Investigation on the effect of injection on a vertical plate in a porous medium with transpiration cooling and heat source

S Sheeba Juliet¹, M Vidhya², AGovindarajan³, E Priyadarshini⁴

¹Department of Mathematics, C.S.I.Ewart Women's Christian College, Melrosapuram, 603204.
²,⁴Department of Mathematics, Sathyabama Institute of Science and Technology, Sholinganallur, 600 119
³Department of Mathematics, SRM Institute of Science and Technology, Kattankolathur, 603 203

mvidhya_1978@yahoo.co.in

Abstract. Investigation on 3D convective flow of a viscous incompressible fluid through a vertical plate in a porous medium with heat source and whose one side is made of a porous plate while the other is impermeable non porous plate is considered. The fluid is injected with a uniform velocity. The effects of injection and permeability parameters on flow variables with heat source have been analyzed graphically. It is noted that the axial velocity profiles increase with an increase in permeability of the porous medium. It is reversed in the case of lower injection rate and permeability. It is observed that the heat transfer increases with an increase in Reynolds number for both air and water.

1. Introduction

The study of natural convection in a vertical parallel plate channel is an important subject due to increasing practical applications in industries. Several practical systems such as electronic equipment, furnace and heat exchangers are some of the example of this model. Viscous flow through a porous medium has attracted the attention of many scholars due to its applications in branches of engineering and technology namely in the field of agricultural engineering to study the underground water resources, seepage of water in river beds, in chemical engineering for filtration and purification process, also in petroleum technology to study the movement of natural gas, oil and water through the oil reservoirs. Vidhya et al [1] discussed about laminar convection through porous medium between two vertical parallel plates with heat source. Loganathan et al [2] studied about unsteady three dimensional dusty couette flows through porous plates with heat transfer and periodic suction. Gireesha et al [3] analyzed three dimensional couette flows of an unsteady dusty fluid and heat transfer through a porous medium with variable permeability. Das [4] studied the effect of suction and injection on MHD three dimensional couette flow and heat transfer through a porous medium. Singh et al [5] discussed on the three dimensional couette flows through porous medium with heat transfer.Attia et al [6] reported on MHDcouette flow and heat transfer of a dusty fluid with exponential decaying pressure gradient. Chand et al [7] investigated on Hydro magnetic oscillatory flow through a porous medium bounded by two vertical porous plates with heat source and soret effect. Gireesha et al [8] studied about three dimensional couette flow of a dusty fluid with heat transfer.Govindarajan et al [9] discussed 3D couette flow of dusty fluid with transpiration cooling.
Govindarajan et al. [10] analyzed Chemical reaction effects on unsteady magnetohydrodynamic free convective flow in a rotating porous medium with mass transfer.

2. Mathematical Analysis

Consider $u$, $v$, $w$ be the velocity components in the directions of $x$, $y$, $z$ directions respectively. The plate $y = 0$ is impermeable and a fluid is driven in through the plate at $y = d$ with uniform velocity $v$. Due to gravity acting in the $z$-direction the fluid will flow out through the sides and the bottom of the plate. The temperature of the plate $y = 0$ is $T_0$ and $y = d$ be $T_1$ respectively. The length of the plate is much greater than the breadth and breadth is to the thickness of the plate is assumed in this problem. Due to this assumption the edge effect are ignored and isobars are parallel to the $z$-axis. We further assume that all the fluid properties are constant. The viscous dissipation effects are neglected in the energy equation and heat source parameter is considered in the heat equation. The equations governing the fluid motion are:

Continuity equation:

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

Momentum equation:

$$\frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \tag{2}$$

$$\frac{\partial v}{\partial x} + u \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial y} + \nu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \tag{3}$$

$$\frac{\partial w}{\partial x} + u \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial z} + \nu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \tag{4}$$

Energy equation:

$$\rho C_p \left( \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = K \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + Q(T - T_0) \tag{5}$$

Where $\nu$ is the kinematic viscosity, $\rho$ the density, $P$ the pressure, $K_0$ the permeability parameter, $g$ is the acceleration due to gravity and $Q$ is the heat source parameter in dimensional form.

The boundary conditions of the problem are:

$$y = 0; \quad u = 0, \quad v = 0, \quad w = 0, \quad T = T_0 \tag{6}$$

$$y = d; \quad u = 0, \quad v = -V, \quad w = 0, \quad T = T_1$$

Using the symmetry of the problem we substitute

$$u = \frac{V}{d} \hat{x}(\eta), \quad v = -V \hat{f}(\eta), \quad w = \frac{d^2}{v} \hat{h}(\eta)$$

$$P = \frac{\rho}{2} \left( AV \hat{x}^2 + V^2 \hat{f}^2(\eta) + \frac{2V}{d} \hat{f}(\eta) - \frac{2V}{K} \int f(\eta) d\eta \right) \tag{7}$$

$$T = T_0 + (T_1 - T_0) \theta(\eta), \quad \eta = \frac{y}{d}, \quad S = \frac{K}{d^2}$$

into the governing equations.

The following set of ordinary differential equations is obtained as

$$f' - Re \hat{f} - ReA - \frac{\hat{f}'}{S} = 0 \tag{8}$$

$$h' + Re \hat{f}' - \frac{\hat{h}}{S} + 1 = 0 \tag{9}$$

$$\theta' + Re Pr f \theta' + D \theta = 0 \tag{10}$$
Where
\[ \text{Re} = \frac{V_d}{\nu} = \text{Reynolds number,} \]
\[ \text{Pr} = \frac{\mu C_p}{K} = \text{Prandtl number,} \]
\[ D = \frac{Q_d^2}{K} = \text{heat source parameter in non-dimensional form} \]

A is a constant to be determined and prime denotes the differentiation with respect to \( \eta \).

The corresponding boundary conditions are:
\[ \eta = 0; \quad f'(0) = 0, \quad f(1) = 0, \quad h(0) = 0, \quad \theta(0) = 0 \]
\[ \eta = 1; \quad f'(1) = 0, \quad f(1) = 1, \quad h(1) = 0, \quad \theta(1) = 1 \]

Using equations (8) and (11) we have
\[ A = -\frac{1}{\text{Re}} f''(0) \]

Solutions:
As it is assumed that \( \text{Re} \) is a small quantity, we can expand \( f(\eta) \), \( h(\eta) \) and \( \theta(\eta) \) in power series in \( \text{Re} \) as
\[ f(\eta) = f_0(\eta) + \text{Re} f_1(\eta) + \ldots \]
\[ h(\eta) = h_0(\eta) + \text{Re} h_1(\eta) + \ldots \]
\[ \theta(\eta) = \theta_0(\eta) + \text{Re} \theta_1(\eta) + \ldots \]

The equations (8) to (10) with the help of (11) and (13) gives,
\[ f_0(\eta) = \frac{(\cosh m - 1)(1 - \cosh m\eta) + \sinh m(\sinh m\eta - m\eta)}{(2\cosh m - m\sinh m - 2)} \]
\[ h_0(\eta) = \frac{\sinh m(1 - \cosh m\eta) + \sinh m\eta(\cosh m - 1)}{m^2\sinh m} \]
\[ \theta_0(\eta) = \frac{\sin \sqrt{D} \eta}{\sin \sqrt{D}} \]

\[ f_1(\eta) = c_1 + \eta c_2 + c_3 \cosh m\eta + c_4 \sinh m\eta \]
\[ + \frac{1}{4(2\cosh m - m\sinh m - 2)^2} \left( (\cosh m - 1)^2 2\eta \cosh m\eta \right. \]
\[ - \sinh m(\cosh m - 1)(m\eta^2 \cosh m\eta - 5\eta \sinh m\eta) \]
\[ + \sinh^2 m(m\eta^2 \sinh m\eta - 7\eta \cosh m\eta) \]
\[ h_1(\eta) = c_5 \cosh m\eta + c_6 \sinh m\eta \]
\[ - \frac{1}{m \sinh m(2\cosh m - m \sinh m - 2)} \left( (\cosh m - 1)^2 \left( -\frac{\eta}{2m} \sinh m\eta - \frac{\cosh 2m\eta}{6m^2} + \frac{1}{2m^2} \right) \right. \]
\[ + \sinh m(\cosh m - 1) \left( \frac{\sinh 2m\eta}{3m^2} - \frac{\eta}{4m} \cosh m\eta - \frac{\eta^2}{4} \sinh m\eta \right) \]
\[ \left. - \sinh^2 m \left( \frac{\cosh 2m\eta}{6m^2} + \frac{\eta}{4m} \sinh m\eta + \frac{1}{2m^2} \frac{\eta^2}{4} \cosh m\eta \right) \right] \]
$$\theta_1(\eta) = B_1 \cos \sqrt{D} \eta + B_2 \sin \sqrt{D} \eta - \frac{Pr \sqrt{D}}{\sin \sqrt{D}(2\cosh m - \sinh m - 2)}$$

$$\begin{aligned}
\left\{ \frac{(\cosh m - 1)\eta}{2\sqrt{D}} \sin \sqrt{D} \eta - (\cosh m - 1)(m^2 \cos \sqrt{D} \eta \cosh m\eta) \right\} \\
\frac{2m\sqrt{D} \sin \sqrt{D} \eta \cosh m\eta}{m^4 + 4m^2 D} + \frac{\sinh m}{m^4 + 4m^2 D} \left( (m^2 \cos \sqrt{D} \eta \sinh m\eta) \right) \\
+ \frac{2m\sqrt{D} \sin \sqrt{D} \eta \cos \sqrt{D} \eta}{m^4 + 4m^2 D} \left( \frac{\sinh m}{4D} \right)^2 \left( \eta^2 \sqrt{D} \sin \sqrt{D} \eta + \eta \cos \sqrt{D} \eta \right) \\
\end{aligned}$$

(19)

where $m^2 = \frac{1}{s}$, $c_1 = -c_3$

$$c_2 = -mc_4 - \frac{1}{4(2\cosh m - \sinh m - 2)^2} \left[ 2(\cosh m - 1)^2 - 7\sinh^2 m \right]$$

$$c_3 = \frac{A_1(\cosh m - 1) - A_2(\sinh m - m)}{(2\cosh m - \sinh m - 2)}$$

$$c_4 = \frac{A_1(\cosh m - 1) - A_2 \sinh m}{(2\cosh m - \sinh m - 2)}$$

$$c_5 = \frac{[\cosh m - 1]^2 - 2\sinh^2 m}{3m \sinh m (2\cosh m - \sinh m - 2)}$$

$$\begin{aligned}
\frac{1}{m^2 + 4D} \\
\left[ (\cosh m - 1)^3 (6m \sinh m - 2\cosh 2m + 6 - 4\cosh m) \right. \\
+ \cosh m - 1)(4\sinh 2m - 3m \cosh m - 3m \sinh m) \\
- \sinh m (6 + 2\cosh 2m - 3m^2 \cosh m + 3m \sinh m) \\
+ 8\cosh m) \\
\end{aligned}$$

$$c_6 = -\frac{12m \sinh m (2\cosh m - \sinh m - 2)}{m^2 + 4D}$$

$$B_1 = \frac{a(1 - \cosh m)}{m^2 + 4D}$$

$$B_2 = a \left( \frac{\cosh m - 1}{2\sqrt{D}} \sin \sqrt{D} - (\cosh m - 1) \right)$$

$$\begin{aligned}
\frac{mc \cot \sqrt{D} \cosh m + 2\sqrt{D} \sinh m}{m^3 + 4m D} + \frac{\sinh m}{m^3 + 4m D} \\
\frac{mc \cot \sqrt{D} \sinh m + 2\sqrt{D} \cosh m + \sinh m}{4D} \\
\end{aligned}$$

$$\begin{aligned}
- \frac{a(1 - \cosh m)}{m^2 + 4D} \cot \sqrt{D} \\
\left[ 2(\cosh m - 1)^3 - \sinh m (\cosh m - 1)(m \cosh m - 5 \sinh m) \right. \\
+ \sinh^2 m (m \sinh m - 7 \cosh m + 7) \\
\end{aligned}$$

$$A_1 = \frac{4(2\cosh m - \sinh m - 2)^2}{m^2 + 4D}$$
Skin friction at the impermeable wall for the normal velocity profile is given as

\[ f'(\eta) = \frac{(\cosh m - 1)(-\sinh m \eta) + (m \sinh \text{coshm} \eta - \sinh m \eta)}{(2 \cosh m - \sinh m \eta - 2)} + \text{Re} \left[ \begin{bmatrix} 1 \\ 2 \cosh m \eta - 1 \\ \sinh m \eta \end{bmatrix} \begin{bmatrix} 1 \\ 2 \cosh m \eta - 1 \\ \sinh m \eta \end{bmatrix} \right] \]

Skin friction at the permeable wall for the normal velocity profile is given as

\[ f'(0) = \text{Re} \left( c_2 + m \sinh \eta \right) + \frac{2(\cosh m - 1)^2 - 7 \sinh^2 m}{4(2 \cosh m - \sinh m \eta - 2)^2} \]

Skin friction at the impermeable wall for the axial velocity profile is given as

\[ h'(\eta) = \frac{\sinh m (-\sinh m \eta) + m \cosh m \eta (1 - \cosh m)}{m^2 \sinh m} + \text{Re} \left[ \begin{bmatrix} m \cosh m \eta + m \cosh m \eta \end{bmatrix} \begin{bmatrix} m \cosh m \eta + m \cosh m \eta \end{bmatrix} \right] \]

Skin friction at the permeable wall for the axial velocity profile is calculated as

\[ h'(0) = \frac{1 - \cosh m}{m \sinh m} + \text{Re} \left( m c_6 + \sinh m (\cosh m - 1) \right) \frac{5}{12 m} \]

Skin friction at the permeable wall for the axial velocity profile is calculated as
\[
h'(1) = \frac{(\cosh m - 1)}{\sinh m} + \text{Re}[mc_4 \sinh m + mc_4 \cosh m] \\
- \frac{1}{\sinh m (2 \cosh m - \sinh m - 2)} (\cosh m - 1)^2 \\
\left( \frac{1}{6} \sinh + \frac{1}{2} \cosh m \right) + \sinh m (\cosh m - 1) \left( \frac{2}{3m} \cosh 2m \\
- \frac{1}{4m} \cosh m - \frac{m}{4} \cosh m - \frac{3}{4} \sinh m \right) \\
- \sinh^2 m \left( \frac{7}{12} \sinh m - \frac{1}{4} \cosh m - \frac{m}{4} \sinh m \right) \]

From the temperature field, the rate of heat transfer in terms of Nusselt number is given as

\[
Q(\eta) = \frac{K(T_s - T_0)}{d} \theta'(\eta) \tag{20}
\]

where

\[
\theta'(\eta) = \frac{\sqrt{D}}{\sin \sqrt{D}} \cos \sqrt{D} \eta + \text{Re} \left[ -B_1 \sqrt{D} \sin \sqrt{D} \eta + B_2 \sqrt{D} \cos \sqrt{D} \eta \right] \\
- a \left( \frac{(\cosh m - 1)}{2\sqrt{D}} \right) \left( \sin \sqrt{D} \eta + \eta \sqrt{D} \cos \sqrt{D} \eta \right) \\
- \left( \frac{(\cosh m - 1)}{m^2 + 4m} \right) \left( m^4 \cos \sqrt{D} \eta \sinh m \eta - m \sqrt{D} \sin \sqrt{D} \eta \cosh m \eta \right) \\
+ 2m \sqrt{D} \sin \sqrt{D} \eta \cosh m \eta + 2m \sqrt{D} \eta \sinh m \eta \right) \tag{21}
+ \frac{\sinh m}{4mD + m} \left( m^4 \cos \sqrt{D} \eta \cosh m \eta - m \sqrt{D} \sin \sqrt{D} \eta \sinh m \eta \right) \\
+ 2m \sqrt{D} \sin \sqrt{D} \eta \sinh m \eta + 2D \sqrt{D} \eta \cosh m \eta \right) \\
+ \frac{m \sinh m}{4D} \left( 2 \eta \sqrt{D} \sin \sqrt{D} \eta + \eta^2 D \cos \sqrt{D} \eta + \cos \sqrt{D} \eta \right) \\
- \eta \sqrt{D} \sin \sqrt{D} \eta \right] \]

For impermeable plate

\[
\theta'(0) = \frac{\sqrt{D}}{\sin \sqrt{D}} + \text{Re} \left[ B_1 \sqrt{D} - \frac{\text{asinh} m}{4mD + m} (m^2 + 2D) + \frac{m \sinh m}{4D} \right] \tag{22}
\]

For porous plate

\[
\theta'(1) = \frac{\sqrt{D}}{\sin \sqrt{D}} \cos \sqrt{D} + \text{Re} \left[ -B_1 \sqrt{D} \sin \sqrt{D} + B_2 \sqrt{D} \cos \sqrt{D} \right] \\
- a \left( \frac{(\cosh m - 1)}{2\sqrt{D}} \right) \left( \sin \sqrt{D} \eta + \sqrt{D} \cos \sqrt{D} \eta \right) - \left( \frac{(\cosh m - 1)}{m^2 + 4m} \right) \left( m^4 \cos \sqrt{D} \eta \sinh m \eta + m \sqrt{D} \sin \sqrt{D} \eta \cosh m \eta \right) + 2D \sqrt{D} \cos \sqrt{D} \eta \right) \tag{23}
+ \frac{\sinh m}{4mD + m} \left( m^4 \cos \sqrt{D} \eta \cosh m \eta + m \sqrt{D} \sin \sqrt{D} \eta \sinh m \right) \\
+ 2D \sqrt{D} \cos \sqrt{D} \eta \sinh m \eta + \frac{m \sinh m}{4D} \left( \sqrt{D} \sin \sqrt{D} + D \sqrt{D} \eta + \cos \sqrt{D} \right) \}
\]

3. Results and Discussions

Figure 1 gives the normal velocity profiles for various values for the permeability parameter \( S \) and \( Re = 0.2 \). An increase in \( S \) reduces the magnitude of the normal velocity up to the half of the distance
between the plates from the impermeable wall and then onwards reverse effect is observed as the fluid particles go nearer to the permeable plate. There is a kink in the fluid near the middle of the plates.

![Figure 1](image1.png)

**Figure 1.** Normal velocity profiles for Re = 0.2

Figure 2 depicted the axial velocity profiles for various values of S and Re. Increasing the permeability the axial velocity which is due to the gravity only is g neatly increased. For lower injection rate and permeability it is greatly reduced. The maximum of the velocity occurs in the fluid between the plates.

![Figure 2](image2.png)

**Figure 2.** Axial velocity profiles

| Table 1. Variation of skin friction component for normal velocity profiles with Re and S |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Re              | S = 0.25        | S = 0.5         | S = 0.75        |
| Re              | Tₓ               | Tₓ               | Tₓ               |
| 0.1             | 0.6422           | 4.0524           | 12.5927          |
| 0.2             | 1.2844           | 8.1048           | 25.1853          |
| 0.3             | 1.9265           | 12.1572          | 37.7780          |
| 0.4             | 2.5687           | 16.2096          | 50.3706          |
| 0.5             | 3.2109           | 20.2621          | 62.9633          |
| 0.6             | 3.8531           | 24.3145          | 75.5559          |
| 0.7             | 4.4952           | 28.3669          | 88.1486          |
| 0.8             | 5.1374           | 32.4193          | 100.7413         |
| 0.9             | 5.7796           | 36.4717          | 113.3339         |
| 1.0             | 6.4218           | 40.5241          | 125.9266         |
Table 2. Variation of skin friction component for axial velocity profiles with Re and S

| Re | S = 0.25 | Tz | S = 0.5 | Tz | S = 0.75 | Tz |
|----|---------|----|---------|----|---------|----|
| 0.1| 0.7715  | -0.4524 | -0.4851 |
| 0.2| 2.4618  | -0.0979 | -0.2478 |
| 0.3| 4.1521  | 0.2566  | -0.0104 |
| 0.4| 5.8424  | 0.6111  | 0.2270  |
| 0.5| 7.5327  | 0.9656  | 0.4644  |
| 0.6| 9.2230  | 1.3200  | 0.7018  |
| 0.7| 10.9133 | 1.6745  | 0.9391  |
| 0.8| 12.6036 | 2.0290  | 1.1765  |
| 0.9| 14.2939 | 2.3835  | 1.4139  |
| 1.0| 15.9841 | 2.7380  | 1.6513  |

It is observed in Table 1 and Table 2 that both the skin friction components for normal velocity and axial velocity profiles increase when there is an increase in Reynolds number. But, when there is an increase in permeability parameter skin friction for normal velocity profiles (Table 1) shows an increasing trend whereas reverse trend is noticed in the case of axial velocity profiles (Table 2).

Table 3. Variation of heat transfer with respect to heat source parameter

| D | Nu  | Nu  |
|---|-----|-----|
|   | Pr = 7.0 | Pr = 0.71 |
| 1 | 1.1884 | 5.72 |
| 2 | 1.4317 | 2.9427 |
| 3 | 1.7548 | 1.9883 |
| 4 | 2.1995 | 1.4953 |
| 5 | 2.8422 | 1.1898 |
| 6 | 3.8364 | 0.9796 |
| 7 | 5.5610 | 0.8249 |
| 8 | 9.1811 | 0.7059 |
| 9 | 21.2585 | 0.6111 |

It is obvious from Table 3 that the rate of heat transfer in the case of water (Pr = 7.0) increases when there is an increase in the heat source parameter whereas it decreases in the case of air (Pr = 0.71).

The $0'(\eta)$ for $\eta = 0$ (impermeable plate) and $\eta = 1$ (porous plate) is plotted in Figure 3 against cross flow Reynolds number for different values of S and Pr. It is observed that for small permeability, the heat transfer is more in the case of air (Pr = 0.7) than that of water (Pr = 7.0) on the impermeable plate. However, the reverse effect is seen on the porous plate. For higher permeability parameter the heat transfer remains the same on the walls and also for (Pr = 0.7) air and (Pr = 7.0) water. It is concluded that for higher Prandtl numbers, the heat transfer on the impermeable plate is considerably higher than that of the porous plate. It is also observed that the heat transfer coefficient increases with an increase in the Reynolds number Re for both air and water for both permeable and impermeable plates.

It is also observed that the heat transfer decreases when there is a small increase in heat source parameter in the case of a small permeability parameter for both air and water. But a reverse effect is seen in the case of higher permeability parameter for both air and water.
4. Conclusion
1) Reynolds number has the effect of increasing the normal velocity skin friction, axial velocity skin friction and heat transfer.
2) Permeability parameter has the effect of increasing axial velocity and normal velocity but, it has opposite effect on axial velocity skin friction.

References
[1] Vidhya M, Sundarammal Kesavan 2010 Laminar Convection through porous medium between two vertical parallel plate with heat sourceIEEE Transaction 195–200
[2] Loganathan C, Gomathi S 2016 Unsteady Three Dimensional Dusty couette flows through porous plates with heat transfer and periodic suctionProgress in Nonlinear Dynamics and Chaos4(2) 59–76
[3] Gireesha B J, Vishalakshi C S 2013 Three dimensional couette flows of an unsteady dusty fluid and heat transfer through a porous medium withvariable permeabilityMathematical Sciences International Research Journal2(2) 370–391
[4] Das S S 2009 Effect of suction and injection on MHD three dimensional couette flow and heat transfer through a porous mediumJournal of Naval and Architecture and Marine Engineering6 41–51
[5] Singh K D, Rakesh Sharma 2001 Three dimensional couette flows through porous medium with heat transferIndian Journal of Pure and Applied Mathematics32(12) 1819–1829
[6] Attia H A, Al-kaisy A M A, Ewis K M 2011 MHD couette flow and heat transfer of a dusty fluid with exponential decaying pressure gradientTamkang Journal of Science and Engineering14(2) 91–96
[7] Chand K, Kumar R, Sharma S 2012 Hydro magnetic oscillatory flow through a porous medium bounded by two vertical porous plates with heat source and soret effectAdvances in Applied Science Research3(4) 2169–2178
[8] Gireesha B J, Chamkha A J, Visalakshi C S, Bagawade C S 2012 Three dimensional couette flow of a dusty fluid with heat transferApplied Mathematical Modelling36(2) 683–701
[9] Govindarajan A, Ramamurthy V, Sundarammal K 2007 3D couette flow of dusty fluid with transpiration coolingJournal of Zhejiang University SCIENCE A8(2) 313–322
[10] Govindarajan A, Ali chamkha, Sundarammal Kesavan, Vidhya M 2014 Chemical reaction effects on unsteady magneto hydrodynamic free convective flow in a rotating porous medium with mass transfer Thermal Science18(2) 515–526