to reduce the effect of aspect ratio l/s ⁽¹⁾. The parameters of B and $h_w s/\lambda_p$ denote the effects of the flow and thermal

resistances near the wall, respectively. It is seen that in the limit of low porous Rayleigh number, the analytical results approach the solution of heat conduction given by

$$Nu_{\text{cnd}} = \frac{1}{1 - 2(b/s) + 2/(h_w s / \lambda_p)}. \quad (23)$$

The analytical results for $B=50$ and $h_w s/\lambda_p=5$ are close to the experimental results for $B=35$ and $h_w s/\lambda_p=4.5$ obtained by Masuoka et al.⁽⁶⁾, and the critical porous Rayleigh number for the onset of convective effect agrees rather well.

The analytical and experimental results indicate that an increase of B reduces the thermal insulation capacity and that such a tendency is remarkable in the region of high porous Rayleigh number. This suggests that a decrease of flow resistance in the gap region enhances the enthalpy transfer. Furthermore, it may be deduced that an increase of B quickens the onset of convective effect. Also, it is noted that the average Nusselt number decreases with decrease in $h_w s/\lambda_p$ for low porous Rayleigh number. However, this effect of thermal resistance in the fluid layer can be reversed with increasing porous Rayleigh number. These results show that the existence of a fluid layer near the wall not only decreases the flow resistance, but also increases the thermal resistance. That is, the heat transfer characteristics are governed by the enthalpy transfer according to the flow channelling through the fluid layer at high $Ra_s k/(sl)$ and by the heat conduction due to the thermal resistance of fluid layer at low $Ra_s k/(sl)$. In other words, the existence of the fluid layer near the wall lessens the thermal insulation capacity for the region where convection dominates, but improves that for the region where conduction dominates.

For the application of the present analysis to the practical porous insulating layer composed of spherical particles, it is necessary to estimate the equivalent

Fig. 7 Effect of the flow and thermal resistance on heat transfer characteristics

gap width for the high-porosity region near the bounding wall. Utilizing the relation by Kimura et al.⁽¹²⁾ on the porosity distribution at the near-wall region, and dividing the inhomogeneous porous layer into the equivalent fluid gap and the homogeneous porous layer, where the equivalent gap width b_{eff} is estimated to be

$$b_{\text{eff}} = 0.15d_p, \quad (24)$$

B and h_{ws}/λ_p are given by

$$B = 3.08 \left(\frac{d_p}{s} \right), \quad \frac{h_{ws}}{\lambda_p} = 6.49 \left(\frac{\lambda_f}{\lambda_p} \right) \left(\frac{s}{d_p} \right). \quad (25)$$

Here, a value of 0.4 is used for the porosity ε and the permeability k is estimated by the Blake-Kozeny equation⁽¹³⁾. The apparent mean heat transfer coefficient h_w in this paper is related to Ofuchi and Kunii's wall heat transfer coefficient $h_w^{(2)}$ by the following equation.

$$q_p = h_w(T_w - T_{ha}) = h_w^{(2)}(T_w - T_{wa}) \quad (26)$$

From this equation a value of $h_w d_p / \lambda_f = 6$ may be close to the Ofuchi-Kunii experimental range $8 < h_w^{(2)} d_p / \lambda_f < 20$.

Equation (25) gives a condition of $B < \sim 1$ as a value of equivalent gap width for an ordinary porous medium packed with spheres. It may therefore be considered from Fig. 7 that there will be no effect of enthalpy transfer due to channelling flow for this condition of B , while the heat transfer characteristics depend on the wall thermal resistance determined by the thermal conductivity ratio of the fluid to the solid matrix.

5. Conclusions

The high porosity near the wall of the porous insulating layer can either decrease the heat transfer rate due to the induced thermal resistance or increase the rate due to the enthalpy transfer caused by the channelling flow. In the present study, we considered the effect of channelling flow by introducing the concept of the equivalent fluid layer adjacent to the wall surface and discussed the boundary condition at the interface between the porous and fluid layers. On the basis of the extended boundary condition, the fundamental characteristics of heat transfer in the vertical porous insulating layer were clarified with both the effects of buoyancy channelling flow and the near-wall thermal resistance. The conclusions are:

(1) The boundary condition for the shear stress term at the interface between the porous and fluid layers can be approximated by

$$\mu \frac{du_f}{dy} = \frac{\mu}{\varepsilon} \frac{du_p}{dy}$$

and the Beavers-Joseph condition is extended as

$$\mu \frac{du_f}{dy} = \frac{\mu}{\varepsilon \sqrt{k/\varepsilon}} \left[u_f - \left\{ u_{p,D} + \sqrt{k/\varepsilon} \frac{du_{p,D}}{dy} \right\} \right].$$

(2) In the vertical porous insulating layer, the enthalpy transfer due to the channelling flow at the gap fluid layer reduces the thermal insulation capacity. The effect of channelling flow is notable for the larger nondimensional gap width; however, it can be neglected for $B < \sim 1$. The near-wall thermal resistance induced by the high-porosity region or the equivalent gap fluid layer suppresses the heat transfer rate.

(3) When the equivalent gap width B is not too large, the average Nusselt number is expressed by

$$Nu = \frac{1.52}{2\sqrt{2}} \left(Ra_s \frac{k}{sl} \right)^{1/2} (1 - \theta)^{3/2} + \frac{1}{24} Ra_s \frac{k}{sl} B \times \left\{ \frac{12(R/A) - (4 - \theta)}{4} \right\} \left(\frac{2 - \theta}{4} \right),$$

where

$$\frac{h_{ws}}{2\lambda_p} \theta = \frac{1.52}{2\sqrt{2}} \left(Ra_s \frac{k}{sl} \right)^{1/2} (1 - \theta)^{3/2}.$$

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