THERMAL RADIATION EFFECT ON LAMINAR MIXED CONVECTION FLOW IN A VERTICAL POROUS STRATUM WITH SOURCE OR SINK

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ABSTRACT

The fully developed laminar mixed convection in a vertical channel embedded in porous medium is analyzed in the presence of heat source or heat sink and thermal radiation effect. The governing equations are developed and three types of thermal boundary conditions namely isothermal-isothermal, isoflux-isothermal and isothermal-isoflux for the left-right walls of the channel are prescribed. Including the effects of both viscous and Darcy dissipation, the velocity and temperature fields are obtained analytically by perturbation series method. The results are presented graphically illustrating the effects of the various parameters such as porous parameter σ , perturbation parameter $\mathcal{E}$, heat source or heat sink coefficient ϕ and radiation parameter F on velocity and temperature fields.

KEYWORDS: *Laminar Mixed Convection, Thermal Radiation, Darcy Dissipation, Perturbation Series Method, Thermal Boundary Conditions*

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1. INTRODUCTION

Transport phenomena in porous media has got extensive consideration because of the expanding enthusiasm for geothermal activities, building thermal insulation heat exchangers, petroleum reservoirs, chemical catalytic reactors and numerous different zones. Likewise, extensive research interest has been given to the investigation of heat transfer induced by buoyancy effect in a porous medium saturated with fluids. Motivation in these convective flow phenomena has enhanced much further by such assorted engineering issues as geothermal energy extraction, underground heat exchangers for energy storage, recovery systems in the extraction of crude oil and petroleum products and temperature controlled reactors, electronic system cooling, ground water hydrology, coal combustors, grain storage, fiber and granular insulation, to name only some of the utilizations of the convective flow in porous media.

The linear stability analysis of mixed convection in a heated vertical channel filled with a fluid saturated porous medium was studied by Yen-Cho Chen (2004). M Anwar Hossain and Mike Wilson (2002) have proved that increasing the porosity of the medium reduces the flow rate of the fluid and also leads to general reduction in heat transfer at the walls. Patil Mallikarjun B (2014, 2015) in his work has proved that when the Darcy parameter increases, the velocity of the fluid decreases. Radiation effect on convective heat transfer through a porous medium in a vertical channel with quadratic temperature variation has been studied by P Reddaiah and D R V Prasada Rao (2010). Increasing the porous medium parameter, it is observed by Alireza Taklifi and Cyrus Aghanajafi (2012) that the dimensionless velocity and the

dimensionless temperature increases. Also the influence of thermal radiation on hydromagnetic Darcy-Forchheimer mixed convection flow has been studied by Dulal Pal and Hiranmoy Mondal (2011). Mixed convection in a vertical channel with sources, sinks and thermal radiation has been analyzed by Patil Mallikarjun and Kavitha L (2018) and found that viscous dissipation enhances the flow reversal in the case of downward flow while it counters the flow in the case of upward flow. JC Umavathi and MH Manjula (2010) have proved that the velocity and temperature can be controlled effectively by altering the values of Grashoff number, radiation parameter and heat generation and absorption coefficient. Radiation effects on mixed convection flow and viscous heating in a vertical channel partially filled with a porous medium has been analyzed by Dileep Singh Chauhan and Vikas Kumar (2011). Ali J Chamkha (2013) has analyzed the radiation effects on mixed convection about a cone embedded in a porous medium filled with a nanofluid. Laminar mixed convection flow in a vertical porous stratum with asymmetric wall heating conditions has been investigated by Patil Mallikarjun B (2006)..

2. MATHEMATICAL FORMULATION

The physical configuration of flow geometry is shown in the figure below which shows open-ended vertical channel filled with porous material.

Figure 1: Physical Configuration of the Porous Stratum in the Vertical Channel

Figure 1 shows a Cartesian coordinate system is chosen with the transverse coordinate Y and the coordinate in the direction parallel to the walls is X . The origin of the axes is such that the channel walls are at positions $Y = -L/2$ and $Y = L/2$. The fluid is assumed to be Newtonian and the porous medium is isotropic and homogeneous. The thermal conductivity, the dynamic viscosity and the thermal expansion coefficient are considered as constant. Also Oberbeck-Boussinesq approximation is assumed to hold

$$\rho = \rho_0 (1 - \beta(T - T_0)) \quad (1)$$

The stream wise and the transverse momentum balance equations yield,

$$g\beta(T-T_0)-\frac{1}{\rho_0}\frac{\partial P}{\partial X}+\frac{\mu_{eff}}{\rho_0}\frac{d^2U}{dY^2}-\frac{\mu}{\rho_0 k}U=0 \quad (2)$$

$$\frac{\partial P}{\partial Y}=0 \quad (3)$$

Where $P = p + \rho_0 gX$ is the difference between the pressure and the hydrostatic pressure? We assume that the walls of the channel are isothermal, In particular, the temperature of the boundary at $Y = -L/2$ is T_1 , while the temperature at $Y = L/2$ is T_2 , with $T_2 \geq T_1$. These boundary conditions are compatible with equation (2) if and only if dP/dX is independent of X . Therefore, there exists a constant A such that

$$\frac{dP}{dX}=A \quad (4)$$

Differentiating equation (2) with respect to X , and by using the equation (3), one obtains

$$\frac{\partial T}{\partial X}=0 \quad (5)$$

Which implies that the temperature also depends only on Y .

By taking into account the effect of viscous and Darcy dissipation in the presence of heat source or sink, the energy balance equation can be written as

$$\alpha\frac{d^2T}{dY^2}+\frac{\mu_{eff}}{\rho_0 C_p}\left(\frac{dU}{dY}\right)^2+\frac{\mu}{\rho_0 k C_p}U^2\pm\frac{Q(T-T_0)}{\rho_0 C_p}-\frac{1}{\rho_0 C_p}\frac{dq_R}{dY}=0 \quad (6)$$

Brinkman in his extension of the Darcy law made the assumption that. Using the equations (2) and (6), we obtain a differential equation for U , namely

$$\frac{d^4U}{dY^4}=\left(\frac{1}{k}+\frac{Q}{K}\right)\frac{d^2U}{dY^2}+\frac{\mu\beta g}{K\gamma}\left(\frac{dU}{dY}\right)^2+\frac{\mu\beta g}{Kk\gamma}U^2\pm\frac{Q}{Kk}U\pm\frac{QA}{K\mu}-\frac{\beta g}{K\gamma}\frac{dq_R}{dY} \quad (7)$$

where Q is the rate of internal heat source or sink. The boundary conditions on U are both the no slip conditions

$$U=0 \quad \text{at } Y=\pm\frac{L}{2} \quad (8)$$

and the thermal boundary conditions on T are simplified by using the equations (2) and (4) which are given by

$$\frac{d^2U}{dY^2}=\frac{A}{\mu}-\frac{\beta g(T_1-T_0)}{\nu} \text{ at } Y=-\frac{L}{2} \text{ and } \frac{d^2U}{dY^2}=\frac{A}{\mu}-\frac{\beta g(T_2-T_0)}{\nu} \text{ at } Y=\frac{L}{2} \quad (9)$$

The following quantities are employed for writing the equations (6) to (9) in the dimensionless form

$$u = \frac{U}{U_0}; \theta = \frac{T - T_0}{\Delta T}; y = \frac{Y}{D}; Gr = \frac{g \beta \Delta T D^3}{\nu^2}; \sigma^2 = \frac{D^2}{k}; F^2 = \frac{CD^2}{K}; R_T = \frac{T_2 - T_1}{\Delta T}; \lambda = \frac{Gr}{Re};$$

$$Re = \frac{U_0 D}{\nu}; Pr = \frac{\nu}{\alpha}; Br = \frac{\mu U_0^2}{K \Delta T}; \phi = \frac{QD^2}{K}; \alpha = \frac{k}{\rho_0 C_P}; \nu = \frac{\mu}{\rho_0}; \frac{dq_R}{dY} = c(T - T_0)$$
(10)

The reference velocity U_0 and the reference temperature T_0 are given by

$$U_0 = -\frac{AD^2}{48\mu}; T_0 = \frac{T_1 + T_2}{2}$$
(11)

The temperature difference ΔT is as follows,

$$\Delta T = T_2 - T_1 \text{ if } T_1 < T_2 \text{ or by}$$
(12)

$$\Delta T = \frac{\nu^2}{C_p D^2} \text{ if } T_1 = T_2$$
(13)

The dimensionless parameter R_T becomes zero for symmetric heating ($T_1 = T_2$) and is one for asymmetric heating ($T_1 < T_2$).

Equation (4) implies that A can be either positive or negative. If $A > 0$, then U_0 , Re and λ are negative, i.e., the flow is downward. On the contrary, if $A < 0$ the flow is upward, so that U_0 , Re and λ are positive.

By using the dimensionless parameters from equation (10), the momentum balance and energy balance equations (6) to (9) reduces to

$$\frac{d^2 \theta}{dy^2} \pm (\phi - F^2) \theta = -Br \left(\frac{du}{dy} \right)^2 - \sigma^2 Bru^2$$
(14)

$$\frac{d^4 u}{dy^4} = \left(\sigma^2 \mp \phi + F^2 \right) \frac{d^2 u}{dy^2} + \lambda Br \left(\frac{du}{dy} \right)^2 + \sigma^2 \lambda Bru^2 - (F^2 \mp \phi) \sigma^2 u + 48(F^2 \mp \phi)$$
(15)

$$u = 0 \text{ at } y = \pm \frac{1}{4}$$
(16)

$$\frac{d^2 u}{dy^2} = -48 + \frac{R_T \lambda}{2} \text{ at } y = -\frac{1}{4} \text{ and } \frac{d^2 u}{dy^2} = -48 - \frac{R_T \lambda}{2} \text{ at } y = \frac{1}{4}$$
(17)

Using equation (10) and (11) in equation (2) we obtain

$$\theta = -\frac{1}{\lambda} \left(48 - \sigma^2 u + \frac{d^2 u}{dy^2} \right)$$
(18)

3. ANALYTICAL SOLUTION BY PERTURBATION METHODS

Equation (15) along with boundary conditions given by (16) and (17) is nonlinear and hence it is difficult to find closed form solution. However, to obtain an analytical solution of equation (15), we employ the perturbation method using the dimensionless parameter $\mathcal{E}$ ($\ll 1$), which is defined as

$$\mathcal{E} = Br\lambda = Re Pr \frac{\beta g D}{C_p} \quad (19)$$

Then the temperature field is obtained using equation (18). Thus, we assume that U can be expressed as

$$u(y) = u_0(y) + \mathcal{E} u_1(y) + \mathcal{E}^2 u_2(y) + \dots = \sum_{n=0}^{\infty} \mathcal{E}^n u_n(y) \quad (20)$$

The second and higher order terms of $\mathcal{E}$ give a correction to u_0 and θ_0 accounting for the viscous and Darcy dissipation effects. Substituting equation (20) in equation (15) and equating coefficients of like powers of $\mathcal{E}$ to zero, one obtains the boundary value problem for $n=0$ and $n=1$ as

3.1. Isothermal-Isothermal Case (T_1 - T_2)

$$\frac{d^4 u_0}{dy^4} = (\sigma^2 \mp \phi + F^2) \frac{d^2 u_0}{dy^2} - (F^2 \mp \phi) \sigma^2 u_0 + (F^2 \mp \phi) 48 \quad (21)$$

$$\frac{d^4 u_1}{dy^4} = (\sigma^2 \mp \phi + F^2) \frac{d^2 u_1}{dy^2} + \left(\frac{du_0}{dy} \right)^2 + \sigma^2 u_0^2 - (F^2 \mp \phi) \sigma^2 u_1 \quad (22)$$

for the case of heat source or sink respectively. The boundary conditions of these equations are

$$u_0 = 0 \quad \text{at} \quad y = \pm \frac{1}{4} \quad (23)$$

$$\frac{d^2 u_0}{dy^2} = -48 + \frac{R_T \lambda}{2} \quad \text{at} \quad y = -\frac{1}{4} \quad \text{and} \quad \frac{d^2 u_0}{dy^2} = -48 - \frac{R_T \lambda}{2} \quad \text{at} \quad y = \frac{1}{4} \quad (24)$$

$$u_1 = 0 \quad \text{at} \quad y = \pm \frac{1}{4} \quad (25)$$

$$\frac{d^2 u_1}{dy^2} = 0 \quad \text{at} \quad y = \pm \frac{1}{4} \quad (26)$$

Equations (21) and (22) are ordinary linear differential equations and their exact solutions can be easily found. These solutions obviously coincide with the solution of equation (15) in the case $Br = 0$. Evaluation of exact solution for $n=2$ becomes very tedious and hence neglecting the terms for $n=2$ the solution is obtained up to terms of

$O(\varepsilon^I)$ to get

$$u_0 = C_1 \cosh \sigma y + C_2 \sinh \sigma y + C_3 \cos(\sqrt{\phi - F^2} y) + C_4 \sin(\sqrt{\phi - F^2} y) + \frac{48}{\sigma^2} \quad (27)$$

for the case of heat source and

$$u_0 = C_1 \cosh \sigma y + C_2 \sinh \sigma y + C_3 \cosh \sqrt{\phi + F^2} y + C_4 \sinh \sqrt{\phi + F^2} y + \frac{48}{\sigma^2} \quad (28)$$

for the case of heat sink.

$$\begin{aligned} u_1 = & C_5 \cosh \sigma y + C_6 \sinh \sigma y + C_7 \cos(\sqrt{\phi - F^2} y) + C_8 \sin(\sqrt{\phi - F^2} y) + l_1 \cosh 2\sigma y + \\ & l_2 \cos(2\sqrt{\phi - F^2} y) + l_3 \sinh 2\sigma y + l_4 \sin(2\sqrt{\phi - F^2} y) + l_5 \cosh \sigma y \cos(\sqrt{\phi - F^2} y) + \\ & l_6 \sinh \sigma y \sin(\sqrt{\phi - F^2} y) + l_7 \cosh \sigma y \sin(\sqrt{\phi - F^2} y) + l_8 \sinh \sigma y \cos(\sqrt{\phi - F^2} y) + \\ & l_9 y \sinh \sigma y + l_{10} y \cosh \sigma y + l_{11} y \sin(\sqrt{\phi - F^2} y) + l_{12} y \cos(\sqrt{\phi - F^2} y) + l_{13} \end{aligned} \quad \text{for the case of} \quad (29)$$

heat source and

$$\begin{aligned} u_1 = & C_5 \cosh \sigma y + C_6 \sinh \sigma y + C_7 \cosh(\sqrt{\phi + F^2} y) + C_8 \sinh(\sqrt{\phi + F^2} y) + l_1 \cosh 2\sigma y + \\ & l_2 \cosh(2\sqrt{\phi + F^2} y) + l_3 \sinh 2\sigma y + l_4 \sinh(2\sqrt{\phi + F^2} y) + l_5 \cosh(\sigma + \sqrt{\phi + F^2} y) + \\ & l_6 \cosh(\sigma - \sqrt{\phi + F^2} y) + l_7 \sinh(\sigma + \sqrt{\phi + F^2} y) + l_8 \sinh(\sigma - \sqrt{\phi + F^2} y) + \\ & l_9 y \sinh \sigma y + l_{10} y \cosh \sigma y + l_{11} y \sinh(\sqrt{\phi + F^2} y) + l_{12} y \cosh(\sqrt{\phi + F^2} y) + l_{13} \end{aligned} \quad \text{for the case of} \quad (30)$$

heat sink

The dimensionless temperature field is obtained from the equation (18) by using the velocity fields from equations (27) to (30) which is given by

$$\begin{aligned} \theta = & \frac{1}{\lambda} [((\sigma^2 + \phi - F^2)(C_3 + \varepsilon(C_7 + l_{12}y))\cos(\sqrt{\phi - F^2} y)) + ((\sigma^2 + \phi - F^2)(C_4 + \\ & \varepsilon(C_8 + l_{11}y))\sin(\sqrt{\phi - F^2} y)) - \varepsilon\{(3\sigma^2(l_1 \cosh 2\sigma y + l_3 \sinh 2\sigma y) - \\ & ((\sigma^2 + 4(\phi - F^2))(l_2 \cos(2\sqrt{\phi - F^2} y) + l_4 \sin(2\sqrt{\phi - F^2} y))) - ((l_5(\phi - F^2) - \\ & 2l_6\sigma\sqrt{\phi - F^2})\cosh \sigma y \cos(\sqrt{\phi - F^2} y) - ((l_6(\phi - F^2) + 2l_5\sigma\sqrt{\phi - F^2})\sinh \sigma y \sin(\sqrt{\phi - F^2} y)) \\ & - ((l_7(\phi - F^2) + 2l_8\sigma\sqrt{\phi - F^2})\cosh \sigma y \sin(\sqrt{\phi - F^2} y) - ((l_8(\phi - F^2) \\ & - 2l_7\sigma\sqrt{\phi - F^2})\sinh \sigma y \cos(\sqrt{\phi - F^2} y) + 2l_9\sigma \cosh \sigma y + 2l_{10}\sigma \sinh \sigma y \\ & + 2l_{11}\sqrt{\phi - F^2} \cos(\sqrt{\phi - F^2} y) - 2l_{12}\sqrt{\phi - F^2} \sin(\sqrt{\phi - F^2} y) - l_{13}\sigma^2\}]] \end{aligned} \quad \text{for} \quad (31)$$

the case of heat source and

$$\begin{aligned} \theta = \frac{1}{\lambda} [& ((\sigma^2 - (\phi + F^2))(C_3 + \varepsilon(C_7 + l_{12}y))\cosh(\sqrt{\phi + F^2}y) + ((\sigma^2 - (\phi + F^2))(C_4 + \\ & \varepsilon(C_8 + l_{11}y))\sinh(\sqrt{\phi + F^2}y) - \varepsilon\{(3\sigma^2(l_1\cosh 2\sigma y + l_3\sinh 2\sigma y) - (\sigma^2 - 4(\phi + F^2)) \\ & (l_2\cosh(2\sqrt{\phi + F^2}y) + l_4\sinh(2\sqrt{\phi + F^2}y) + ((l_5(\phi + F^2 + 2\sigma\sqrt{\phi + F^2})\cosh(\sigma + \sqrt{\phi + F^2}y) \\ & + l_6(\phi + F^2 - 2\sigma\sqrt{\phi + F^2})\cosh(\sigma - \sqrt{\phi + F^2}y) + l_7(\phi + F^2 + 2\sigma\sqrt{\phi + F^2})\sinh(\sigma + \sqrt{\phi + F^2}y) \\ & + l_8(\phi + F^2 - 2\sigma\sqrt{\phi + F^2})\sinh(\sigma - \sqrt{\phi + F^2}y) + 2l_9\sigma\cosh\sigma y + 2l_{10}\sigma\sinh\sigma y + \\ & 2l_{11}\sqrt{\phi + F^2}\cosh(\sqrt{\phi + F^2}y) + 2l_{12}\sqrt{\phi + F^2}\sinh(\sqrt{\phi + F^2}y) - l_{13}\sigma^2\})] \end{aligned} \quad \text{for the case}$$

of heat sink. (32)

3.2. Isoflux-Isothermal Case (q_1 - T_2)

For this case, the thermal boundary conditions for the channel walls can be written in the non-dimensional form as

$$q_1 = -K \frac{dT}{dY} \text{ at } Y = -\frac{L}{2} \text{ and } T = T_2 \text{ at } Y = \frac{L}{2} \quad (33)$$

The dimensionless form of above equation can be obtained by using the non-dimensional terms from the equation (10) with $\Delta T = q_1 D / K$, gives

$$\frac{d\theta}{dy} = -1 \text{ at } y = -\frac{1}{4} \text{ and } \theta = R_{qt} \text{ at } y = \frac{1}{4} \quad (34)$$

where $R_{qt} = (T_2 - T_0) / \Delta T$ is the thermal ratio parameter. Other than the no-slip conditions at the channel walls, two more boundary conditions in terms of U are needed to solve equation (7). These are induced by the conditions given in equation (33) and are obtained from equation (2) as follows.

Differentiating equation (2) with respect to Y , with $dP/dX = A$ gives

$$\frac{d^3U}{dY^3} - \frac{1}{k} \frac{dU}{dY} + \frac{\beta g}{\nu} \frac{dT}{dY} = 0 \quad (35)$$

Equation (35) is non-dimensionalized by using equation (10) to give

$$\frac{d^3u}{dy^3} - \sigma^2 \frac{du}{dy} + \lambda \frac{d\theta}{dy} = 0 \quad (36)$$

Evaluating the above equation at the left wall ($y = -1/4$) yields

$$\frac{d^3u}{dy^3} - \sigma^2 \frac{du}{dy} = \lambda \quad \text{at } y = -\frac{1}{4} \quad (37)$$

The other boundary condition at the right wall can be shown to be the same as that

given for the isothermal-isothermal case with R_t replaced by R_{qt} such that

$$\frac{d^2 u}{dy^2} = -48 - \frac{\lambda R_{qt}}{2} \quad \text{at} \quad y = \frac{l}{4} \quad (38)$$

The integrating constants appeared in equations (27) to (37) are evaluated using the boundary conditions from equations (23) to (26) and (37).

3.3. Isothermal-Isflux Case (T_1 - q_2)

For this case the thermal boundary conditions are given by

$$q_2 = -K \frac{dT}{dY} \text{ at } Y = \frac{Y}{2} \text{ and } T = T_1 \text{ at } Y = -\frac{Y}{2} \quad (39)$$

The dimensionless form of equation (39) can be obtained by using equation (10) with $\Delta T = q_2 D / K$ to give

$$\frac{d\theta}{dy} = -1 \text{ at } y = \frac{l}{4} \text{ and } \theta = R_{tq} \text{ at } y = -\frac{l}{4} \quad (40)$$

where $R_{tq} = (T_1 - T_0) / \Delta T$ is the thermal ratio parameter for the isothermal-isoflux case. Similar to the procedure done in the previous section on isoflux-isothermal walls, the dimensionless form of the boundary conditions obtained from equation (2) and applying equation (40) can be written as

$$\frac{d^3 u}{dy^3} - \sigma^2 \frac{du}{dy} = \lambda \quad \text{at} \quad y = \frac{l}{4} \quad (41)$$

The other boundary condition at the right wall can be shown to be the same as that given for the isothermal-isothermal case with R_t replaced by R_{tq} such that

$$\frac{d^2 u}{dy^2} = -48 + \frac{\lambda R_{tq}}{2} \quad \text{at} \quad y = -\frac{l}{4} \quad (42)$$

Using these boundary conditions, the integrating constants appeared in equations (21), (22) and (18) are evaluated.

4. RESULTS AND DISCUSSIONS

The problem of mixed convection in a vertical porous stratum with asymmetric and symmetric wall heating conditions is studied. The effect of radiation on the velocity and temperature fields are analyzed for different values of λ and $\mathcal{E}$ taking the porous parameter value as $\sigma = 3$, for three different wall heating conditions namely Isothermal-isothermal, isoflux-isothermal and isothermal-isoflux walls.

In Graphs 1 and 2, the effect of radiation on velocity and temperature fields is studied. The plots of 'u' for

$\lambda = 500$ and $\varepsilon = 0.1$ displays a flow reversal at the boundary walls $y = -1/4$. The plots of 'u' for $\lambda = -500$ and $\varepsilon = -0.1$ displays a flow reversal at the boundary walls $y = 1/4$. It is observed that velocity 'u' increases with the increase in the radiation parameter $F=1,2,3$ for $\lambda = 500$ and $\varepsilon = 0.1$. On the contrast, velocity 'u' decreases with the increase in the radiation parameter $F=1,2,3$ for $\lambda = -500$ and $\varepsilon = -0.1$. This is because of the damping effect of Darcy resistance. The plots of ' θ ' for $\lambda = \pm 500$, $\varepsilon = \pm 0.1$ shows that the temperature increases with the increase in the values of radiation parameter F for asymmetric heating.

In Graphs 3 and 4, the plots of the velocity 'u' and the temperature θ are plotted for the case of symmetric heating i.e., $R=0$ for the values of $\lambda = \pm 500$, $\varepsilon = \pm 0.1$ with the fixed value of heat generation coefficient $\phi = 10$ and porous parameter $\sigma = 3$. The velocity profile shows no much significance for both the values of ε . For $\varepsilon < 0$, i.e., for downward flow, it is observed that the dimensionless temperature profiles is more significant than in the case of upward flow for $\varepsilon > 0$. Comparing the two types of flow for asymmetric and symmetric heating, we infer that the increase in the buoyancy force increase the velocity field in the case of upward flow, whereas there is a decrease in the velocity field in the case of downward flow.

In Graphs 5 and 6, the cases of $\lambda = \pm 500$ is considered. The plots of 'u' for $\varepsilon = \pm 0.1$ and $\varepsilon = \pm 8$ displays a flow reversal at the boundaries $y = \pm 1/4$. The velocity profile decreases with the increase in the values of the radiation parameter $F=1,2,3$ keeping the heat absorption coefficient $\phi = 10$ and porous parameter $\sigma = 3$ fixed for $\lambda = 500$ and $\varepsilon = 0.1, 8$, whereas the velocity profile increases with the increasing values of radiation parameter $F=1,2,3$ keeping the heat absorption coefficient $\phi = 10$ and porous parameter $\sigma = 3$ fixed for $\lambda = -500$ and $\varepsilon = -0.1, -8$. The plots of θ for $\varepsilon = \pm 0.1$ and $\varepsilon = \pm 8$ shows that the temperature increases with the increase in the values of radiation parameter F when $\lambda = \pm 500$.

In Graphs 7 and 8, plots of 'u' and θ for different values of radiation parameter $F=1,2,3$ when $\lambda = \pm 500$ and $\varepsilon = \pm 0.1$ keeping the fixed values for heat generation coefficient and radiation parameter for the Isoflux-isothermal case is considered. The velocity increases with the increase in the values of the radiation parameter for $\lambda = 500$ and $\varepsilon = 0.1$, whereas the velocity decreases when $\lambda = -500$ and $\varepsilon = -0.1$. The temperature θ keeps decreasing with the increase in the values of the radiation parameter $F=1,2,3$ when $\lambda = \pm 500$ and $\varepsilon = \pm 0.1$.

In Graphs 9 and 10, plots of 'u' and θ for different values of radiation parameter $F=1, 2, 3$ when $\lambda = \pm 500$ and $\varepsilon = \pm 0.1$ is considered for the isothermal-Isoflux case. In this case, the velocity profile is opposite in direction when compared to the case of Isoflux-isothermal condition, whereas the temperature θ goes on increasing with the increase in the values of radiation parameter $F=1, 2, 3$ for $\lambda = \pm 500$ and $\varepsilon = \pm 0.1$.

Graph 1 Plots of u/y in the case of asymmetric heating for different values of F with heat generation coefficient $\phi=10$ and $\sigma=3$

Figure 2

Graph 2. Plots of θ/y in the case of asymmetric heating for different values of s and F with heat generation coefficient $\phi=10$ and $\sigma=3$

Figure 3

Graph 3 Plots of u/y in the case of symmetric heating for different values of F with heat generation coefficient $\phi=10$ and $\sigma=3$

Figure 4

Graph 4. Plots of θ/y in the case of symmetric heating for different values of F with heat generation coefficient $\phi=10$ and $\sigma=3$

Figure 5

Graph 5 Plots of u/y in the case of asymmetric heating for different values of ϵ and F with heat absorption coefficient $\phi=10$ and $\sigma=3$

Figure 6

Graph 6. Plots of θ/y in the case of asymmetric heating for different values of ϵ and F with heat absorption coefficient $\phi=10$ and $\sigma=3$

Figure 7

Graph 7 Plots of u/y for different values of ϵ and F for the Isoflux-Isothermal case with heat generation coefficient $\phi=10$ and $\sigma=3$

Figure 8

Graph 8 Plots of θ/y for different values of ϵ and F for the Isoflux-Isothermal case with heat generation coefficient $\phi=10$ and $\sigma=3$

Figure 9

Graph 9 Plots of u/y for different values of ε and F for the Isothermal-Isoflux case with heat generation coefficient $\phi=10$ and $\sigma=3$

Figure 10

Graph 10. Plots of θ/y for different values of ε and F for the Isothermal-Isoflux case with heat generation coefficient $\phi=10$ and $\sigma=3$

Figure 11

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