Heat Transfer—Asian Research, **43** (8), 2014

Mixed Convection Over a Vertical Plate in a Doubly Stratified Fluid-Saturated Non-Darcy Porous Medium with Cross-Diffusion Effects

D. Srinivasacharya and O. Surender
Department of Mathematics, National Institute of Technology, Warangal-506004, A.P., India

The present article investigates the influence of Dufour and Soret effects on mixed convection heat and mass transfer over a vertical plate in a doubly stratified fluid-saturated porous medium. The plate is maintained at a uniform and constant wall heat and mass fluxes. The Darcy–Forchheimer model is employed to describe the flow in porous medium. The nonlinear governing equations and their associated boundary conditions are initially transformed into dimensionless forms. The resulting system of nonlinear partial differential equations is then solved numerically by the Keller-box method. The variation of the dimensionless velocity, temperature, concentration, heat, and mass transfer rates for different values of governing parameters involved in the problem are analyzed and presented graphically. © 2013 Wiley Periodicals, Inc. Heat Trans Asian Res; Published online in Wiley Online Library (wileyonlinelibrary.com/journal/htj). DOI 10.1002/htj.21114

Key words: mixed convection, double stratification, Dufour and Soret effects, non-Darcy porous medium, heat and mass transfer

1. Introduction

The study of mixed convective transport in a doubly stratified (thermal and/or solutal stratification) fluid-saturated porous medium has been a topic of continuing interest in the past decades due to its importance in many industrial and engineering applications. These applications include electronic devices cooled by fans, nuclear reactors cooled during an emergency shutdown, a heat exchanger placed in a low-velocity environment, solar collectors, and so on. In many practical situations the porous medium is bounded by an impermeable wall, has higher flow rates, and reveals the non-uniform porosity distribution near the wall region, making Darcy's law inapplicable. To model the real physical situation better, it is therefore necessary to include the aforementioned non-Darcian terms in the analysis of convective transport in a porous medium. Non-Darcy models are the extensions of the classical Darcy formulation to incorporate inertial drag effects, vorticity diffusion, and combinations of these effects. Different models such as Brinkman-extended Darcy, Forchheimer-extended Darcy, and the generalized flow models were proposed in the literature to analyze the non-Darcian flow in porous media. Several authors have reported the study of mixed convection heat and mass transfer in porous medium for which the Forchheimer-extended Darcy model is employed. Comprehensive reviews of convective heat transfer in Darcy and non-Darcy porous medium can be found in Nield and Bejan [1], Ingham and Pop [2, 3], Bejan [4], Vafai [5], and Vafai and Hadim [6].

Stratification of fluid is a deposition/formation of layers, which occurs due to temperature variations, concentration differences, or the presence of different fluids. In practical situations where the heat and mass transfer mechanisms occur simultaneously, it is important to analyze the effect of double stratification (stratification of the medium with respect to the thermal and concentration fields) on the convective transport. Ishak et al. [7] investigated the mixed convection boundary layer flow through a stable stratified porous medium bounded by a vertical surface. The analytic solution of the steady mixed-convection boundary-layer flow through a stable stratified medium adjacent to a vertical surface has been obtained using the homotopy analysis method by Ganji et al. [8]. Bansod and Jadhav [9] studied the mixed convection heat and mass transfer near a vertical surface in a stratified porous medium using an integral method. Geetha and Moorthy [10] analyzed the heat and mass transfer characteristics in a viscous fluid over a semi-infinite vertical porous plate by taking into account the variable viscosity, chemical reaction, and thermal stratification effects. The effects of thermal and solutal stratification on mixed convection along a vertical plate embedded in a micropolar fluid saturated non-Darcy porous medium have been analyzed by Srinivasacharya and RamReddy [11]. An analysis for the axisymmetric laminar boundary layer mixed convection flow of a viscous and incompressible fluid towards a stretching cylinder immersed in a thermally stratified medium has been presented by Mukhopadhyay and Ishak [12]. The mixed convection flow in a concentration-stratified fluid-saturated vertical square porous enclosure has been investigated numerically using the Galerkin finite element method by Rathish Kumar and Krishnamurthy [13].

In all the aforementioned papers, the significance of the Dufour and Soret effect was neglected on the basis that they were of a smaller order of magnitude than the effects described by Fourier's and Fick's laws. However, Eckert and Drake [14] reported several cases when the Dufour effect cannot be neglected. Diffusion-thermo or the Dufour effect corresponds to the energy flux caused by a concentration gradient. On the other hand, thermal diffusion or the Soret effect corresponds to species differentiation occurring in an initial homogeneous mixture submitted to a thermal gradient. Due to the importance of the Dufour and Soret effects for the fluids with very light molecular weight as well as medium molecular weight, many investigators have studied and reported results for these flows. A remarkable number of studies have been carried out by many authors concentrating on the problem of coupled heat and mass transfer past different geometries embedded in porous media with Dufour and Soret effects. The Dufour and Soret effects on mixed convection flow past a vertical porous flat plate embedded in a porous medium have been studied numerically by Alam and Rahman [15]. Chamkha and Ben-Nakhi [16] focused on the numerical modelling of steady, laminar, heat, and mass transfer by MHD mixed convection from a semi-infinite, isothermal, vertical, and permeable surface immersed in a uniform porous medium in the presence of thermal radiation, Dufour, and Soret effects. Shateyi et al. [17] investigated the influence of a magnetic field on heat and mass transfer by mixed convection from vertical surfaces in the presence of Hall, radiation, Soret, and Dufour effects. A study has been carried out to analyze the combined effects of Soret and Dufour on unsteady, MHD, non-Darcy mixed convection over a stretching sheet embedded in a saturated porous medium in the presence of thermal radiation, viscous dissipation, and first-order chemical reaction by Pal and Mondal [18]. Makinde [19] studied the mixed convection flow of an incompressible Boussinesq fluid under the simultaneous action of buoyancy and a transverse magnetic field with Soret and Dufour effects over a vertical porous plate with constant heat flux embedded in a porous medium. The steady natural convection along an inclined stretching surface in the presence of chemical reaction under thermal-diffusion and diffusion-thermo effects has been studied by Huang et al. [20]. The non-similar solutions for the problem of Soret and Dufour effects on the boundary layer flow due to mixed convection heat and mass transfer over a downward-pointing vertical wedge in a porous medium saturated with Newtonian fluids with constant wall temperature and concentration have been obtained using the cubic spline collocation method by Cheng [21].

Previous studies on convective transport focused on obtaining a similarity solution because similar variables can give great physical insight with minimal effort. However, the non-similarity boundary layer flows are more general in nature in our everyday life, and thus are more important than the similarity ones. To the best of the authors' knowledge, it may be noticed that previous studies did not include the effect of double stratification on double diffusive mixed convection flow of a viscous fluid past a semi-infinite vertical flat plate embedded in a porous medium in the presence of Soret and Dufour effects. Hence we have made an attempt to present the non-similar solutions for the problem of mixed convection on a vertical plate with constant and uniform heat and mass fluxes in a stable doubly stratified non-Darcian fluid in which the ambient temperature and concentration varies linearly. The presence of Soret and Dufour effects are considered. The Keller-box method given in Cebeci and Bradshaw [22] is employed to solve the nonlinear system of this particular problem. The influence of stratification parameters, Lewis number, Forchheimer number, buoyancy parameter, mixed convection parameter, Soret, and Dufour parameters on physical quantities are examined and displayed graphically.

2. Mathematical Formulation

Consider a steady, laminar, incompressible, two-dimensional mixed convective heat and mass transfer along a semiinfinite vertical plate in a stable, doubly stratified viscous fluid-saturated non-Darcy porous medium in the presence of Dufour and Soret effects. The porous medium is considered to be homogeneous and isotropic (i.e., uniform with a constant porosity and permeability). The fluid has constant properties except the density in the buoyancy term of the balance of momentum equation. The fluid flow is moderate, so the pressure drop is proportional to the linear combination of fluid velocity and the square of the velocity (Forchheimer flow model is considered). The x coordinate is taken along the plate in the ascending direction and the y coordinate is measured normal to the plate, while the origin of the reference system is considered at the leading edge of the vertical plate. The physical model and the coordinate system are shown in Fig. 1. The plate is subjected to uniform and constant heat and mass fluxes q_w and q_m, respectively. The ambient medium is assumed to be vertically linearly stratified with respect to both temperature and concentration in the form $T_\infty(x) = T_{\infty,0} + Ax$, $C_\infty(x) = C_{\infty,0} + Bx$, where A and B are constants are varied to alter the intensity of stratification in the medium, and the $T_{\infty,0}$ and $C_{\infty,0}$ are ambient temperature and concentration, respectively. By employing laminar boundary layer flow assumptions, Boussinesq approximation and using the Darcy–Forchheimer model, the governing equations for flow are given by

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (1)$$

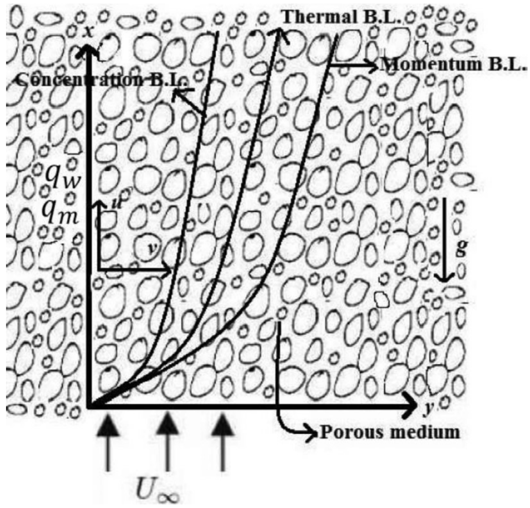

Fig. 1. Physical model and coordinate system.

$$\frac{\partial u}{\partial y}+\frac{2c\sqrt{K}}{\nu}u\frac{\partial u}{\partial y}=\left(\frac{Kg\beta_T}{\nu}\right)\frac{\partial T}{\partial y}+\left(\frac{Kg\beta_C}{\nu}\right)\frac{\partial C}{\partial y} \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{DK_T}{C_sC_p}\frac{\partial^2 C}{\partial y^2} \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}+\frac{DK_T}{T_m}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

where u and v are the average velocity components in x and y directions, respectively, T is the temperature, C is the concentration, β_T and β_C are the thermal and solutal expansion coefficients, respectively, ν is the kinematic viscosity of the fluid, K is the permeability, g is the acceleration due to gravity, α is the thermal diffusivity of the porous medium, D is the solutal diffusivity of the porous medium, Le is thermal diffusion ratio, C_s is concentration susceptibility, C_p is specific heat capacity, and T_m is mean fluid temperature. The last terms in Eqs. (3) and (4) are due to Dufour and Soret effects, respectively.

The boundary conditions are

$$v=0,\ q_w=-k\frac{\partial T}{\partial y},\ q_m=-D\frac{\partial C}{\partial y}\quad \text{at } y=0 \tag{5a}$$

$$u\to u_\infty,\ T\to T_\infty(x),\ C\to C_\infty(x)\quad \text{as } y\to\infty \tag{5b}$$

where the subscripts w, (∞, 0), and ∞ indicate the conditions at the wall, at some reference point in the medium, and at the outer edge of the boundary layer, respectively.

Introducing the following non-dimensional variables

$$\left.\begin{aligned}
&\xi = \frac{x}{L}, \eta = \frac{\mathrm{Pe}^{1/3}}{L\xi^{1/3}} y, \psi = \alpha Pe^{1/3}\xi^{2/3} f(\xi,\eta) \\
&T - T_\infty(x) = \frac{q_w L}{kPe^{1/3}}\xi^{1/3}\theta(\xi,\eta) \\
&C - C_\infty(x) = \frac{q_m L}{DPe^{1/3}}\xi^{1/3}\phi(\xi,\eta)
\end{aligned}\right\} \tag{6}$$

In view of the continuity Eq. (1), we introduce the stream function ψ by

$$u = \frac{\partial\psi}{\partial y}, \qquad v = -\frac{\partial\psi}{\partial x}$$

and substituting Eq. (6) into Eqs. (1) to (4), we obtain

$$f'' + 2F_c\xi^{1/3} f' f'' = \frac{Ra}{Pe}(\theta' + \mathrm{B}\phi') \tag{7}$$

$$\theta'' + \frac{2}{3} f\theta' - \frac{1}{3} f'\theta - \varepsilon_1 \xi^{2/3} f' + D_f \phi'' = \xi\left(f'\frac{\partial\theta}{\partial\xi} - \theta'\frac{\partial f}{\partial\xi}\right) \tag{8}$$

$$\frac{1}{Le}\phi'' + \frac{2}{3} f\phi' - \frac{1}{3} f'\phi - \varepsilon_2 \xi^{2/3} f' + S_r \theta'' = \xi\left(f'\frac{\partial\phi}{\partial\xi} - \phi'\frac{\partial f}{\partial\xi}\right) \tag{9}$$

where the prime denotes differentiation with respect to η, $Ra = Kg\beta_T q_w L^2/\alpha\nu$ is the Rayleigh number, $Pr = \nu/\alpha$ is the Prandtl number, $F_c = c\sqrt{K}Pe^{2/3}/L\,Pr$ is the Forchheimer number, $Le = \alpha/D$ is the diffusivity ratio, $B = \beta_c q_m k/\beta_T q_w D$ is the buoyancy ratio, and $\varepsilon_1 = kPe^{1/3}A/q_w$ and $\varepsilon_2 = DPe^{1/3}B/q_m$ are the thermal and solutal stratification parameters, respectively. $D_f = (DK_T/C_sC_p\alpha)(q_m k/q_w D)$ is the Dufour parameter and $S_r = (DK_T/T_m\alpha)(q_w D/q_m k)$ is the Soret parameter.

The boundary conditions Eq. (5) becomes

$$2f(\xi,0) + 3\xi\left(\frac{\partial f}{\partial\xi}\right)_{\eta=0} = 0,\ \theta'(\xi,0) = -1,\ \phi'(\xi,0) = -1 \tag{10a}$$

$$f'(\xi,\infty) = 1,\quad \theta(\xi,\infty) = 0,\ \phi(\xi,\infty) = 0 \tag{10b}$$

Results of practical interest are both heat and mass transfer rates. The local Nusselt number Nu_ξ and the local Sherwood number Sh_ξ are respectively, given by

$$\frac{Nu_\xi}{Pe^{1/3}} = \frac{\xi^{2/3}}{\varepsilon_1\xi^{2/3} + \theta(\xi,0)} \tag{11a}$$

$$\frac{Sh_\xi}{Pe^{1/3}} = \frac{\xi^{2/3}}{\varepsilon_2\xi^{2/3} + \phi(\xi,0)} \tag{11b}$$

3. Results and Discussion

Equations (7) to (9) with the boundary conditions (10) constitute nonlinear non-homogeneous differential equations for which a closed form solution cannot be obtained. Hence, these equations have been solved numerically using an implicit finite-difference method known as the Keller-box scheme [22]. First the second-order equations have been converted to first-order equations by substituting $f' = F$, $\theta' = G$, and $\phi' = P$. Then the partial derivatives with respect to ξ and η are written in difference form by using central difference approximation and averaged at the midpoints of net rectangles in the (ξ, η) domain to obtain finite difference equations. The resulting nonlinear algebraic equations have been linearized by applying the Newton method and are cast as the block matrix system. Using the block-tridiagonal-elimination technique, the linear system has been solved. The initial values for the velocity, temperature, and concentration are arbitrarily chosen such that they satisfy the boundary conditions. The independence of the results at least up to the 4th decimal place on the mesh density was examined. A convergence criterion based on the relative difference between the current and previous iterations was used. When this difference reached 10^{-5}, the solutions were assumed to converge and the iterative process was terminated. This method has been proven to be adequate and to give accurate results for boundary layer equations. In the present study, the boundary conditions for η at ∞ are replaced by sufficiently large value of η, where the velocity, temperature, and concentration profiles approach zero. We have taken $\eta_\infty = 6$, a grid size of $\eta = 0.01$, and $\xi = 0.3$ as fixed. In order to study the effects of stratification parameters ε_1 and ε_2 computations were carried out for the fixed values of $F_c = 0.5$, $B = 0.5$, $Le = 1.0$, while ε_1 and ε_2 were varied over a range.

The variation of the non-dimensional velocity, temperature, and concentration profiles with η for different values of thermal stratification parameter ε_1 is illustrated in Fig. 2. It is observed from Fig. 2(a) that the velocity of the fluid decreases with the increase of thermal stratification parameter. This is due to thermal stratification which reduces the effective convective potential between the heated plate and ambient fluid in the medium. Hence, the thermal stratification effect reduces the velocity in the boundary layer. From Fig. 2(b), it is clear that the temperature of the fluid decreases with the increase of thermal stratification parameter. When the thermal stratification is taken into consideration, the effective temperature difference between the plate and the ambient fluid will decrease; therefore, the thermal boundary layer is thickened and the temperature is reduced. It is noticed from Fig. 2(c) that the concentration of the fluid increases with the increase of thermal stratification parameter.

Figure 3 depicts the effect of solutal stratification parameter ε_2 on the non-dimensional velocity, temperature, and concentration. It is noticed from Fig. 3(a) that the velocity of the fluid decreases with the increase of solutal stratification parameter. It is demonstrated from Fig. 3(b) that the temperature of the fluid increases with the increase of solutal stratification parameter. From Fig. 3(c), it is observed that the concentration of the fluid decreases with the increase of the solutal stratification parameter. It is observed that the non-dimensional temperature and concentration values are becoming negative inside the boundary layer for different values of the stratification parameters depending on the values of other parameters. This is in tune with the observations made by Prandtl [23], Jaluria and Himasekhar [24], Gebhart et al. [25], and Lakshmi Narayana and Murthy [26]. This is because the fluid near the plate can have a temperature or concentration lower than the ambient medium.

The effect of buoyancy parameter B on the non-dimensional velocity, temperature, and concentration is shown in Fig. 4. It is clear from Fig. 4(a) that the velocity of the fluid increases near the plate and decreases away from the plate with the increase of the buoyancy parameter. It is noticed from Fig. 4(b) that the temperature of the fluid decreases with the increase of the buoyancy parameter.

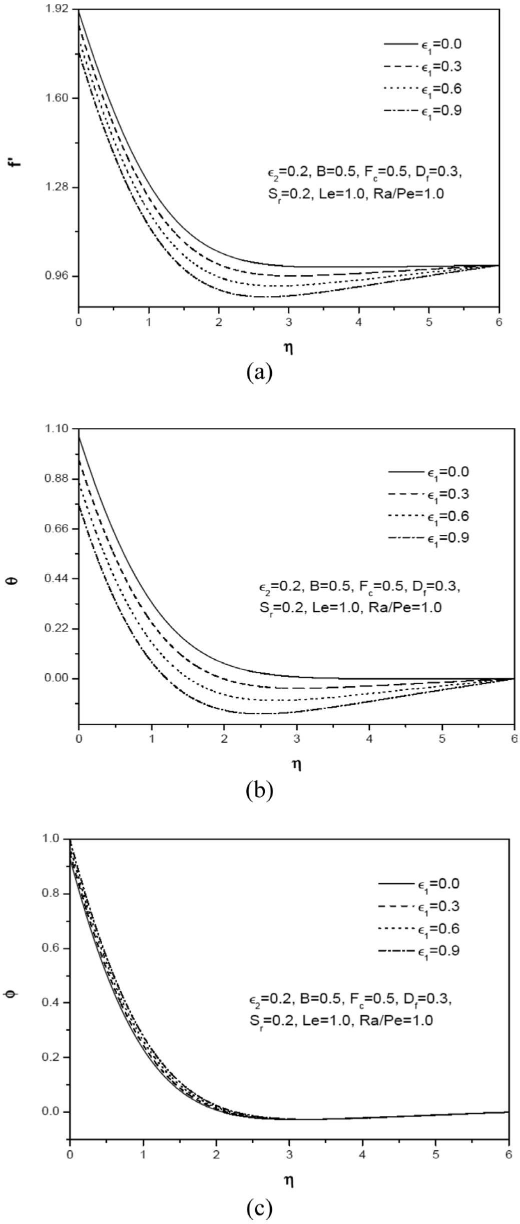

Fig. 2. (a) Velocity, (b) temperature, and (c) concentration profiles for various values of ε_1.

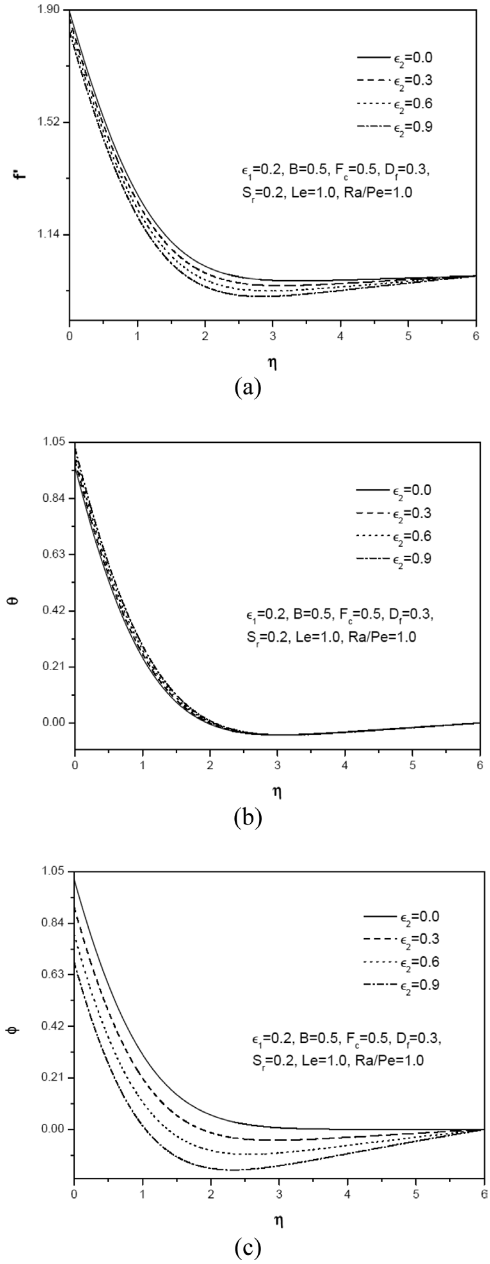

Fig. 3. (a) Velocity, (b) temperature, and (c) concentration profiles for various values of ε_2.

From Fig. 4(c), it is observed that the concentration of the fluid decreases with the increase of the buoyancy parameter. This is because increasing the buoyancy ratio *B* will enhance the surface heat and mass transfer rates. Increasing the buoyancy parameter increases the velocity near the vertical flat plate and the high velocity near the surface will carry more heat out of the surface, thus decreases the thermal and solutal boundary layer thickness and then increases the heat and mass transfer rates.

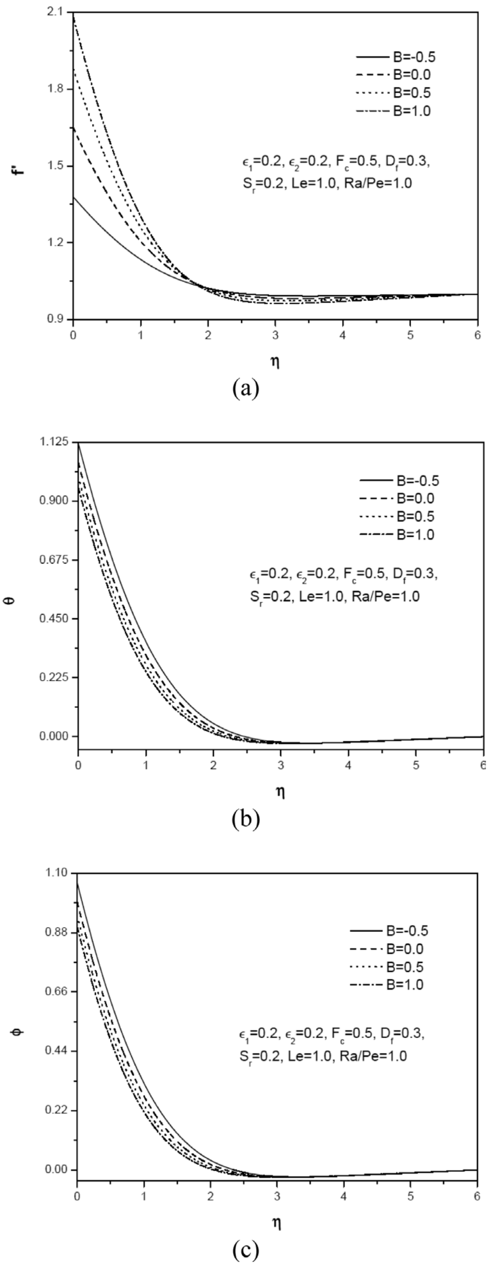

Fig. 4. (a) Velocity, (b) temperature, and (c) concentration profiles for various values of B.

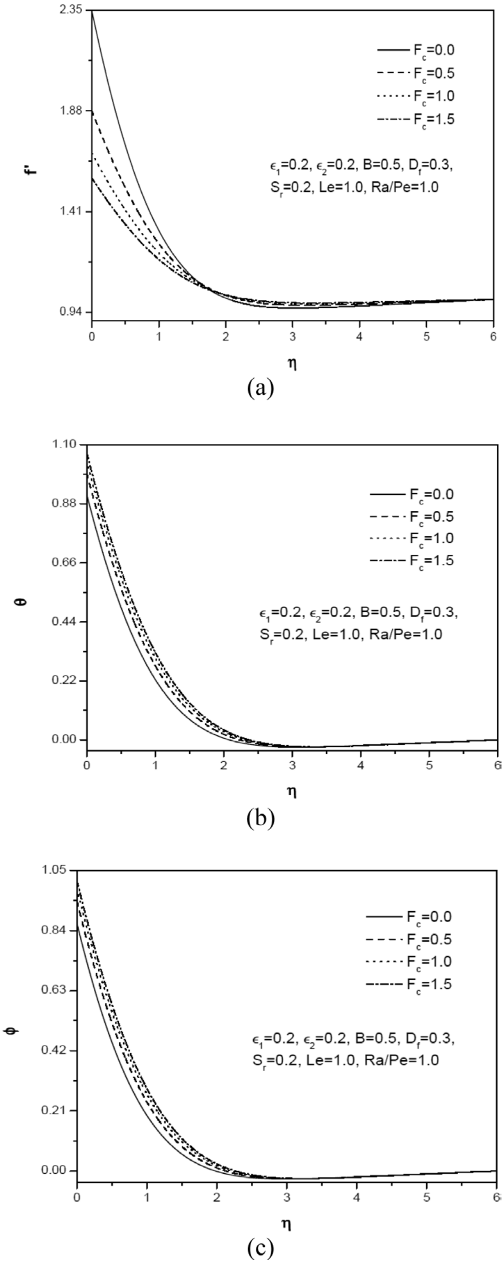

Fig. 5. (a) Velocity, (b) temperature, and (c) concentration profiles for various values of F_c.

Figure 5 depicts the effect of Forchheimer number F_c on the non-dimensional velocity, temperature, and concentration. It is observed from Fig. 5(a) that the velocity of the fluid decreases near the plate and increases away from the plate with the increase of the Forchheimer number. Since F_c represents the inertial drag, an increase in the Forchheimer number increases the resistance to the flow and so a decrease in the fluid velocity near the plate ensues. Here $F_c = 0$ represents the case where the flow is Darcian. The velocity is maximum in this case due to the total absence of inertial drag. It is noticed from Fig. 5(b) that the temperature of the fluid increases with the increase of the Forchheimer number. An increase in F_c increases temperature values, since as the fluid is decelerated, energy is dissipated as heat and serves to increase temperatures. From Fig. 5(c), it is observed that the concentration of the fluid increases with the increase of the Forchheimer number. As the Forchheimer number increases, the concentration boundary layer thickness increases. The increase in non-Darcy parameter reduces the intensity of the flow but enhances the thermal and concentration boundary layer thicknesses.

Figure 6 presents the variation of non-dimensional velocity, temperature, and concentration with the Dufour parameter D_f. It is seen from Fig. 6(a) that the higher values of the Dufour parameter results in higher velocity of the fluid. The non-dimensional temperature is enhanced with the increase of the Dufour parameter as shown in Fig. 6(b). Figure 6(c) exhibits that the non-dimensional concentration is reduced with the increase of the Dufour parameter.

Figure 7 depicts the effect of the Soret parameter S_r on non-dimensional velocity, temperature, and concentration. It is noticed from Fig. 7(a) that the velocity of the fluid increased with enhancement of the Soret parameter. Figure 7(b) reveals that the non-dimensional temperature is reduced with the increase of the Soret parameter. Figure 7(c) shows that the non-dimensional concentration is enhanced with the rise in the Soret parameter.

The variation of local heat transfer coefficient (Nusselt number Nu_ξ) with thermal and solutal stratification parameters is presented in Fig. 8(a). It is found from Fig. 8(a) that the local heat transfer rate enhances with the increase in the value of thermal stratification parameter ε_1. Physically, positive values of the stratification parameter have the tendency to decrease the boundary layer thickness due to the reduction in the temperature difference between the plate and the free stream. This causes an increase in the Nusselt number. It is also clear from the same graph that the local heat transfer rate slightly decreases with the rise of ε_2. The influence of thermal and solutal stratification parameters on local mass transfer coefficient (Sherwood number Sh_ξ) is shown in Fig. 8(b). Figure 8(b) illustrates that the local mass transfer coefficient slightly decreases with the increase in the thermal stratification parameter. This is due to the fact that effective mass transfer between the plate and the ambient medium decreases as the thermally stratified effect increases. It is seen from the same figure that the local mass transfer coefficient enhances with the increase of solutal stratification parameter.

The effect of the Dufour and Soret parameters on local heat transfer coefficient is exhibited in Fig. 9(a). It is found from Fig. 9(a) that the local heat transfer rate enhances with the increase in Soret parameter S_r but decreases with the raise of Dufour parameter D_f. The influence of the Dufour and Soret parameters on local mass transfer coefficient is shown in Fig. 9(b). Figure 9(b) reveals that the local mass transfer coefficient increases with the increase in the Dufour parameter D_f and we notice that the local mass transfer coefficient enhances with the decrease in the Soret parameter S_r.

The variation of local heat and mass transfer coefficients with Forchheimer number F_c is shown in Fig. 10(a). It is found from Fig. 10(a) that both local heat and mass transfer rates decrease with the increase in Forchheimer number F_c. Since F_c represents the inertial drag, an increase in the Forchheimer number increases the resistance to the flow. The effect of Lewis number on local heat and mass transfer coefficients is shown in Fig. 10(b). Figure 10(b) shows that the local heat transfer

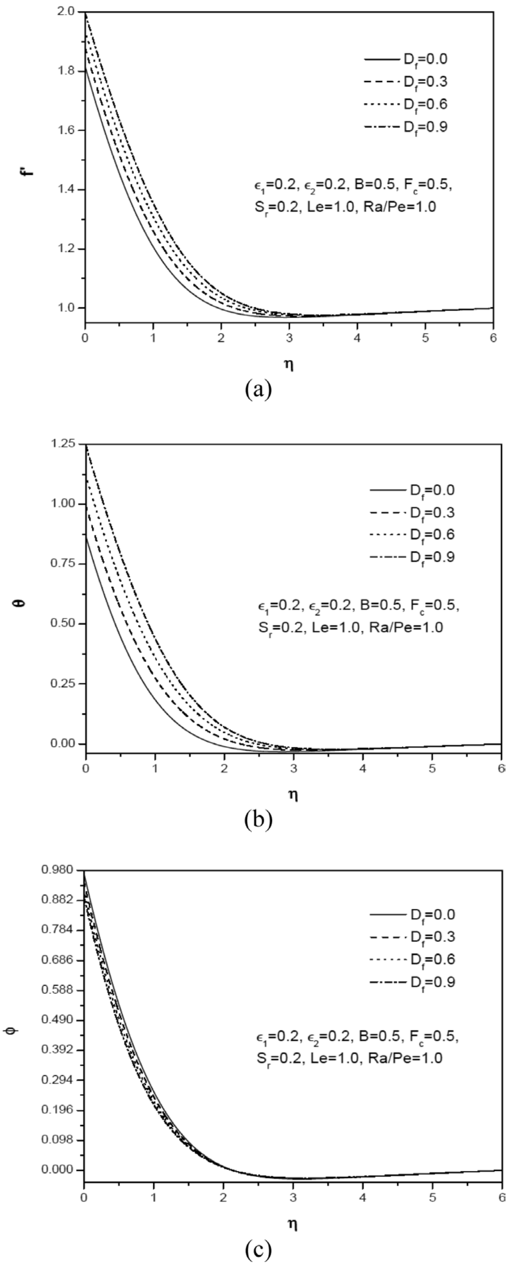

Fig. 6. (a) Velocity, (b) temperature, and (c) concentration profiles for various values of D_f.

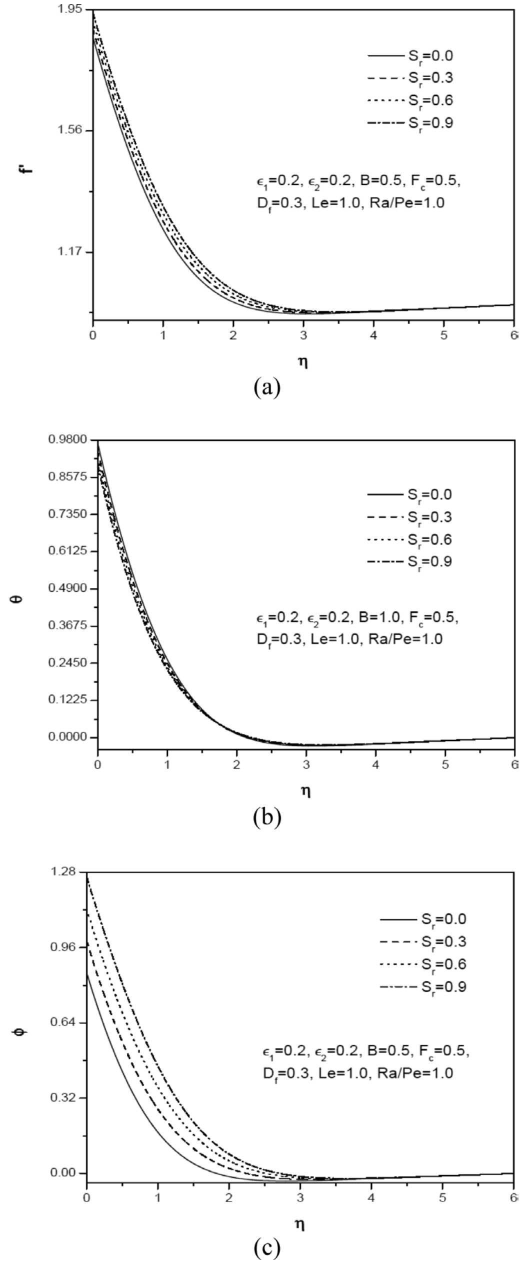

Fig. 7. (a) Velocity, (b) temperature, and (c) concentration profiles for various values of S_r.

rate decreases with the increase in Lewis number *Le* whereas the mass transfer rate is enhanced with the rise of the Lewis number.

The effect of mixed convection parameter *Ra/Pe* on the non-dimensional heat and mass transfer coefficients is presented in Fig. 11. It can be observed from Fig. 11 that the non-dimensional

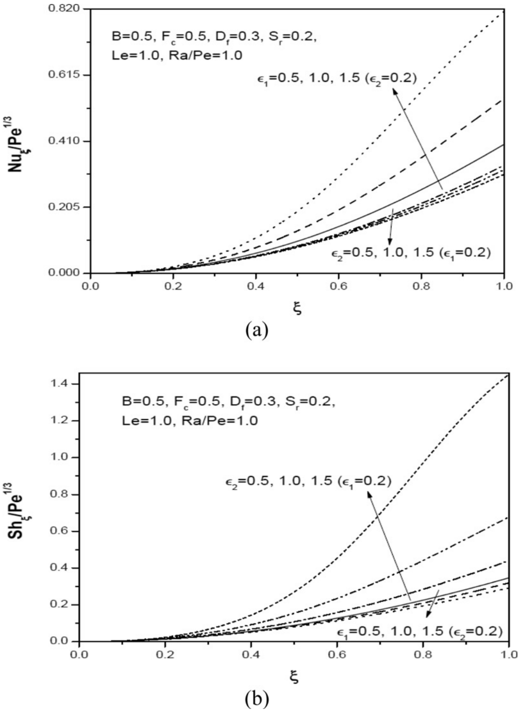

Fig. 8. (a) Heat transfer rate, (b) mass transfer rates for different values of both ε_1 and ε_2.

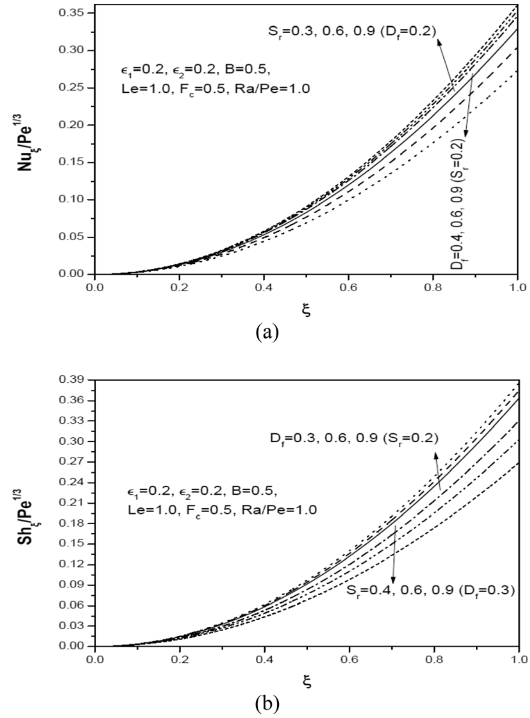

Fig. 9. (a) Heat transfer rate, (b) mass transfer rates for different values of both D_f and S_r.

heat and mass transfer coefficients increase with the increasing values of mixed convection parameter *Ra/Pe*. Hence the mixed convection parameter has an important role in controlling the temperature and concentration.

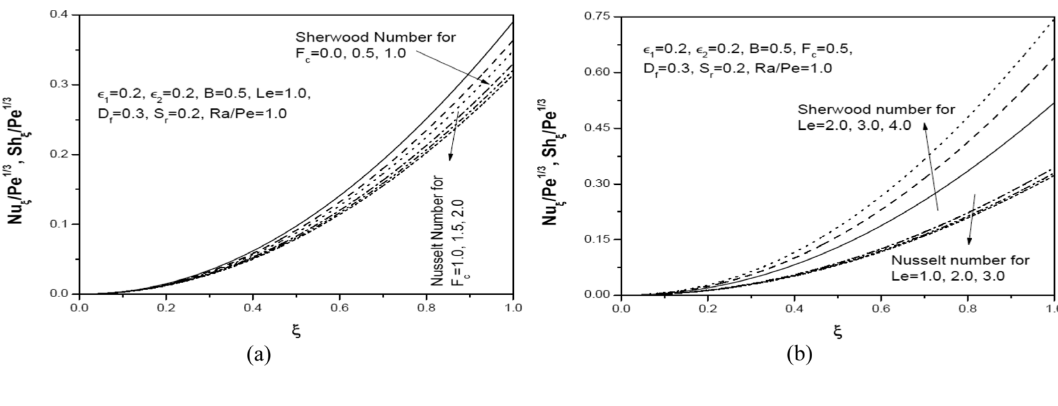

Fig. 10. (a) Heat and mass transfer rates, (b) heat and mass transfer rates for different values of F_c and Le, respectively.

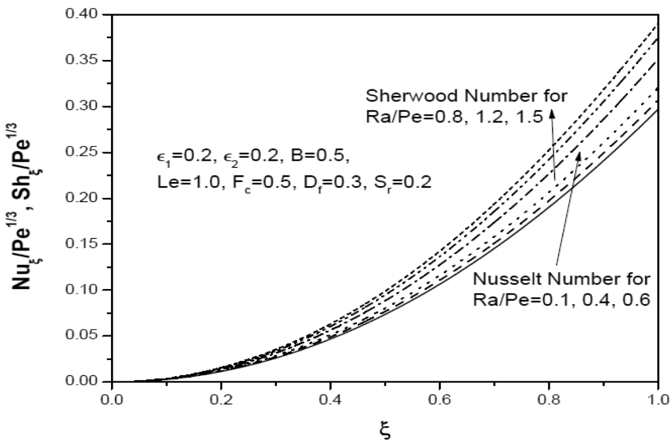

Fig. 11. Heat transfer rate and mass transfer rate for different values of mixed convection parameter.

4. Conclusions

Mixed convection heat and mass transfer from a vertical surface embedded in a doubly stratified viscous fluid-saturated non-Darcy porous medium in the presence of Soret and Dufour effects is analyzed. Numerically, non-similar solutions are obtained for different values of the thermal stratification parameter, solutal stratification parameter, buoyancy parameter, Forchheimer number, mixed convection parameter, and Soret and Dufour parameters. An increase in the thermal stratification parameter ε_1 decreases the velocity, temperature, and local mass transfer coefficient but increases the concentration and local heat transfer coefficient. The higher value of solutal stratification parameter ε_2 results in lower velocity, concentration, and local heat transfer coefficient but higher temperature and local mass transfer coefficient. The effect of the buoyancy parameter is to increase the velocity near the plate and to decrease the velocity away from the plate, temperature, and concentration whereas the opposite trend is observed in the case of the Forchheimer number. The influence of Forchheimer number is to decrease both the local heat and mass transfer coefficients whereas the significance of the mixed convection parameter is to increase both local heat and mass transfer coefficients. The influence of the Dufour parameter is to increase the non-dimensional velocity, and temperature, and to decrease the concentration. The higher values of the Soret parameter result in higher velocity, concentration, and lower temperature. The presence of the Soret parameter increases the local heat transfer rate but decreases the local mass transfer rate. The local heat transfer rate is decreased and local mass transfer rate is increased due to the presence of the Dufour parameter. The local heat transfer rate is decreased whereas the local mass transfer rate is increased with the increase of the Lewis number.

Literature Cited

1. Nield DA, Bejan A. Convection in porous media, 4th ed. Springer-Verlag; 2013.
2. Ingham DB, Pop I (editors). Transport phenomenon in porous media, vol. I. Pergamon; 1998.
3. Ingham DB, Pop I (editors). Transport phenomenon in porous media, vol. III. Elsevier; 2005.

4. Bejan A. Convection heat transfer. John Wiley; 1994.
5. Vafai K. Handbook of porous media, 2nd ed. Taylor and Francis Group; 2005.
6. Vafai K, Hadim H. Overview of current computational studies of heat transfer in porous media and their applications—natural convection and mixed convection. Adv Numer Heat Transf 2000;2:331–371.
7. Ishak A, Nazar R, Pop I. Mixed convection boundary layer flow over a vertical surface embedded in a thermally stratified porous medium. Phys Lett A 2008;372:2355–2358.
8. Ganji DD, Asgharian A, Sedaghati Zadeh N. Approximate solution of mixed convection boundary-layer flow adjacent to a vertical surface embedded in a stable stratified medium. Heat Transf Res 2009;40:729–745.
9. Bansod VJ, Jadhav RK. Effect of double stratification on mixed convection heat and mass transfer from a vertical surface in a fluid-saturated porous medium. Heat Transf Asian Res 2010;39(6):378–395.
10. Geetha P, Moorthy MBK. Variable viscosity, chemical reaction and thermal stratification effects on mixed convection heat and mass transfer along a semi infinite vertical plate. Am J Appl Sci 2011;8(6):628–634.
11. Srinivasacharya D, RamReddy Ch. Mixed convection in a doubly stratified micropolar fluid saturated non-Darcy porous medium. Can J Chem Eng 2011;90(5):1311–1322.
12. Mukhopadhyay S, Ishak A. Mixed convection flow along a stretching cylinder in a thermally stratified medium. J Appl Math 2012;491695.
13. Rathish Kumar BV, Krishnamurthy SVSSNVG. A finite element study of double diffusive mixed convection in a concentration stratified Darcian fluid saturated porous enclosure under injection/suction effect. J Appl Math 2012;594701.
14. Eckert ERG, Drake RM. Analysis of heat and mass transfer. McGraw Hill; 1972.
15. Alam MS, Rahman MM. Dufour and Soret effects on mixed convection flow past a vertical porous flat plate with variable suction. Nonlinear Analysis: Modeling and Control 2006;11:3–12.
16. Chamkha AJ, Ben-Nakhi A. MHD mixed convection–radiation interaction along a permeable surface immersed in a porous medium in the presence of Soret and Dufour effects. Heat Mass Transf 2008;44:845–856.
17. Shateyi S, Motsa SS, Sibanda P. The effects of thermal radiation, hall currents, Soret and Dufour on MHD flow by mixed convection over a vertical surface in porous media. Math Prob Eng 2010;627475.
18. Dulal Pal, Hiranmoy Mondal. Effects of Soret, Dufour, chemical reaction and thermal radiation on MHD non-Darcy unsteady mixed convective heat and mass transfer over a stretching sheet. Commun Nonlinear Sci Numer Simulat 2011;16:1942–1958.
19. Makinde OD. On MHD mixed convection with Soret and Dufour effects past a vertical plate embedded in a porous medium. Latin Am Appl Res 2011;41:63–68.
20. Huang JS, Tsai R, Huang KH, Huang CH. Thermal-diffusion and diffusion thermo effects on natural convection along an inclined stretching surface in a porous medium with chemical reaction. Chem Eng Commun 2010;198:453–473.
21. Cheng CY. Soret and Dufour effects on mixed convection heat and mass transfer from a vertical wedge in a porous medium with constant wall temperature and concentration. Transp Porous Med 2012;94:123–132.
22. Cebeci T, Bradshaw P. Physical and computational aspects of convective heat transfer. Springer-Verlag; 1984.
23. Prandtl L. Essentials of fluid dynamics. Blackie; 1952.
24. Jaluria Y, Himasekhar K. Buoyancy induced two dimensional vertical flows in a thermally stratified environment. Comput Fluids 1983;11:39–49.

25. Gebhart B, Jaluria Y, Mahajan R, Sammakia B. Buoyancy induced flows and transport. Hemisphere Publishing Co; 1988.
26. Lakshmi Narayana PA, Murthy PVSN. Soret and Dufour effects in a doubly stratified Darcy porous medium. J Porous Media 2007;10:613–624.

□♦ ♦ ♦□