INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 1, Issue 5, 2010 pp.757-768
Journal homepage: www.IJEE.IEEFoundation.org

Effect of periodic suction on three dimensional flow and heat transfer past a vertical porous plate embedded in a porous medium

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Abstract
This paper theoretically analyzes the effect of periodic suction on three dimensional flow of a viscous incompressible fluid past an infinite vertical porous plate embedded in a porous medium. The governing equations for the velocity and temperature of the flow field are solved employing perturbation technique and the effects of the pertinent parameters such as suction parameter α, permeability parameter K_p, Reynolds number R_e etc. on the velocity, temperature, skin friction and the rate of heat transfer are discussed with the help of figures and tables.

Keywords: Heat transfer, Periodic suction, Porous medium, Three dimensional flow, Vertical plate.

1. Introduction
Flow problems through porous media over a flat surface are of great theoretical as well as practical interest in view of their varied applications in different fields of science and technology such as aerodynamics, extraction of plastic sheets, cooling of infinite metallic plates in a cool bath, liquid film condensation process and in major fields of glass and polymer industries. In view of these applications, a series of investigations were made to study the flow past a vertical wall. Hasimoto [1] discussed the boundary layer growth on a flat plate with suction or injection. Gersten and Gross [2] analyzed the flow and heat transfer along a plane wall with periodic suction. Soundalgekar [3] studied the free convection effects on steady MHD flow past a vertical porous plate. Yamamoto and Iwamura [4], Raptis [5], Raptis *et al.* [6], Govindarajulu and Thangaraj [7] and Mansutti and his associates [8] investigated the free convective flow of viscous fluids along a vertical plate in presence of variable suction or injection under different physical situations.
The phenomenon of free convection and mass transfer flow through a porous medium past an infinite vertical porous plate with time dependant temperature and concentration was studied by Sattar [9]. Hayat *et al.* [10] have analyzed the periodic unsteady flow of a non-Newtonian fluid. The unsteady MHD convective heat transfer past a semi-infinite vertical porous moving plate with variable suction was investigated by Kim [11]. Singh and Sharma [12] analyzed the three dimensional free convective flow and heat transfer through a porous medium with periodic permeability. Chauhan and Sahal [13] analyzed the flow and heat transfer over a naturally permeable bed of very small permeability with a variable suction. Das *et al.* [14] numerically studied the effect of mass transfer on unsteady flow past an accelerated vertical porous plate with suction. Das and his co-workers [15] discussed the effect of mass transfer on MHD flow and

heat transfer past a vertical porous plate through a porous medium under oscillatory suction and heat source.

The study reported herein analyzes the effect of periodic suction on the three dimensional flow of a viscous incompressible fluid past an infinite vertical porous plate embedded in a porous medium. The governing equations for the velocity and temperature of the flow field are solved employing perturbation technique and the effects of the pertinent parameters on the velocity, temperature, skin friction and the rate of heat transfer are discussed with the help of figures and tables.

2. Mathematical formulation of the problem

Consider the three dimensional flow of a viscous incompressible fluid past an infinite vertical porous plate embedded in a porous medium in presence of periodic suction. A coordinate system is chosen with the plate lying vertically on x^*-z^* plane such that x^*-axis is taken along the plate in the direction of flow and y^*-axis is taken normal to the plane of the plate and directed into the fluid which is flowing with the free stream velocity U. The plate is assumed to be at constant temperature T_w and is subjected to a transverse sinusoidal suction velocity of the form:

$$v^*(z^*) = -V(1+\varepsilon\cos\pi z^*/d), \tag{1}$$

where ε (<<1) is a very small positive constant quantity, d is taken equal to the half wavelength of the suction velocity. The negative sign in the above equation indicates that the suction is towards the plate. Due to this kind of injection velocity the flow remains three dimensional. All the physical quantities involved are independent of x^* for this fully developed laminar flow. Denoting the velocity components u^*, v^*, w^* in x^*, y^*, z^* directions, respectively, and the temperature by T^*, the problem is governed by the following equations:

Continuity equation:

$$\frac{\partial v^*}{\partial y^*}+\frac{\partial w^*}{\partial z^*}=0, \tag{2}$$

Momentum equation:

$$v^*\frac{\partial u^*}{\partial y^*}+w^*\frac{\partial u^*}{\partial z^*}=\nu\left(\frac{\partial^2 u^*}{\partial y^{*2}}+\frac{\partial^2 u^*}{\partial z^{*2}}\right)-\frac{\nu}{K^*}u^*, \tag{3}$$

$$v^*\frac{\partial v^*}{\partial y^*}+w^*\frac{\partial v^*}{\partial z^*}=-\frac{1}{\rho}\frac{\partial p^*}{\partial y^*}+\nu\left(\frac{\partial^2 v^*}{\partial y^{*2}}+\frac{\partial^2 v^*}{\partial z^{*2}}\right)-\frac{\nu}{K^*}v^*, \tag{4}$$

$$v^*\frac{\partial w^*}{\partial y^*}+w^*\frac{\partial w^*}{\partial z^*}=-\frac{1}{\rho}\frac{\partial p^*}{\partial z^*}+\nu\left(\frac{\partial^2 w^*}{\partial y^{*2}}+\frac{\partial^2 w^*}{\partial z^{*2}}\right)-\frac{\nu}{K^*}w^*, \tag{5}$$

Energy equation:

$$\rho C_p\left(v^*\frac{\partial T^*}{\partial y^*}+w^*\frac{\partial T^*}{\partial z^*}\right)=k\left(\frac{\partial^2 T^*}{\partial y^{*2}}+\frac{\partial^2 T^*}{\partial z^{*2}}\right)+\mu\phi^*, \tag{6}$$

where

$$\phi^*=2\left\{\left(\frac{\partial v^*}{\partial y^*}\right)^2+\left(\frac{\partial w^*}{\partial z^*}\right)^2\right\}+\left\{\left(\frac{\partial u^*}{\partial y^*}\right)^2+\left(\frac{\partial w^*}{\partial y^*}+\frac{\partial v^*}{\partial z^*}\right)^2+\left(\frac{\partial u^*}{\partial z^*}\right)^2\right\}, \tag{7}$$

ρ is the density, σ is the electrical conductivity, p^* is the pressure, K^* is the permeability of the porous medium, ν is the coefficient of kinematic viscosity and k is the thermal conductivity.

The initial and the boundary conditions of the problem are

$$u^*=0,\ v^*=-V(1+\varepsilon\cos\pi z^*/d),\ w^*=0,\ T^*=T_w^* \ \text{at}\ y^*=0,$$
$$u^*=U,\ v^*=V,\ w^*=0,\ p^*=p_\infty^* \ \text{as}\ y^*\to\infty. \tag{8}$$

Introducing the following non-dimensional quantities

$$y = \frac{y^*}{d},\ z = \frac{z^*}{d},\ u = \frac{u^*}{U},\ v = \frac{v^*}{U},\ w = \frac{w^*}{U},\ p = \frac{p^*}{\rho U^2},\ \theta = \frac{T^* - T_\infty^*}{T_w^* - T_\infty^*}, \tag{9}$$

equations (2) - (6) reduce to the following forms:

$$\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \tag{10}$$

$$v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = \frac{1}{R_e}\left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) - \frac{u}{K_p}, \tag{11}$$

$$v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{R_e}\left(\frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) - \frac{v}{K_p}, \tag{12}$$

$$v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{R_e}\left(\frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) - \frac{w}{K_p}, \tag{13}$$

$$v\frac{\partial \theta}{\partial y} + w\frac{\partial \theta}{\partial z} = \frac{1}{R_e P_r}\left(\frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2}\right) + \frac{E_c}{R_e}\phi, \tag{14}$$

where

$$\phi = 2\left\{\left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right\} + \left\{\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial z}\right)^2\right\}, \tag{15}$$

$R_e = \frac{Ud}{\nu}$ (Reynolds number), $P_r = \frac{\mu C_p}{k}$ (Prandtl number), $E_c = \frac{U^2}{C_p\left(T_w^* - T_\infty^*\right)}$ (Eckert number),

$K_p = \frac{K^* U}{\nu d}$ (Permeability parameter), $\alpha = \frac{V}{U}$ (Suction parameter). (16)

The corresponding boundary conditions now reduce to the following form:

$u = 0,\quad v = 1 + \varepsilon \cos \pi z,\quad w = 0,\quad \theta = 1$ at $y = 0$,

$u = 1,\quad v = 1,\ p = p_\infty,\quad w = 0,\quad \theta = 0$ as $y \to \infty$. (17)

3. Method of solution

In order to solve the problem, we assume the solutions of the following form because the amplitude ε (<< 1) of the permeability variation is very small:

$$u(y, z) = u_0(y) + \varepsilon u_1(y, z) + \ldots\ldots \tag{18}$$

$$v(y, z) = v_0(y) + \varepsilon v_1(y, z) + \ldots\ldots \tag{19}$$

$$w(y, z) = w_0(y) + \varepsilon w_1(y, z) + \ldots\ldots \tag{20}$$

$$p(y, z) = p_0(y) + \varepsilon p_1(y, z) + \ldots\ldots \tag{21}$$

$$\theta(y, z) = \theta_0(y) + \varepsilon \theta_1(y, z) + \ldots\ldots \tag{22}$$

When $\varepsilon = 0$, the problem reduces to the two dimensional free convective flow through a porous medium with constant permeability which is governed by the following equations:

$$\frac{dv_0}{dy} = 0, \tag{23}$$

$$\frac{d^2u_0}{dy^2}+\alpha R_e\frac{du_0}{dy}-\frac{R_e}{K_p}u_0=0\,, \tag{24}$$

$$\frac{d^2\theta_0}{dy^2}+\alpha R_eP_r\frac{d\theta_0}{dy}=-2E_cP_ru_0'^{\,2}\,, \tag{25}$$

The corresponding boundary conditions become

$u_0 = 0,\quad v_0 = -\alpha,\ w_0=0,\quad \theta_0 = 1$ at $y = 0$,

$u_0= 1,\ p= p_\infty,\ v_0 =1,\ w_0=0,\qquad \theta_0 = 0$ as $y\to\infty$. (26)

The solutions for $u_0(y)$ and $\theta_0(y)$ under boundary conditions (26) for this two dimensional problem are

$$u_0(y)=1-e^{-my}\,, \tag{27}$$

$$\theta_0(y)=e^{\alpha P_rR_ey}+m_1\left(e^{-\alpha P_rR_ey}-e^{-2my}\right), \tag{28}$$

with $v_0 = -\alpha,\ w_0 =0,\ p_0$ =constant, (29)

where

$$m=\frac{1}{2}\left[\alpha R_e+\sqrt{\alpha^2R_e^2+\frac{4R_e}{K_p}}\right] \text{ and } m_1=\frac{mE_cP_r}{2\left(2m-\alpha R_eP_r\right)}\,.$$

When $\varepsilon \neq 0$, substituting equations (18)-(22) into equations (10) - (14) and comparing the coefficients of like powers of ε, neglecting those of ε^2, we get the following first order equations with the help of equation (29):

$$\frac{\partial v_1}{\partial y}+\frac{\partial w_1}{\partial z}=0, \tag{30}$$

$$v_1\frac{\partial u_0}{\partial y}-\alpha\frac{\partial u_1}{\partial y}=\frac{1}{R_e}\left(\frac{\partial^2u_1}{\partial y^2}+\frac{\partial^2u_1}{\partial z^2}\right)-\frac{u_1}{K_p}\,, \tag{31}$$

$$-\alpha\frac{\partial v_1}{\partial y}=-\frac{\partial p_1}{\partial y}+\frac{1}{R_e}\left(\frac{\partial^2v_1}{\partial y^2}+\frac{\partial^2v_1}{\partial z^2}\right)-\frac{v_1}{K_p}\,, \tag{32}$$

$$-\alpha\frac{\partial w_1}{\partial y}=-\frac{\partial p_1}{\partial z}+\frac{1}{R_e}\left(\frac{\partial^2w_1}{\partial y^2}+\frac{\partial^2w_1}{\partial z^2}\right)-\frac{w_1}{K_p}\,, \tag{33}$$

$$v_1\frac{\partial\theta_0}{\partial y}-\alpha\frac{\partial\theta_1}{\partial y}=\frac{1}{R_eP_r}\left(\frac{\partial^2\theta_1}{\partial y^2}+\frac{\partial^2\theta_1}{\partial z^2}\right)+\frac{2E_c}{R_e}.\frac{\partial u_0}{\partial y}.\frac{\partial u_1}{\partial y}\,, \tag{34}$$

The corresponding boundary conditions are

$u_1 = 0,\quad v_1 = -\alpha\cos\pi z,\quad w_1=0,\quad \theta_1 = 0$ at $y = 0$,

$u_1=0,\quad v_1=0,\ p_1=0,\ w_1=0,\quad \theta_1 = 0$ as $y\to\infty$. (35)

Equations (30) - (34) are the linear partial differential equations which describe the three-dimensional flow through a porous medium. For solution, we shall first consider three equations (30), (32) and (33) being independent of the main flow component u_1 and the temperature field θ_1. We assume v_1, w_1 and p_1 of the following form:

$$v_1(y,z)=v_{11}(y)\cos\pi z\,, \tag{36}$$

$$w_1(y,z)=-\frac{1}{\pi}v_{11}'(y)\sin\pi z\,, \tag{37}$$

$$p_1(y,z) = p_{11}(y)\cos\pi z, \tag{38}$$

where the prime in $v'_{11}(y)$ denotes the differentiation with respect to y. Expressions for $v_1(y, z)$ and $w_1(y, z)$ have been chosen so that the equation of continuity (30) is satisfied. Substituting these expressions (36)-(38) into (32) and (33) and solving under corresponding transformed boundary conditions, we get the solutions of v_1, w_1 and p_1 as:

$$v_1 = \frac{\alpha}{A_1 - A_2}\left(A_2 e^{-A_1 y} - A_1 e^{-A_2 y}\right)\cos\pi z, \tag{39}$$

$$w_1 = \frac{\alpha A_1 A_2}{\pi(A_1 - A_2)}\left(e^{-A_1 y} - e^{-A_2 y}\right)\sin\pi z, \tag{40}$$

where

$$A_1 = \frac{1}{2}\left[m + \sqrt{m^2 + 4\pi^2}\right],\ A_2 = \frac{1}{2}\left[n + \sqrt{n^2 + 4\pi^2}\right],$$

$$n = \frac{1}{2}\left[\alpha R_e - \sqrt{\alpha^2 R_e^2 + \frac{4R_e}{K_p}}\right].$$

In order to solve equations (31) and (34), we assume

$$u_1(y,z) = u_{11}(y)\cos\pi z, \tag{41}$$

$$\theta_1(y,z) = \theta_{11}(y)\cos\pi z. \tag{42}$$

Substituting equations (41) and (42) in equations (31) and (34), we get

$$u''_{11} + \alpha u'_{11} - \left(\pi^2 + \frac{R_e}{K_p}\right)u_{11} = R_e v_{11} u'_0, \tag{43}$$

$$\theta''_{11} + \alpha P_r \theta'_{11} - \pi^2 \theta_{11} = R_e P_r \theta'_0 v_{11} - 2E_c P_r u'_0 u'_{11}. \tag{44}$$

The corresponding boundary conditions are

$u_{11} = 0$, $\theta_{11} = 0$ at $y = 0$,

$u_{11}=0$, $\theta_{11} = 0$ as $y \to \infty$. (45)

Solving equations (43) and (44) under boundary condition (45) and using equations (18), (22), (25) and (26), we get

$$u = 1 - e^{-my} + B_1 e^{-my}\left[B_3 e^{(m-A_1)y} - B_4 e^{-(m+A_2)y} - e^{-B_5 y}\right]\cos\pi z \tag{46}$$

$$\theta = e^{\alpha P_r R_e y} + m_1\left(e^{-\alpha P_r R_e y} - e^{-2my}\right) + B_0\left[B_7 e^{(\alpha P_r R_e - A_1)y} - B_8 e^{(\alpha P_r R_e - A_2)y} - B_9 e^{-(\alpha P_r R_e + A_1)y}\right.$$
$$\left. + B_{10} e^{-(\alpha P_r R_e + A_2)y}\right] + \varepsilon B_2\left[A_{11} e^{-(A_1+2m)y} - B_{12} e^{(2m-A_2)y} - B_{13} e^{-(m+B_5)y}\right] - \varepsilon B_{14} e^{-B_6 y} \tag{47}$$

where

$$B_0 = \frac{\varepsilon\alpha^2 R_e^2 P_r^2}{A_1 - A_2},\ B_1 = \frac{\varepsilon\alpha R_e m}{A_1 - A_2},\ B_2 = \frac{2m\alpha R_e P_r}{A_1 - A_2},\ B_3 = \frac{A_2}{(A_1 + m)^2 - \alpha R_e (A_1 + m) - \left(\pi^2 + \frac{R_e}{K_p}\right)},$$

$$B_4 = \frac{A_1}{(A_2 + m)^2 + \alpha R_e (A_2 + m) - \left(\pi^2 + \frac{R_e}{K_p}\right)},\ B_5 = \frac{1}{2}\left[\alpha R_e + \sqrt{\alpha^2 R_e^2 + 4\left(\pi^2 + \frac{R_e}{K_p}\right)}\right],$$

$$B_6 = \frac{1}{2}\left[\alpha R_e P_r + \sqrt{\alpha^2 R_e^2 P_r^2 + 4\pi^2}\right], B_7 = \frac{A_2}{(A_1 - \alpha P_r)^2 - \alpha P_r(A_1 - \alpha P_r) - \pi^2},$$

$$B_8 = \frac{A_1}{(A_2 - \alpha P_r)^2 - \alpha P_r(A_2 - \alpha P_r) - \pi^2}, B_9 = \frac{m_1 A_2}{(A_1 + \alpha P_r)^2 - \alpha P_r(A_1 + \alpha P_r) - \pi^2},$$

$$B_{10} = \frac{A_1 m_1}{(A_2 + \alpha P_r)^2 - \alpha P_r(A_2 + \alpha P_r) - \pi^2}, B_{11} = \frac{B_{15}}{(A_1 + 2m)^2 - \alpha P_r(A_1 + 2m) - \pi^2},$$

$$B_{12} = \frac{B_{16}}{(A_2 + 2m)^2 - \alpha P_r(A_2 + 2m) - \pi^2}, B_{13} = \frac{mE_c B_5}{(B_5 + m)^2 - \alpha P_r(B_5 + m) - \pi^2},$$

$$B_{14} = \frac{\alpha^2 R_e^2 P_r^2}{A_1 - A_2}(B_7 - B_8 - B_9 + B_{10}) - B_2(B_{11} - B_{12} - B_{13}), B_{15} = m_1 A_2 + mE_c B_3(A_1 + m),$$

$$B_{16} = m_1 A_1 + mE_c B_4(A_2 + m).$$

3.1 Skin friction

The x- and z-components of skin friction at the wall are given by

$$\tau_x = \left(\frac{du_0}{dy}\right)_{y=0} + \varepsilon\left(\frac{du_1}{dy}\right)_{y=0}, \tag{48}$$

and

$$\tau_z = \varepsilon\left(\frac{dw_1}{dy}\right)_{y=0}. \tag{49}$$

Using equations (46) and (40) in equation (48) and (49) respectively, the x- and z-components of skin friction at the wall become

$$\tau_x = m - B_1(A_1 B_3 - A_2 B_4 - B_5 - m)\cos \pi z, \tag{50}$$

$$\tau_z = -\frac{\varepsilon\alpha A_1 A_2}{\pi}\sin \pi z. \tag{51}$$

3.2 Rate of heat transfer

The rate of heat transfer i.e. heat flux at the wall in terms of Nusselt number (N_u) is given by

$$N_u = \left(\frac{d\theta_0}{dy}\right)_{y=0} + \varepsilon\left(\frac{d\theta_1}{dy}\right)_{y=0} \tag{52}$$

Using equation (47) in equation (52), the heat flux at the wall becomes

$$N_u = \alpha R_e P_r + m_1(-\alpha R_e P_r + 2m) + B_0[B_7(\alpha R_e P_r - A_1) - B_8(\alpha R_e P_r - A_2) + B_9(\alpha R_e P_r + A_1)$$
$$- B_{10}(\alpha R_e P_r + A_2)] + \varepsilon B_2[-B_{11}(2m + A_1) - B_{12}(2m - A_2) + B_{13}(m + B_5)] + \varepsilon B_6 B_{14}. \tag{53}$$

4. Results and discussion

The problem discusses the effect of periodic suction on three dimensional flow of a viscous incompressible fluid past an infinite vertical porous plate embedded in a porous medium. The governing equations for the velocity and temperature of the flow field are solved employing perturbation technique and the effects of the flow parameters on the velocity and temperature of the flow field and also on the skin friction and the rate of heat transfer have been discussed with the help of Figures 1-5 and Tables 1-2, respectively.

4.1 Velocity field

The velocity of the flow field is found to change substantially with the variation of suction parameter α, permeability parameter K_p and Reynolds number R_e. These variations are show in Figures 1-3.

The effect of permeability of the medium on the velocity of the flow field is shown in Figure 1. Keeping other parameters of the flow field constant, the permeability parameter K_p is varied in steps and its effect on the velocity field is studied. It is observed that a growing permeability parameter has an accelerating effect on the velocity of the flow field.

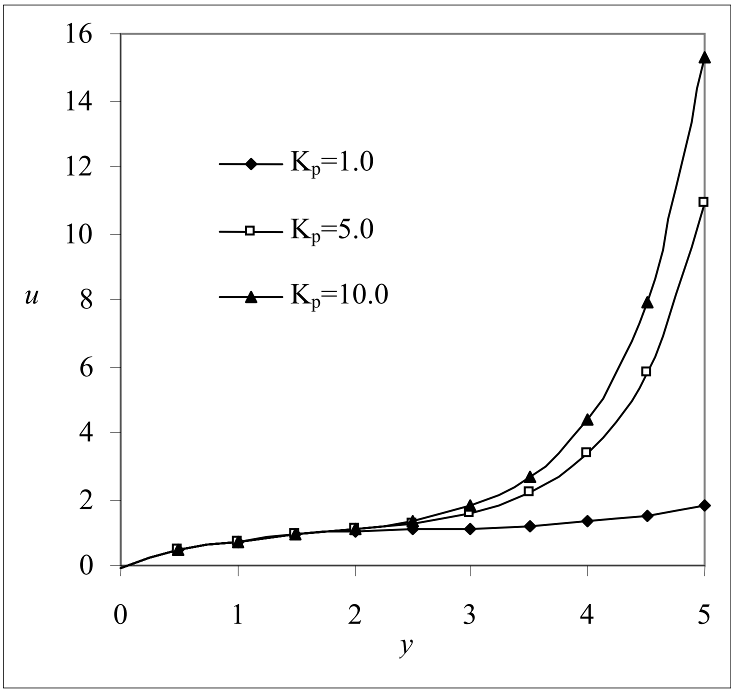

Figure 1. Velocity profiles against y for different values of K_p with $R_e = 1$, $P_r = 0.71$, $\alpha = 0.2$, $E_c = 0.01$, $\varepsilon = 0.2$, $z = 0$

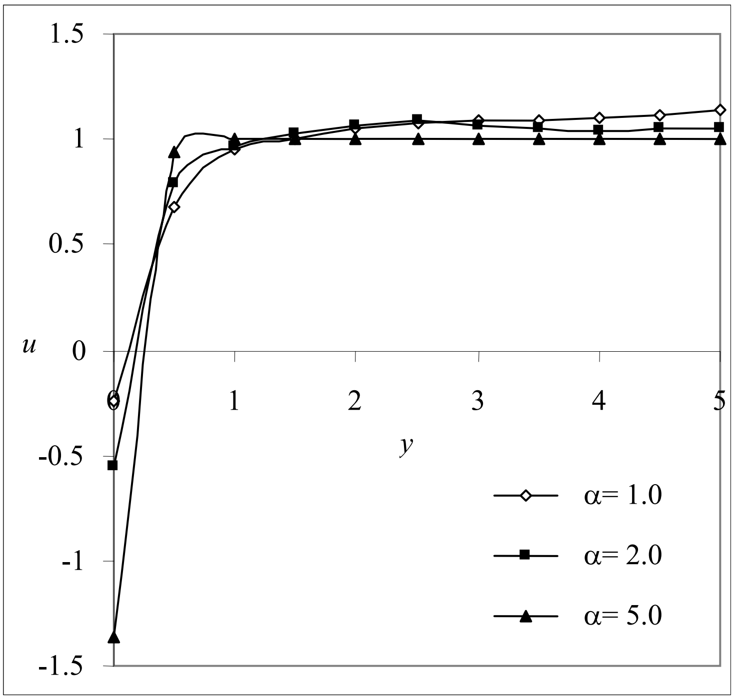

Figure 2. Velocity profiles against y for different values of α with $R_e = 1$, $P_r = 0.71$, $K_p = 1$, $E_c = 0.01$, $\varepsilon = 0.2$, $z = 0$

Figure 2, presents the effect of suction parameter α on the velocity of the flow field. The suction parameter is found to increase the magnitude of the velocity upto a certain distance (y=1.3) near the plate and thereafter the flow behaviour reverses.

Figure 3 depicts the effect of Reynolds number R_e on the velocity of the flow field. A growing Reynolds number leads to increase the velocity near the plate upto y=2 and thereafter, it retards the effect. The behaviour of Reynolds number is similar to the suction parameter in this respect.

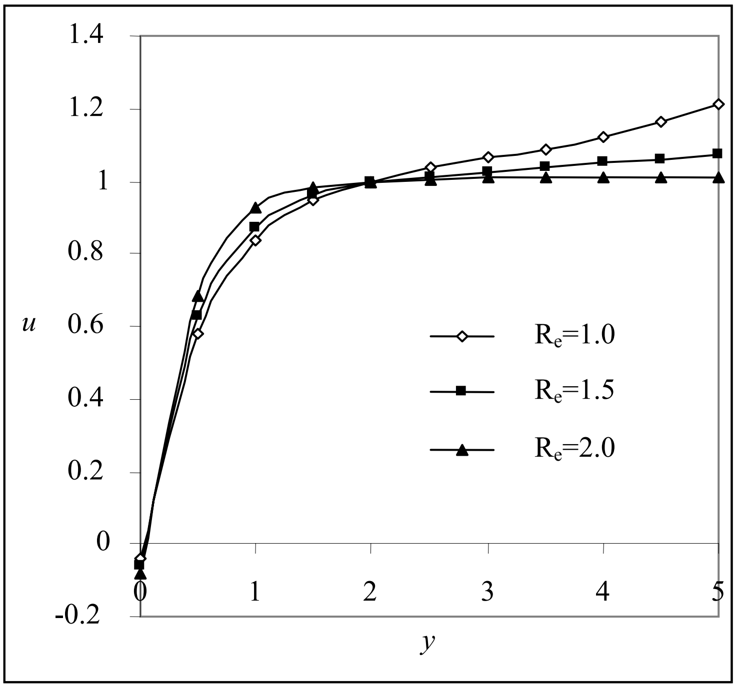

Figure 3. Velocity profiles against y for different values of R_e with $\alpha = 0.2$, $P_r = 0.71$, $K_p = 1$, $E_c = 0.01$, $\varepsilon = 0.2$, $z = 0$

4.2 Temperature field

The variation in the temperature of the flow field is due to suction parameter α and Reynolds number R_e. The effects of these parameters on the temperature field are discussed graphically with the help of Figures 4-5.

In Figures 4 and 5, we present the effect of suction parameter α and the Reynolds number R_e respectively on the temperature of the flow field. A careful observation of the above figures shows that the effect of growing suction parameter or Reynolds number leads to enhance the temperature of the flow field at all points.

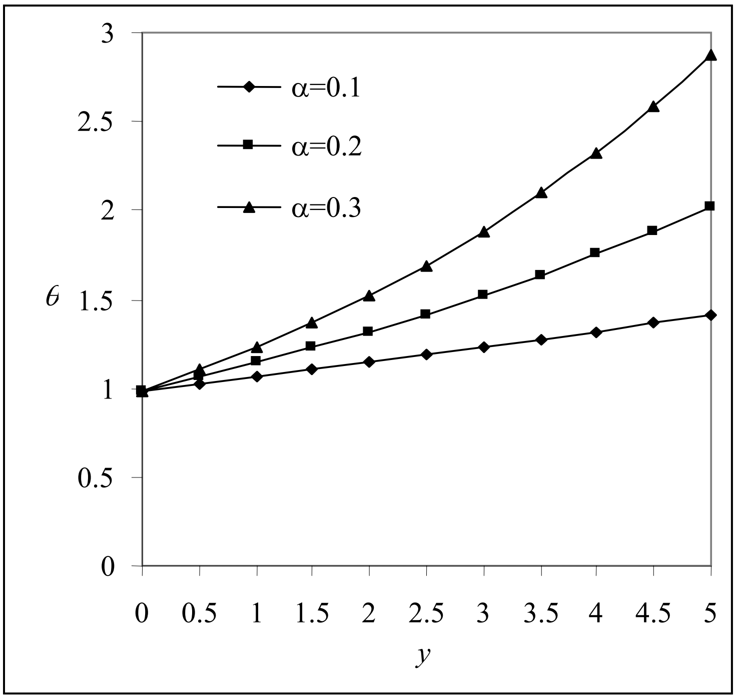

Figure 4. Temperature profiles against y for different values of α with $R_e = 1$, $K_p = 1$, $P_r = 0.71$, $E_c = 0.01$, $\varepsilon = 0.2$

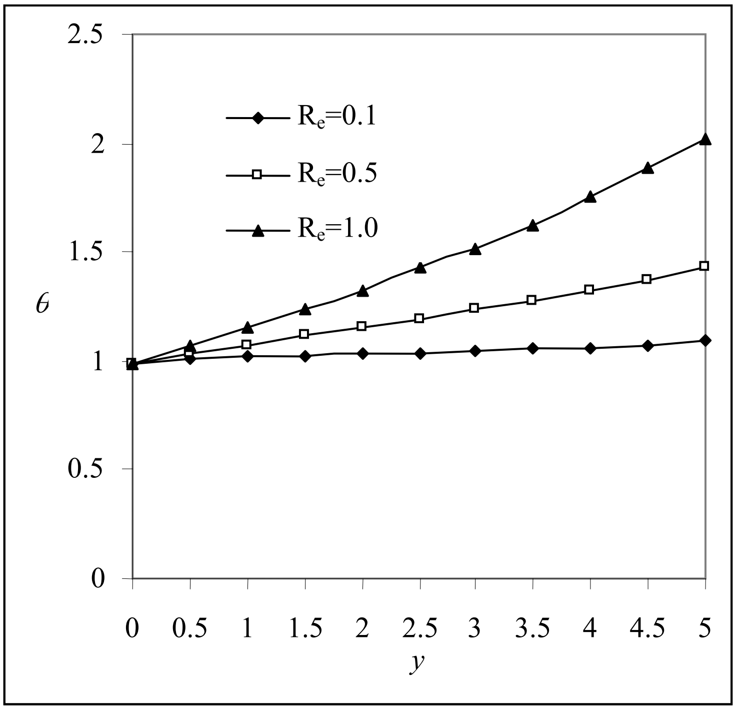

Figure 5. Temperature profiles against y for different values of R_e with $P_r = 0.71$, $K_p = 1$, $\alpha = 0.2$, $E_c = 0.01$, $\varepsilon = 0.2$

4.3 Skin friction

The variations in the value of x- and z-components of skin friction at the wall for different values of α and K_p are entered in Table 1. It is observed that the permeability parameter K_p decreases the x-component and increases the magnitude of z-component of skin friction at the wall. The effect of growing suction parameter is to enhance the magnitude of both the components of skin friction at the wall.

Table1. x- and z-component of skin friction (τ_x, τ_z) against α for different values of K_p with R_e=1 P_r=0.71, E_c = 0.01, α=0.2, ε =0.2 and z = 0 (=1/2 for τ_z)

	K_p=0.2		K_p=1.0		K_p=5.0		K_p=10.0	
α	τ_x	τ_z	τ_x	τ_z	τ_x	τ_z	τ_x	τ_z
0.0	2.4495	0.0000	1.4142	0.0000	1.0955	0.0000	1.0488	0.0000
0.2	2.8162	-0.1293	1.7205	-0.1295	1.3856	-0.1297	1.3367	-0.1298
0.5	3.4317	-0.3382	2.2620	-0.3394	1.9135	-0.3396	1.8632	-0.3398
2.0	7.7599	-1.6834	6.5651	-1.7057	6.3043	-1.7106	6.2722	-1.7112
5.0	22.762	-6.2661	21.947	-6.4261	21.821	-6.4604	21.806	-6.4648

4.4 Rate of heat transfer

The rate of heat transfer at the wall i.e. the heat flux in terms of Nusselt number N_u for different values of α and K_p are entered in Table 2. The heat flux at the wall grows as we increase the suction parameter in the flow field and the effect reverses with the increase of permeability parameter.

Table 2. Rate of heat transfer (N_u) against α for different values of K_p with R_e = 1, P_r = 0.71, α = 0.2, E_c = 0.01 and ε = 0.2

	N_u			
α	K_p=0.2	K_p=1.0	K_p=5.0	K_p=10.0
0.0	0.008696	0.005020	0.003889	0.003723
0.2	0.186269	0.181441	0.180830	0.180797
0.5	0.465496	0.461281	0.460627	0.457991
2.0	2.158400	2.145131	2.120497	2.024807
5.0	9.873545	9.354939	9.287622	9.280233

5. Conclusion

From the above analysis, we summarize the following results of physical interest on the velocity and temperature of the flow field and also on skin friction and the rate of heat transfer at the wall.

1. The effect of growing permeability parameter is to accelerate the velocity of the flow field at all points.
2. A growing suction parameter / Reynolds number is to enhance the magnitude of velocity of the flow field near the plate upto a certain distance and thereafter the flow behaviour reverses.
3. An increase in suction parameter/Reynolds number increases the temperature of the flow field at all points.
4. The permeability parameter decreases the x-component and increases the magnitude of z-component of skin friction at the wall. On the other hand, the effect of increasing suction parameter is to enhance the magnitude of both the components of skin friction at the wall.
5. A growing suction parameter enhances the rate of heat transfer at the wall, while a growing permeability parameter in the flow field reverses the effect.

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