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Research Article

Non-Darcy Mixed Convection in a Doubly Stratified Porous Medium with Soret-Dufour Effects

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This paper presents the nonsimilarity solutions for mixed convection heat and mass transfer along a semi-infinite vertical plate embedded in a doubly stratified fluid saturated porous medium in the presence of Soret and Dufour effects. The flow in the porous medium is described by employing the Darcy-Forchheimer based model. The nonlinear governing equations and their associated boundary conditions are initially cast into dimensionless forms and then solved numerically. The influence of pertinent parameters on dimensionless velocity, temperature, concentration, heat, and mass transfer in terms of the local Nusselt and Sherwood numbers is discussed and presented graphically.

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 owing to its importance in many industrial and engineering applications. These applications include heat rejection into the environment such as lakes, rivers, and seas; thermal energy storage systems such as solar ponds; and heat transfer from thermal sources such as the condensers of power plants. Numerous studies on mixed convection heat and mass transfer have been reported in the past several decades using both Darcian and non-Darcian models for the porous medium. Comprehensive reviews of convective heat transfer in porous medium can be found in the books by Nield and Bejan [1], Pop and Ingham [2], and Bejan [3]. Non-Darcian 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. The Darcy-Forchheimer model is an extension of classical Darcian formulation obtained by adding a velocity squared term in the momentum equation to account for the inertial effects. 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.

Stratification of fluid is a deposition/formation of layers and occurs due to temperature variations, concentration differences, or the presence of different fluids. It is important to examine the temperature stratification and concentration differences of hydrogen and oxygen in lakes and ponds as they may directly affect the growth rate of all cultured species. Also, the analysis of thermal stratification is important for solar engineering because higher energy efficiency can be achieved with better stratification. It has been shown by scientists that thermal stratification in energy storage may considerably increase system performance. Although the effect of stratification of the medium on the heat removal process in a porous medium is important, very little work has been reported in the literature. Mukhopadhyay and Ishak [4] presented 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. The influence of thermal dispersion and stratification on the flow and temperature fields for mixed convection from a vertical plate embedded in a porous medium has been investigated by Hassanien et al. [5]. Steady, laminar, hydromagnetic simultaneous heat and mass transfer by mixed convection flow over a vertical plate embedded in a uniform porous medium with a stratified free stream and taking into account the presence of thermal dispersion has been investigated for the case of power-law variations of both the wall temperature and concentration by Chamkha and Khaled [6]. Ishak et al. [7] investigated the mixed convection boundary layer flow through a stable stratified porous medium bounded by a vertical surface. The effects of variable viscosities and thermal stratification on the MHD mixed convective heat and mass transfer of a viscous, incompressible, and electrically conducting fluid past a porous wedge in the presence of a chemical reaction have been investigated by Muhaimin et al. [8]. Using Galerkin finite element method, numerical investigation of mixed convection flow in a concentration-stratified fluid-saturated vertical square porous enclosure has been investigated by Rathish Kumar and Krishna Murthy [9].

In all the aforementioned papers, the significance of Dufour and Soret was neglected on the basis that they are of a smaller order of magnitude than the effects described by Fourier's and Fick's laws. However, Eckert and Drake [10] reported several cases when the Dufour effect cannot be neglected. Diffusion-thermal or Dufour effect corresponds to the energy flux caused by a concentration gradient. On the other hand, thermal diffusion or Soret effect corresponds to species differentiation occurring in an initial homogeneous mixture submitted to a thermal gradient. Due to the importance of 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. Seddeek [11] analyzed the thermal-diffusion and the diffusion-thermal effects on the mixed free-forced convective and mass transfer steady laminar boundary-layer flow over an accelerating surface with a heat source in the presence of suction and blowing. 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 has been investigated by Shateyi et al. [12]. The Soret and Dufour effects on the steady, laminar mixed convection heat and mass transfer along a semi-infinite vertical plate embedded in a non-Darcy porous medium saturated with micropolar fluid have been studied by Srinivasacharya and Ramreddy [13]. Cheng [14] studied the 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.

In this paper, we made an attempt to obtain the nonsimilar solutions for mixed convection on a vertical plate with constant and uniform wall temperature and concentration in a stable doubly stratified non-Darcian fluid in which the ambient temperature and concentration vary linearly. Soret and Dufour effects are considered. The Keller-box method given in Cebeci and Bradshaw [15] 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 non-Darcian mixed convective heat and mass transfer along a semi-infinite vertical plate in a stable, doubly stratified viscous fluid saturated porous medium with uniform velocity U_∞ far away from the plate with Soret and Dufour effects. In the formulation of the present problem, the following assumptions are made.

(i) The flow is steady, laminar, incompressible, two dimensional.

(ii) The porous medium is homogeneous and isotropic (i.e., uniform with a constant porosity and permeability).

(iii) The fluid has constant properties except the density in the buoyancy term of the balance of momentum equation.

(iv) The fluid flow is moderate, so the pressure drop is proportional to the linear combination of fluid velocity and the square of velocity.

(v) The Boussinesq and boundary-layer approximations are applicable.

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 Figure 1. The plate is maintained at uniform wall temperature and concentration T_w and C_w, 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 varied to alter the intensity of stratification in the medium and $T_{\infty,0}$ and $C_{\infty,0}$ are ambient temperature and concentration, respectively. With the above assumptions and using the Darcy-Forchheimer model, the governing equations for flow are given by

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{1}$$

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

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

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

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 and D is the solutal diffusivity of the porous medium, K_T is thermal diffusion ratio, C_s is concentration susceptibility, C_p

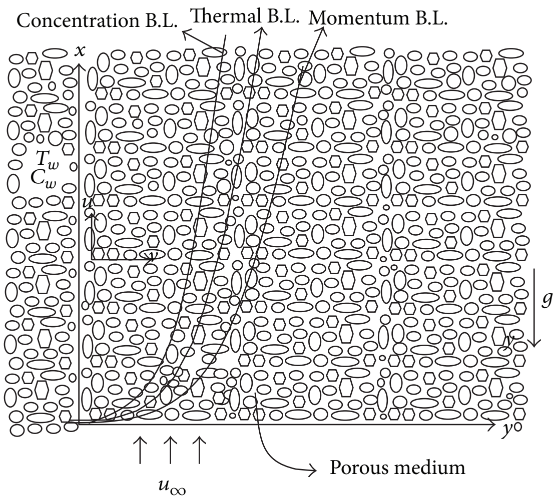

Figure 1: Physical model and coordinate system.

is specific heat capacity, and T_m is mean fluid temperature. The last terms in (3) and (4) are due to Dufour and Soret effects, respectively.

The boundary conditions are

$$v = 0, \quad T = T_w, \quad C = C_w \quad \text{at } y = 0, \tag{5a}$$

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

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

3. Method of Solution

The continuity equation (1) is satisfied by introducing the stream function ψ such that

$$u = \frac{\partial \psi}{\partial y}, \qquad v = -\frac{\partial \psi}{\partial x}. \tag{6}$$

Introducing the following nondimensional variables:

$$\begin{gathered} \xi = \frac{x}{L}, \quad \eta = \frac{\mathrm{Pe}^{1/2}}{L\xi^{1/2}} y, \quad \psi = \alpha \mathrm{Pe}^{1/2} \xi^{1/2} f(\xi, \eta) \\ T - T_\infty(x) = (T_w - T_{\infty,0})\, \theta(\xi, \eta), \\ C - C_\infty(x) = (C_w - C_{\infty,0})\, \phi(\xi, \eta). \end{gathered} \tag{7}$$

Substituting (6) and (7) in (2), (3), and (4), we obtain

$$f'' + 2F_c f' f'' = \frac{\mathrm{Ra}}{\mathrm{Pe}} \left[\theta' + B\phi'\right], \tag{8}$$

$$\theta'' + \frac{1}{2} f\theta' - \epsilon_1 \xi f' + D_f \phi'' = \xi \left[f' \frac{\partial \theta}{\partial \xi} - \theta' \frac{\partial f}{\partial \xi} \right], \tag{9}$$

$$\frac{1}{\mathrm{Le}} \phi'' + \frac{1}{2} f\phi' - \epsilon_2 \xi f' + S_r \theta'' = \xi \left[f' \frac{\partial \phi}{\partial \xi} - \phi' \frac{\partial f}{\partial \xi} \right], \tag{10}$$

where the prime denotes differentiation with respect to η, $\mathrm{Ra} = Kg\beta_T(T_w - T_{\infty,0})L/\alpha\nu$ is the Rayleigh number, $\mathrm{Pr} = \nu/\alpha$ is the Prandtl number, $F_c = c\sqrt{K}\mathrm{Pe}/L\mathrm{Pr}$ is the Forchheimer number, $\mathrm{Le} = \alpha/D$ is the diffusivity ratio and $B = \beta_C(C_w - C_{\infty,0})/\beta_T(T_w - T_{\infty,0})$ is the buoyancy ratio, $\epsilon_1 = AL/(T_w - T_{\infty,0})$ and $\epsilon_2 = BL/(C_w - C_{\infty,0})$ are the thermal and solutal stratification parameters, respectively, $D_f = (DK_T/\alpha C_s C_p)((C_w - C_{\infty,0})/(T_w - T_{\infty,0}))$ is Dufour parameter, and $S_r = (DK_T/\alpha T_m)((T_w - T_{\infty,0})/(C_w - C_{\infty,0}))$ is Soret parameter.

The boundary conditions (5a) and (5b) in terms of f, θ, and ϕ becomes

$$\begin{gathered} f(\xi, 0) + 2\xi \left(\frac{\partial f}{\partial \xi}\right)_{\eta=0} = 0, \qquad \theta(\xi, 0) = 1 - \epsilon_1 \xi, \\ \phi(\xi, 0) = 1 - \epsilon_2 \xi, \end{gathered} \tag{11a}$$

$$f'(\xi, \infty) = 1, \qquad \theta(\xi, \infty) = 0, \qquad \phi(\xi, \infty) = 0. \tag{11b}$$

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

$$\frac{\mathrm{Nu}_\xi}{\mathrm{Pe}^{1/2}} = -\xi^{1/2}\theta'(\xi, 0), \qquad \frac{\mathrm{Sh}_\xi}{\mathrm{Pe}^{1/2}} = -\xi^{1/2}\phi'(\xi, 0). \tag{12}$$

4. Results and Discussion

Equations (8)–(10) with the boundary conditions (11a) and (11b) constitute a nonlinear nonhomogeneous differential equations for which 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 [15]. This method has four main steps. The first step is converting (8) to (10) into a system of first-order equations. The second step is replacing partial derivatives by central finite difference approximation. The third step is linearizing the nonlinear algebraic equations by Newton's method and then casting as the matrix vector form. The last step is solving linearized system of equations using the block-tridiagonal-elimination technique. Here, the initial values for velocity temperature and concentration are arbitrarily chosen so 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 have converged and the iterative process was terminated. This method has been proven to be adequate and 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 to zero. We have taken $\eta_\infty = 8$ and a grid size of η of 0.01 and $\xi = 0.1$ is fixed. In order to study the effects of stratification parameters, ϵ_1 and ϵ_2 computations were carried out for the fixed values of $F_c = 0.5$, $\mathrm{Le} = 1.0$, $B = 0.5$, $D_f = 0.3$, $S_r = 0.2$, and $\mathrm{Ra/Pe} = 1.0$ while ϵ_1 and ϵ_2 were varied over a range.

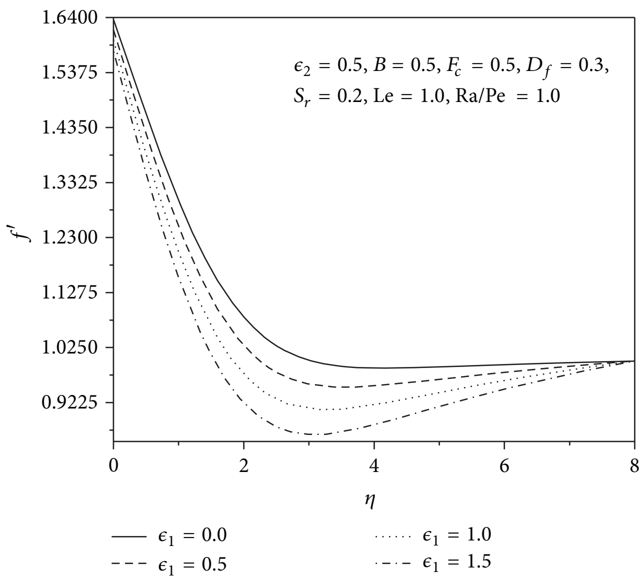

Figure 2: Variation of nondimensional velocity with thermal stratification parameter.

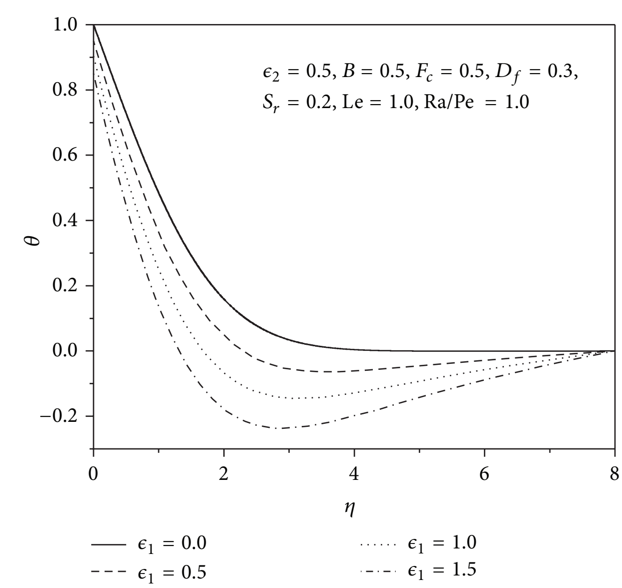

Figure 3: Variation of nondimensional temperature with thermal stratification parameter.

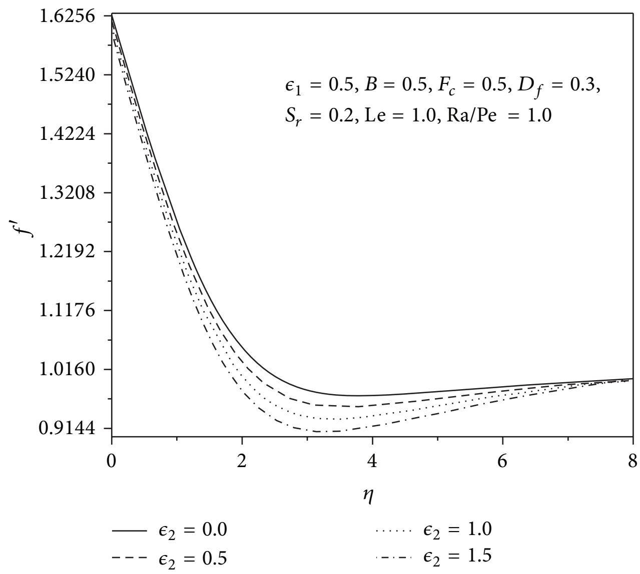

Figure 4: Variation of nondimensional velocity with solutal stratification parameter.

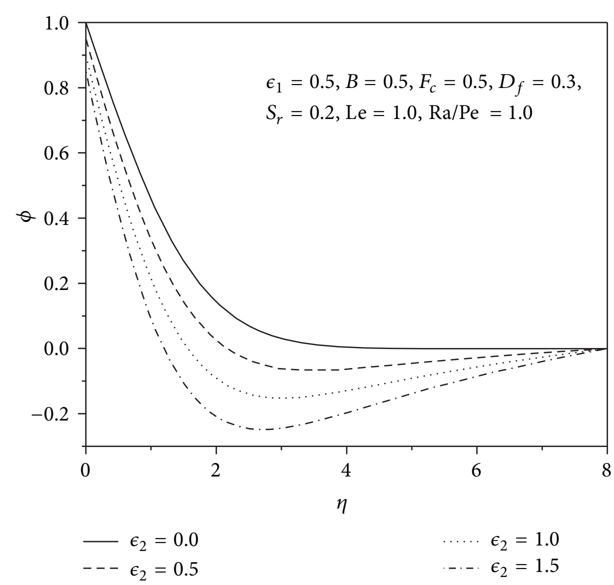

Figure 5: Variation of nondimensional concentration with solutal stratification parameter.

The variation of the nondimensional velocity and temperature profiles with η for different values of thermal stratification parameter ϵ_1 is illustrated in Figures 2 and 3. It is observed from Figure 2 that the velocity of the fluid decreases by nearly 11% with the increase of thermal stratification parameter ϵ_1 from 0 to 1.5. This is due to that thermal stratification 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 Figure 3, it is clear that the temperature of the fluid decreases by around 72% with the increase of thermal stratification parameter ϵ_1 from 0 to 1.5. 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. The figure depicting the effect of thermal stratification parameter on nondimensional concentration is not included as the variation is very less.

Figures 4 and 5 depict the effect of solutal stratification parameter ϵ_2 on the nondimensional velocity, and concentration. It is noticed from Figure 4 that the velocity of the fluid decreases by about 5% with the increase of solutal stratification parameter ϵ_2 from 0 to 1.5. From Figure 5, it

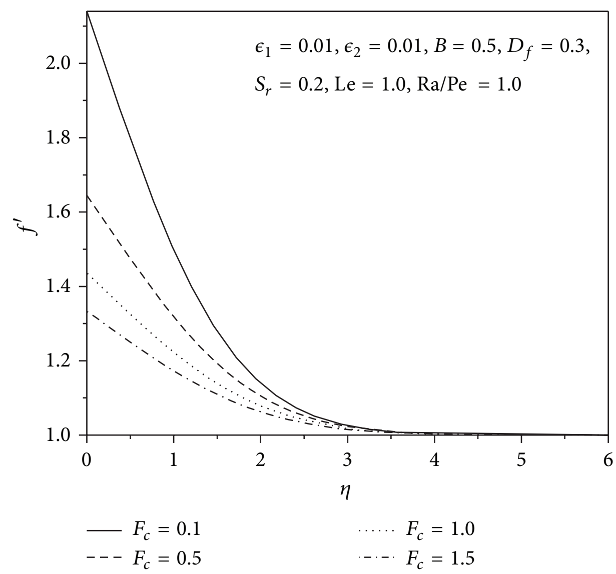

FIGURE 6: Variation of nondimensional velocity with Forchheimer parameter.

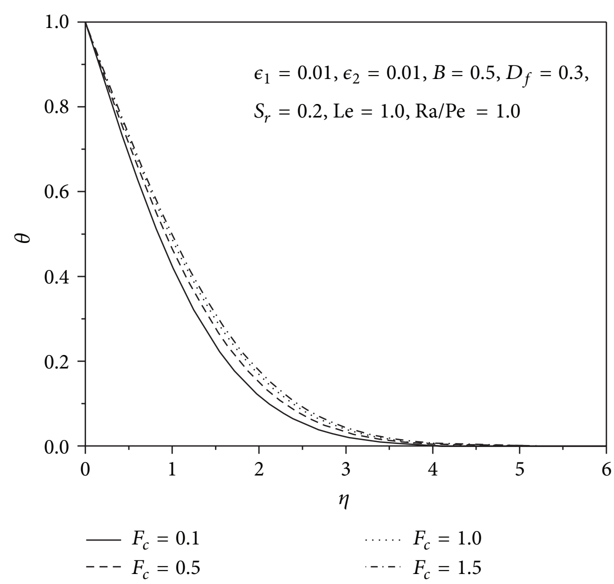

FIGURE 7: Variation of nondimensional temperature with Forchheimer parameter.

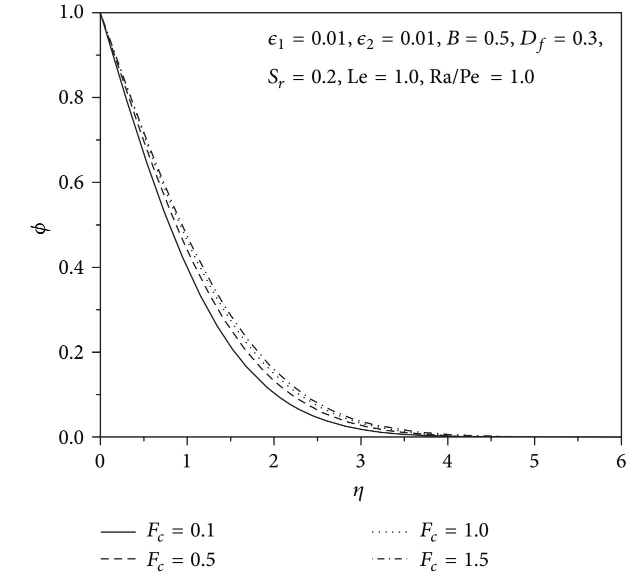

FIGURE 8: Variation of nondimensional concentration with Forchheimer parameter.

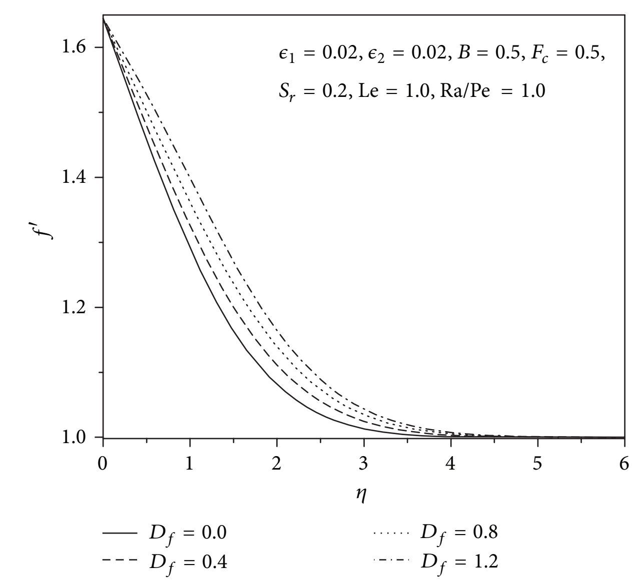

FIGURE 9: Variation of nondimensional velocity with Dufour parameter.

is observed that the concentration of the fluid decreases by about 80% with the increase of the solutal stratification parameter ϵ_2 from 0 to 1.5. The graph showing the influence of solutal stratification on nondimensional temperature is not included as the impact is very low. It is observed that the nondimensional 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 observation made in [16–19]. This is because the fluid near the plate can have temperature or concentration lower than the ambient medium.

Figures 6–8 depict the effect of Forchheimer number F_c on the nondimensional velocity, temperature, and concentration. It is observed from Figure 6 that the velocity of the fluid decreases by nearly 22% with the increase of Forchheimer number F_c from 0.1 to 1.5. Since F_c represents the inertial drag, thus an increase in the Forchheimer number increases the resistance to the flow and so a decrease in the fluid velocity 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 Figure 7 that the temperature of the fluid increases by about 18% with the increase of Forchheimer number F_c from

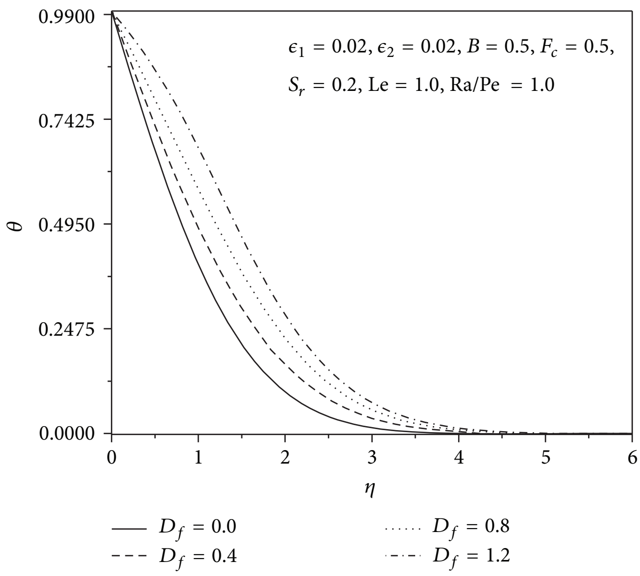

Figure 10: Variation of nondimensional temperature with Dufour parameter.

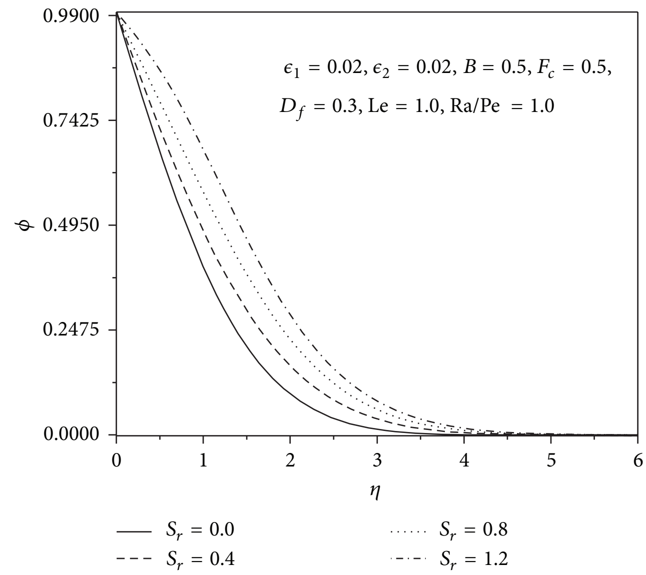

Figure 12: Variation of nondimensional concentration with Soret parameter.

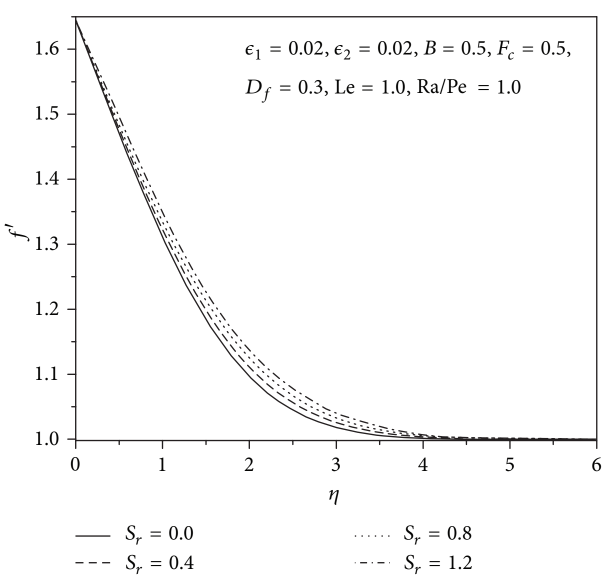

Figure 11: Variation of nondimensional velocity with Soret parameter.

0.1 to 1.5. An increase in F_c leads to rise temperature. As the fluid is decelerated, energy is dissipated as heat and it serves to enhance temperature in the boundary layer. From Figure 8, it is observed that the concentration of the fluid increases 19% with the increase of the Forchheimer number F_c from 0.1 to 1.5. 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.

Figures 9 and 10 present the variation of nondimensional velocity and temperature with Dufour parameter D_f. It is seen from Figure 9 that the velocity of the fluid is enhanced by nearly 9% with the increase of Dufour parameter D_f from 0 to 1.2. The nondimensional temperature is enhanced by around 69% with the increase of Dufour parameter D_f from 0 to 1.2 as shown in Figure 10. The Dufour parameter denotes the contribution of the concentration gradients to the thermal energy flux in the flow. It can be seen that an increase in the Dufour parameter produces a significant increase in the velocity and temperature. The graph showing the effect of Dufour parameter on concentration is not included in the paper as the impact is very low.

Figures 11 and 12 depict the effect of Soret parameter S_r on nondimensional velocity and concentration. It is noticed from Figure 11 that the velocity of the fluid increased by nearly 4% with rise of Soret parameter S_r from 0 to 1.2. Soret parameter is the ratio of temperature difference to the concentration. Hence, the higher value of Soret parameter stands for a larger temperature difference and precipitous gradient. Thus the fluid velocity enhances due to greater thermal diffusion factor. Figure 12 shows that the nondimensional concentration is enhanced by about 70% with the raise of Soret parameter S_r from 0 to 1.2. The figure depicting the effect of Soret parameter on nondimensional temperature is not presented in this paper due to less variation in the temperature with varying Soret parameters.

The variation of local heat and mass transfer coefficients (Nusselt number Nu_ξ and Sherwood number Sh_ξ) with thermal and solutal stratification parameters is presented in Figures 13 and 14. It is found from Figure 13 that the local heat transfer rate enhances by nearly 54% with the increase in the value of thermal stratification parameter ϵ_1 from 1.0 to 2.0. 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 increase in the Nusselt

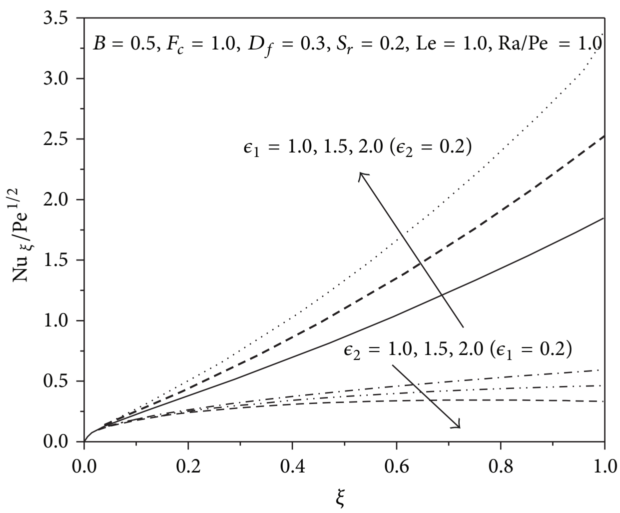

Figure 13: Variation of heat transfer rate with stratification parameters.

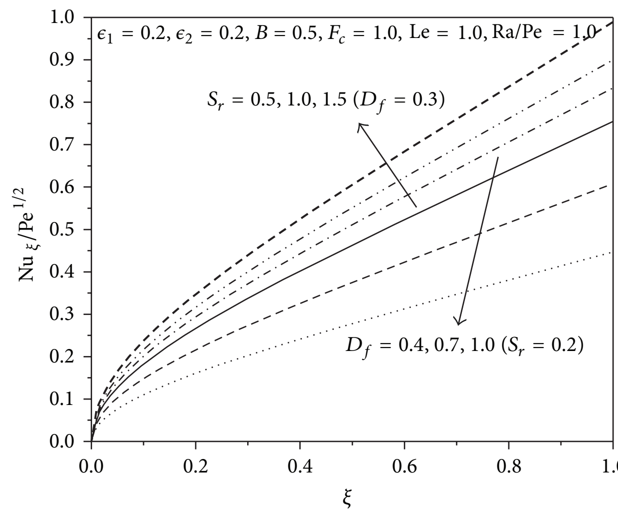

Figure 15: Variation of heat transfer rate with Dufour and Soret parameters.

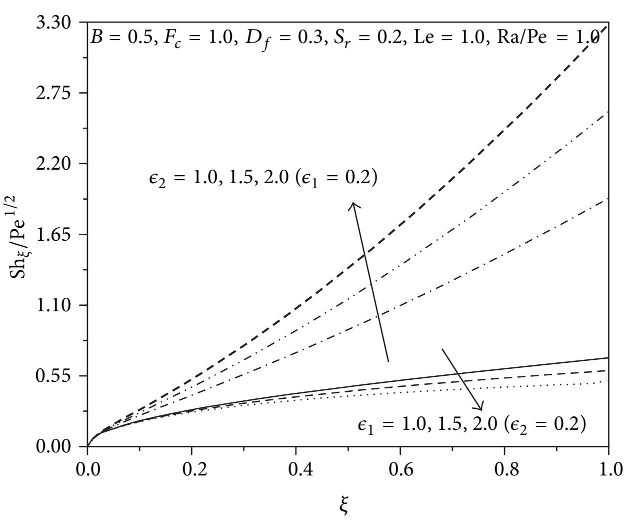

Figure 14: Variation of mass transfer rate with stratification parameters.

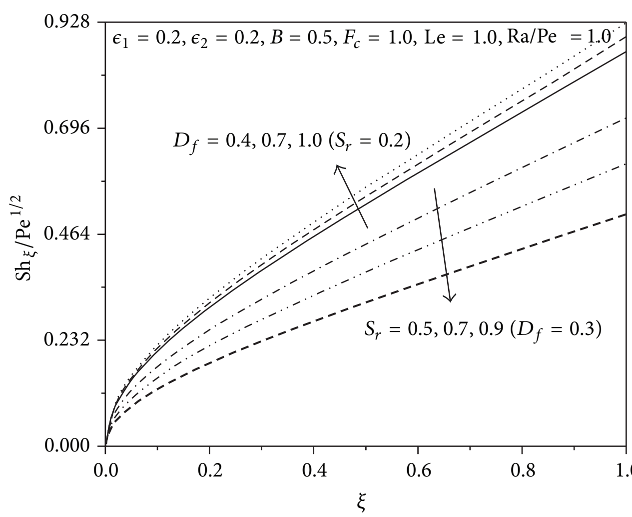

Figure 16: Variation of mass transfer rate with Dufour and Soret parameters.

number. It is also clear from the same graph that the local heat transfer rate decreases by around 22% with the raise of ϵ_2 from 1.0 to 2.0. Figure 14 illustrates that the local mass transfer coefficient decreases by closely 16% with the increase in the thermal stratification parameter ϵ_1 from 1.0 to 2.0. This is due to the effective mass transfer between the plate and the ambient medium decreases as the thermal stratification effect increases. It is seen from the same figure that the local mass transfer coefficient enhances by 53% with the increase of solutal stratification parameter ϵ_2 from 1.0 to 2.0.

The effect of Dufour and Soret parameters on local heat and mass transfer coefficients is exhibited in Figures 15 and 16. It is found from Figure 15 that the local heat transfer rate enhances by about 18% with the increase in Soret parameter S_r from 0.5 to 1.5 but decreases by 40% with the raise of Dufour parameter D_f from 0.4 to 1.0. Figure 16 reveals that the local mass transfer coefficient increases by nearly 7% with the increase in the Dufour parameter D_f from 0.4 to 1.0, and we notice that the local mass transfer coefficient enhances by about 29% with the decrease in the Soret parameter S_r from 0.9 to 0.5.

The variation of local heat and mass transfer coefficients with Forchheimer number and Lewis number is shown in Figures 17 and 18. It is found from Figure 17 that local heat transfer rate decreases by about 5% with the increase of Forchheimer number F_c from 0.5 to 0.9, and mass transfer rate decreases by 7% with the increase in Forchheimer number F_c from 0.1 to 0.5. Since F_c represents the inertial drag, thus an increase in the Forchheimer number increases the resistance to the flow. Figure 18 shows that the local heat transfer rate decreases by about 24% with the increase in Lewis number Le from 1.0 to 3.0, whereas the mass transfer

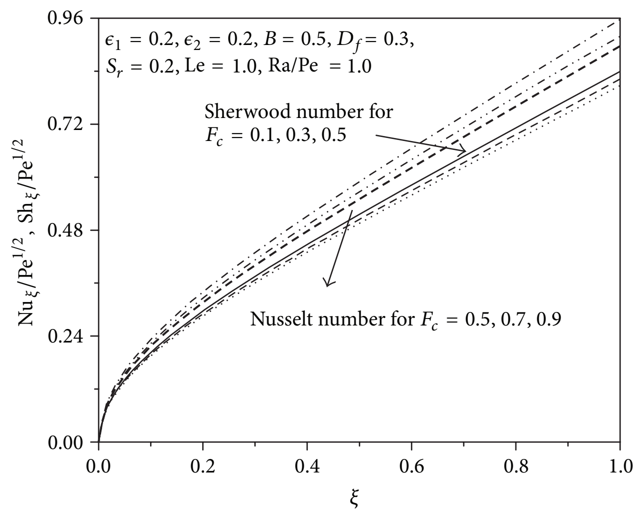

Figure 17: Variation of heat and mass transfer rates with Forchheimer parameter.

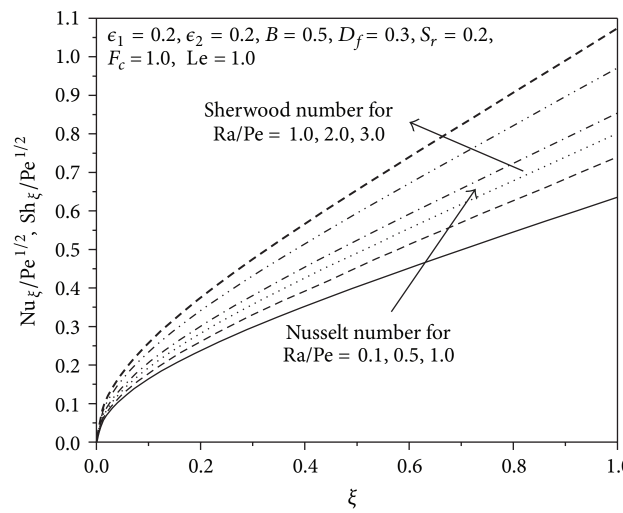

Figure 19: Variation of heat and mass transfer rates with mixed convection parameter.

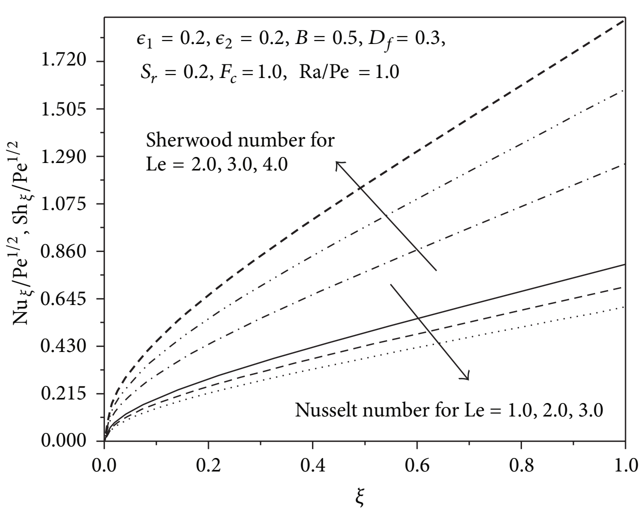

Figure 18: Variation of heat and mass transfer rates with Lewis number.

rate is enhanced by nearly 51% with the raise of Lewis number Le from 2.0 to 4.0.

The influence of mixed convection parameter on local heat and mass transfer coefficients is shown in Figure 19. The figure depicts that the local heat transfer rate increases by 22% with the increase of mixed convection parameter from 0.1 to 1.0, and mass transfer rate increase by about 25% with the increase of mixed convection parameters from 1.0 to 3.0.

5. Conclusions

Mixed convection heat and mass transfer from a vertical plate in a doubly stratified viscous fluid saturated non-Darcy porous medium in the presence of Soret and Dufour effects is studied. Numerically, nonsimilar solutions are obtained for different values of thermal stratification parameter, solutal stratification parameter, buoyancy parameter, Forchheimer number, Soret, and Dufour parameters. An increase in the thermal stratification parameter, ϵ_1, decreases the velocity, temperature, and local mass transfer coefficient but increases local heat transfer coefficient. The higher value of solutal stratification parameter ϵ_2 resulting in lower velocity, concentration, and local heat transfer coefficient but higher local mass transfer coefficient. The influence of Forchheimer number is to decrease the velocity and the local heat and mass transfer coefficients but to increase nondimensional temperature and concentration. The influence of Dufour parameter is to increase the nondimensional velocity and temperature. The higher value of Soret parameter results in the higher velocity and concentration. The presence of 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 Dufour parameter. The local heat transfer rate is decreased whereas the local mass transfer rate is increased with the increase of Lewis number. The significance of mixed convection parameter is to increase both the local heat and mass transfer rates.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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