Three dimensional flow and heat transfer through a porous medium with periodic permeability and variable suction velocity

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Abstract- The effect of periodic permeability and periodic suction velocity on heat transfer and flow through a highly porous medium bounded by infinite flat porous surface is studied. The problem is three dimensional due to periodic permeability and variable suction velocity. The expression for the velocity, temperature, skin friction and rate of heat transfer are obtained by using analytical perturbation techniques. It is observed that an increase in Reynolds number (Re) and suction parameter (α) leads to accelerate the flow velocity. Also, increasing suction parameter (α) results a decrease in temperature. The skin friction and rate of heat transfer are discussed with the help of tables.

Keywords: Periodic suction, three dimensional flow, Porous medium.

1. Introduction

Heat and mass transfer in porous media is discussed in a wide range of disciplines as Mechanical Engineering, Biomedical, Chemical Engineering, Food Technology, Petroleum Engineering, Groundwater Hydrology, and Industrial Engineering. The important applications include packed bed reactors, Filtering dry fuel cell, Contamination migration in groundwater, Insulation nuclear reactors and many more. Heat transfer problems have many practical applications in industrial manufacturing processes such as polymer composition. This rapidly increase in research activity has been many due to number of important applications in modern industries ranging from chemical reactors , underground spread of pollutants , heating of rooms, combustion , fires and many other heat transfer processes , both natural and artificial. Heat transfer plays a vital role in designing of car radiators, solar collection, various parts of power plant and even space craft. The basic three mechanism of heat transfer are convection, conduction and radiation.

The problems of flow through porous medium has numerous scientific and engineering applications, in view of these applications a wide research is done and still going on. Raptis (1981) ,studied the free convective flow and mass transfer through a porous medium bounded by infinite vertical surface with constant suction. Raptis (1983), investigated unsteady free convective flow through a porous medium. Adrian Bejan and R.Khair(1985), studied the heat and mass transfer by natural convection in porous medium.Bestman(1989), analysed the unsteady flow of an incompressible fluid in horizontal porous medium with suction.K.D Singh(1993),studied three dimensional viscous flow and heat transfer along a porous plate. K.D.Singh and G.N.Verma(1995), studied three dimensional oscillatory flow through a porous medium with periodic permeability. They also analysed heat transfer in three dimensional flow through a porous medium with periodic permability. N.Ahmed and D.Sarma (1997), studied three dimensional free convective flow and heat transfer through a porous medium. S.S.Das and U.K. Tripathy(2010) , analysed the effect of periodic suction on three dimensional and heat transfer past a vertical porous plate embedded in porous medium. Ujwanta , Hamza and Ibrahim (2011) ,analysed heat and mass transfer through a porous medium with variable permeability and periodic suction. The aim of this paper is to study the effect of periodic suction on three dimensional flow of a viscous incompressible fluid through a highly porous medium. The porous medium is bounded by an infinite horizontal porous surface with periodic suction. The analysis of skin friction which is very important from industry point of view is also studied.

2. Mathematical Formulation

For mathematical formulation of the problem, we consider the viscous incompressible fluid flow through a highly porous medium bounded by infinite porous surface. The surface lying horizontally on the x*-z* plane, with variable suction. The x*-axis is taken along the infinite surface being the direction of the flow and y*-axis is taken normal to surface directed into fluid flowing laminarly with free stream velocity U. Since surface is considered infinite in x*-direction so all physical quantities are independent of x*, however , flow will be three dimensional due to variation of suction velocity of the form

$$v^*(z^*) = -V\left[1+\varepsilon\cos\frac{\pi z^*}{L}\right] \tag{1}$$

which consists of basic steady distribution V>0 with superimposed weak transversally varying distribution $\varepsilon\cos\frac{\pi z^*}{L}$ Here L is the half wave length of the periodic suction velocity. The negative sign in (1) indicates that suction is towards surface. The permeability of the porous medium is assumed to be of the form

$$k^*(z^*) = \frac{K_0^*}{\left[1+\varepsilon\cos\frac{\pi z^*}{L}\right]} \tag{2}$$

where K^*_0 is mean permeability of the medium , L is wavelength of permeability distribution and ϵ(<<1) is amplitude of permeability variation. Denoting velocity components u* , v* ,w* in the direction x* , y* , z* respectively and temperature T*. The flow in highly porous medium is governed by following equations:

Continuity equation:

$$\frac{\partial v^*}{\partial y^*}+\frac{\partial w^*}{\partial z^*}=0 \tag{3}$$

Momentum equation

$$v^*\frac{\partial u^*}{\partial y^*}+w^*\frac{\partial u^*}{\partial z^*}=\upsilon\left(\frac{\partial^2 u^*}{\partial y^{*2}}+\frac{\partial^2 u^*}{\partial z^{*2}}\right)-\frac{\upsilon}{k^*}(u^*-U) \tag{4}$$

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

$$v^*\frac{\partial w^*}{\partial y^*}+w^*\frac{\partial w^*}{\partial z^*}=-\frac{1}{\rho}\frac{\partial p^*}{\partial z^*}+\upsilon\left(\frac{\partial^2 w^*}{\partial y^{*2}}+\frac{\partial^2 w^*}{\partial z^{*2}}\right)-\frac{\upsilon}{k^*}(w^*) \tag{6}$$

Energy equation:

$$\rho c_p\left(v^*\frac{\partial T^*}{\partial y^*}+w^*\frac{\partial T^*}{\partial z^*}\right)=k\left(\frac{\partial T^*}{\partial y^{*2}}+\frac{\partial^2 T^*}{\partial z^{*2}}\right)+\mu\phi^* \tag{7}$$

Where

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

ρ is the density , μ is the dynamic viscosity, ν is the kinematic viscosity, p* is the pressure , k* is the permeability of porous medium, k is the thermal conductivity of fluid and c_p is the specific heat of fluid at constant pressure.

The initial and boundary condition of the problem are

$$y^* = 0 \;;\quad u^* = 0,\quad w^* = 0,\quad T^* = T^*_w,\quad v^* = -V\left[1+\varepsilon\cos\frac{\pi z^*}{L}\right]$$

$$y^* = \infty \;;\quad u^* = U,\quad w^* = 0,\quad T^* = T^*_\infty,\quad p^* = p^*_\infty,\quad v^* = V \tag{8}$$

The subscripts ' w' and '∞' denote the physical quantities at the surface and in free stream respectively.

Introducing the following non-dimensional quantities

$$y = \frac{y^*}{L}, z = \frac{z^*}{L}, u = \frac{u^*}{U}, v = \frac{v^*}{U}, w = \frac{w^*}{U}, p = \frac{p^*}{\rho U^2}, p_\infty = \frac{p^*_\infty}{\rho U^2}, T = \left(\frac{T^* - T^*_\infty}{T^*_w - T^*_\infty}\right)$$

The other parameters introduced are defined as

$R = \frac{UL}{\upsilon}$ - Reynolds number $\qquad \alpha = \frac{V}{U}$ - Suction parameter

$\Pr = \frac{\mu c_p}{k}$ - Prandlt number

$E = \frac{U^2}{c_p(T^*_w - T^*_\infty)}$ - Eckert number

$K = \frac{k^* U^2}{\upsilon^2}$ - Permeability parameter

Equations (3) –(7) reduces to the following forms:

$$\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{9}$$

$$v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = \frac{1}{R}\left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) - \frac{R}{K_0}(u-1)[1+\varepsilon\cos\pi z] \tag{10}$$

$$v\frac{\partial v}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{R}\left(\frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) - \frac{R}{K_0}v(1+\varepsilon\cos\pi z) \tag{11}$$

$$v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{R}\left(\frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) - \frac{R}{K_0}w(1+\varepsilon\cos\pi z) \tag{12}$$

$$v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \frac{1}{R\Pr}\left(\frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{E}{R}\phi \tag{13}$$

Where

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

The corresponding boundary condition now reduce to the form

$y = 0$; $u = 0$, $w = 0$, $T = 1$, $v = -\alpha\,(1 + \epsilon \cos\pi z)$

$y = \infty$; $u = 1$, $w = 0$, $T = 0$, $p \to p_\infty$ (14)

2.1 Method of solution

In order to solve these differential equations from (9) – (13) , we assume the solution using Perturbation technique. Since ϵ (<<1) the amplitude of permeability variation is very small :

$u(y, z) = u_0(y) + \epsilon\, u_1(y, z) + \epsilon^2 u_2(y, z) + \ldots\ldots\ldots\ldots$

$v(y, z) = v_o(y) + \epsilon\, v_1(y, z) + \epsilon^2 v_2(y, z) + \ldots\ldots\ldots\ldots$

$w(y, z) = w_o(y) + \epsilon\, w_1(y, z) + \epsilon^2 w_2(y, z) + \ldots\ldots\ldots\ldots$

(15)

$p(y, z) = p_o(y) + \epsilon\, p_1(y, z) + \epsilon^2 p_2(y, z) + \ldots\ldots\ldots\ldots$

$T(y, z) = T_o(y) + \epsilon\, T_1(y, z) + \epsilon^2 T_2(y, z) + \ldots\ldots\ldots\ldots$

When $\epsilon = 0$, the problem reduces to the two dimensional flow through a porous medium with constant suction. In this case equations (9) – (13) reduces to

$$\frac{dv_0}{dy} = 0 \tag{16}$$

$$\frac{d^2 u_0}{d\,y^2} - v_0 R \frac{du_0}{dy} - \frac{R^2}{K} u_0 = -\frac{R^2}{K} \tag{17}$$

$$\frac{d^2 T_0}{dy^2} - v_0 R \Pr \frac{dT_0}{dy} = -E \Pr u_0'^2 \tag{18}$$

The corresponding boundary condition now become

$y = 0$; $u_0 = 0$, $w_0 = 0$, $T_0 = 1$, $v_0 = -\alpha$

$y = \infty$; $u_0 = 1$, $w_0 = 0$, $T_0 = 0$, $p_0 = p_\infty$ (19)

The solution for $u_0(y)$ and $T_0(y)$ using the boundary condition (19) are

$u_0(y) = 1 - e^{-my}$ (20)

$T_0(y) = (1 + M)\, e^{-\alpha R \Pr y} - M\, e^{-2my}$ (21)

With $v_0 = -\alpha$, $w_0 = 0$, $p_0 = p_\infty$ (22)

Where

$$m = \frac{R}{2}\left[\alpha + \sqrt{\left(\alpha^2 + \frac{4}{K}\right)}\right] \quad \text{and} \quad M = \frac{E \Pr m}{2(2m - \alpha R \Pr)}$$

When $\epsilon \neq 0$, substituting equations (15) into equations (9) – (13) and comparing the coefficients of like power of ϵ and neglecting higher power of ϵ^2 , we get the following with equations using equation (22):

$$\frac{\partial v_1}{\partial y} + \frac{\partial w_1}{\partial z} = 0 \tag{23}$$

$$v\frac{\partial u_0}{\partial y} - \alpha \frac{\partial u_1}{\partial y} = \frac{1}{R}\left(\frac{\partial^2 u_1}{\partial y^2} + \frac{\partial^2 u_1}{\partial\, z^2}\right) - \frac{R}{K}\left[u_1 + (u_0 - 1)\cos\pi z\right] \tag{24}$$

$$-\alpha\frac{\partial v_1}{\partial y}=-\frac{\partial p_1}{\partial y}+\frac{1}{R}\left(\frac{\partial^2 v_1}{\partial y^2}+\frac{\partial^2 v_1}{\partial z^2}\right)-\frac{R}{K}(v_1-\alpha\cos\pi z) \tag{25}$$

$$-\alpha\frac{\partial w_1}{\partial y}=-\frac{\partial p_1}{\partial z}+\frac{1}{R}\left(\frac{\partial^2 w_1}{\partial y^2}+\frac{\partial^2 w_1}{\partial z^2}\right)-\frac{R}{K}w_1 \tag{26}$$

$$v_1\frac{\partial T_0}{\partial y}-\alpha\frac{\partial T_1}{\partial y}=-\frac{1}{R\Pr}\left(\frac{\partial^2 T_1}{\partial y^2}+\frac{\partial^2 T_1}{\partial z^2}\right)-\frac{2E}{R}\frac{\partial u_0}{\partial y}\frac{\partial u_1}{\partial y} \tag{27}$$

The corresponding boundary condition now become

$y=0$; $u_1=0$, $w_1=0$, $T_1=0$, $v_1=-\alpha\cos\pi z$

$y=\infty$; $u_1=0$, $w_1=0$, $T_1=0$, $p_1=0$ (28)

Equations (23) – (27) are linear partial differential equations which describe the three dimensional flow. We assume the solution of equations (23)-(27) of the form

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

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

$w_1(y,z)=-\dfrac{1}{\pi}v'_{11}(y)\sin\pi z$ (29)

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

$T_1(y,z)=T_{11}(y)\cos\pi z$

where the $v'_{11}(y)$ denotes the differentiation with respect to y. The expressions for $v_1(y,z)$ and $w_1(y,z)$ have been selected so that the equation of continuity (23) is satisfied. Substituting these expressions (29) into (25) and (26) and solving these under transformed boundary conditions (28) , we get the solutions of v_1 , w_1 and p_1 as :

$$v_1(y,z)=\frac{\alpha C_0}{(\lambda-\pi)}\left(\pi e^{-\lambda y}-\lambda e^{-\pi y}\right)\cos\pi z+C_0\cos\pi z \tag{30}$$

$$w_1(y,z)=\frac{\lambda C_0}{(\lambda-\pi)}\left(e^{-\lambda y}-e^{-\pi y}\right)\sin\pi z \tag{31}$$

$$p_1(y,z)=\left(\alpha+\frac{R}{\pi K}\right)\frac{\lambda C_0}{(\pi-\lambda)}\left(e^{-\pi y}\right)\cos\pi z \tag{32}$$

In order to find $u_1(y,z)$ and $T_1(y,z)$ we use (28) and (29) , we get

$$u_1(y,z)=\left[RN_1(e^{-\lambda y}-e^{-my})+\frac{RmC_0}{(\lambda-\pi)}\left\{\frac{\lambda}{N_2}(e^{-\lambda y}-e^{-(m+\pi)y})-\frac{\pi}{N_3}(e^{-\lambda y}-e^{-(m+\lambda)y})\right\}\right]\cos\pi z \tag{33}$$

$T_1(y,z)=$

$$\frac{R\Pr C_0}{(\lambda-\pi)}\left[\begin{array}{l} \frac{2m\lambda}{M_1N_2}\{MN_2+Em(\pi+m)\}(e^{-\bar{\lambda}y}-e^{-(\pi+2m)y})-\frac{2m\pi}{M_2N_3}\{MN_3+Em(\lambda+m)\}(e^{-\bar{\lambda}y}-e^{-(\lambda+2m)y}) \\ +\frac{\alpha R\Pr\pi(1+M)}{M_3}(e^{-\bar{\lambda}y}-e^{-(\lambda+\alpha R\Pr)y})-\frac{\lambda(1+M)}{\pi}(e^{-\lambda^{-}}-e^{-(\pi+\alpha R\Pr)y}) \\ -\frac{2mE\lambda}{M_4}\left\{\frac{N_1(\lambda-\pi)}{C_0}-m\left(\frac{\pi}{N_3}-\frac{\pi}{N_2}\right)\right\}(e^{-\bar{\lambda}y}-e^{-(m+\lambda)y})-\frac{2m(\lambda-\pi)}{M_5}\left\{M-\frac{EmN_1}{C_0}\right\}(e^{-\bar{\lambda}y}-e^{-2my}) \\ \frac{\alpha R\Pr(1+M)(\lambda-\pi)}{\pi^2}(e^{-\bar{\lambda}y}-e^{-\alpha R\Pr y}) \end{array}\right]\cos\pi z$$

Where (34)

$$C_0=\frac{\alpha}{(1+\frac{\pi^2K}{R^2})}, \quad N_1=\frac{1}{\pi^2}(C_0-\frac{R}{K}), \quad N_2=\pi(2m-\alpha R)$$

$$N_3=2m\lambda+\frac{R^2}{K}, \quad M_1=(\pi+2m)^2-\alpha R\Pr(\pi+2m)-\pi^2, \quad M_2=(\lambda+2m)^2-\alpha R\Pr(\lambda+2m)-\pi^2,$$

$$M_3=\alpha R\lambda(\Pr+1)+\frac{R^2}{K}$$

$$M_4=(\lambda+m)^2-\alpha R\Pr(\lambda+m)-\pi^2, \quad M_5=(2m)^2-\alpha R\Pr(2m)-\pi^2$$

$$\lambda=\frac{R}{2}\left[\alpha+\left\{\alpha^2+4\left(\frac{\pi^2}{R^2}+\frac{1}{K}\right)\right\}^{\frac{1}{2}}\right], \quad \bar{\lambda}=\frac{R\Pr}{2}\left[\alpha+\left\{\alpha^2+4(\frac{\pi}{R\Pr})^2\right\}^{\frac{1}{2}}\right]$$

2.2 Skin friction

Now we discuss the important characteristics of the problem. The x and z component of skin friction at the wall are given by

$$\tau_x=\frac{\tau'_x}{\rho U^2}=\frac{\nu}{\rho U^2}\left(\frac{du_0}{dy}\right)_{y=0}+\frac{\nu}{\rho U^2}\varepsilon\left(\frac{du_1}{dy}\right)_{y=0} \qquad \tau_x=\frac{1}{R}\left(\frac{du_0}{dy}\right)_{y=0}+\frac{1}{R}\varepsilon\left(\frac{du_1}{dy}\right)_{y=0}$$

$$\tau_x=\frac{m}{R}+\varepsilon B_1(\alpha,R,K)\cos\pi z$$

where (35)

$$B_1(\alpha,R,K)=N_1(m-\lambda)+\frac{mC_0}{(\lambda-\pi)}\left\{\frac{\lambda(m+\pi-\lambda)}{N_2}-\frac{\pi m}{N_3}\right\} \tag{36}$$

$$\tau_z=\frac{\tau'_z}{\mu V/L}=\frac{U}{V}\left(\frac{dw_1}{dy}\right)_{y=0}, \qquad \tau_z=-\alpha\varepsilon\lambda C_0\sin\pi z \tag{37}$$

2.3 Rate of heat transfer

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

$$Nu = \frac{q_w}{\rho U c_p (T_w - T_\infty)} = \frac{k}{\rho U c_p L}\left(\frac{\partial T}{\partial y}\right)_{y=0} = \frac{2mM}{R\,\mathrm{Pr}} - \alpha(1+M) + \varepsilon B_2(\alpha, R, \mathrm{Pr}, K, E)\cos \pi z \tag{38}$$

Where

$$B_2(\alpha, R, \mathrm{Pr}, K, E) = \left(\frac{dT_1}{dy}\right)_{y=0} \tag{39}$$

3 Results and discussion

The velocity of the flow field found to change with variation of suction parameter α , permeability parameter K and Reynolds number R. The effect of permeability of medium on velocity of flow is shown in Figure 1.

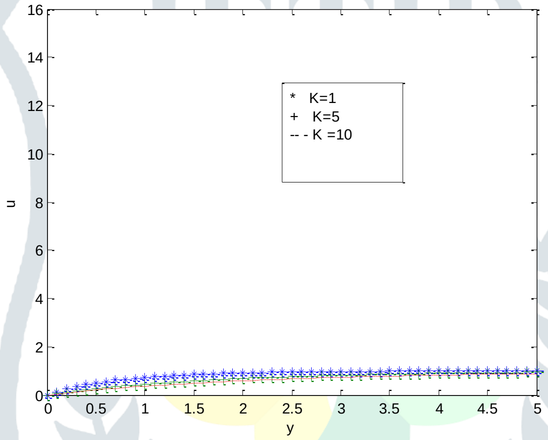

Figure1: velocity profile against y for different values of K with R = 1 , α=0.2 ,K=1,ϵ = 0.2 and z=0.

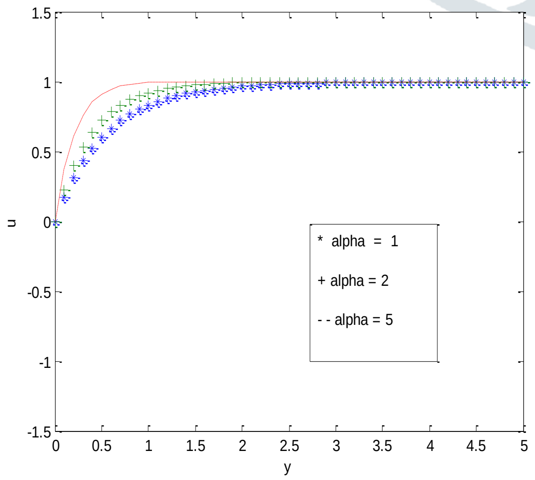

Figure2: velocity profile against y for different values of α with R = 1 , α=0.2 ,ϵ = 0.2 and z=0.

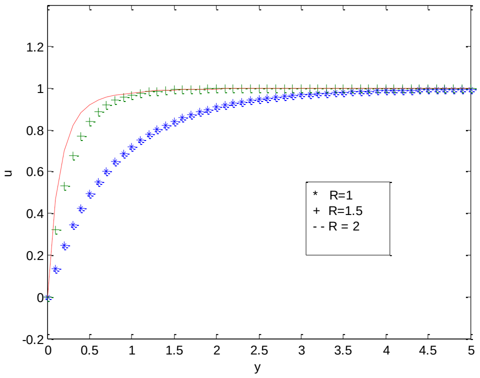

Figure3: velocity profile against y for different values of R with α=0.2 ,K=1,ϵ = 0.2 and z=0

It is also observed that the variation in the temperature of the flow field is due to suction parameter α and Reynolds number R. Also, increasing suction parameter (α) results a decrease in temperature.

3.1 Skin friction

The variations in the value of x and z component of the skin friction at the wall for different values of α and K given in table 1. It is observed that permeability parameter K decreases skin friction. The increasing the suction parameter (α) there is enhancement in the skin friction at the wall.

Table1: x and z component of skin friction (τ_x, τ_z) against α for different values of K with R = 1, α =0.2 , ϵ = 0.2 , and z = 0 and ½(for τ_z)

	K = 0.2	K=0.2	K=1	K=1	K=5	K=5
α	τ_x	τ_z	τ_x	τ_z	τ_x	τ_z
0	2.404	0.0000	1.0466	0.0000	0.5602	0.0000
0.2	2.506	-0.0106	1.1465	-0.0024	0.5708	-0.0005
0.5	2.669	-0.0691	1.3263	-0.0164	0.8623	-0.0031
2.0	3.637	-1.3407	2.4485	-0.3273	2.1101	-0.0675

3.2 Rate of heat transfer

The rate of heat transfer at the wall is calculated in terms of Nusselt number (Nu) for different values of α and K in the table2.It is observed that increasing suction parameter α heat flux at the wall grows and effect is reverse on increasing of permeability parameter K.

Table2: Rate of heat transfer(Nu) against α and different values of K with R = 1 , Pr = 0.71 , α = 0.2, E =0.01 and ϵ = 0.2

α	K=0.2	K=1	K=5
0	0.0114	0.005	0.003
0.2	0.2003	0.1931	0.1869

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