g-Jitter Induced Free Convection of Heat and Mass Transfer Flow near a Two-Dimensional Stagnation Point in Micropolar Fluid

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Abstract: - This paper studies the effect of g-jitter on free convection flow of a viscous and incompressible micropolar fluid near the forward stagnation point of a two-dimensional symmetric body resulting from a step change in its surface temperature. The transformed non-similar boundary layer equations are solved numerically by an implicit finite-difference scheme known as the Keller-box method. The skin friction, rate of heat and mass transfer has been studied for the effect of amplitude of modulation, frequency of oscillation and micropolar parameters. The numerical results are given for the values of the Prandtl number Pr = 0.7 and Schmidt number Sc = 0.94. A comparison with the earlier published results for Newtonian fluid (K = 0) shows a very good agreement.

Key-Words: - g-Jitter; Free convection; Micropolar fluid; Keller-box; Heat and mass transfer

1 Introduction

The studies on non-Newtonian fluids have gained considerable importance due to its great diversity in their physical structure and mainly used in many sciences, engineering, industrial, biomedical engineering, and technological applications. The examples of non-Newtonian fluids are blood, drilling mud, certain oils, shampoo, paints, and ketchup. One of the non-Newtonian fluids is micropolar fluid which is exhibit microscopic effects arising from the local structure and micro-motions of the fluid elements. Eringen [1, 2] was the first who introduce the theory of micropolar fluids that describes microrotation as well as microinertia effects. Then, Wilson [3] introduced the concept of boundary layer approximation in micropolar fluids past surfaces. He obtained the appropriate two-dimensional boundary layer equations using an order-of-magnitude argument and neglecting certain microinertia terms. An excellent analysis about micropolar fluid mechanics has been obtained by Ariman et al. [4] and Kim and Lee [5] which is provided the analytical studies on magnetohydrodynamics (MHD) oscillatory flow of a micropolar fluid over a vertical porous plate, and the effects of non-zero values of micro-gyration vector on the velocity and temperature fields across the boundary layer. There have also been a number of studies which consider the problems of steady state boundary layer flow of micropolar fluids near the two-dimensional stagnation points [6-9].

Obviously, the presence of temperature gradient and gravitational field yields buoyancy convective flows in many situations. However, in space, the gravity effect is suppressed singularly while buoyancy effect also reduces which is enhancing the properties and performance of materials such as crystals [10]. Recent technological implications have given rise to increased interest in oscillating natural and mixed convection driven by g-jitter forces associated with microgravity. g-Jitter or periodical gravity modulation can be defined as the inertia effects due to quasi-steady, oscillatory or transient accelerations arising from crew motions and machinery vibrations in parabolic aircrafts, space shuttles or other microgravity environments. Problem involving the effect of periodical gravity modulation with various physical effects and body have been studied extensively by many authors and can be found in the papers by Amin [11], Farooq and Homsy [12], Li [13], and Chamkha [14]. Beside this paper, Rees and Pop [15] also studied the behaviour of g-jitter induced free convection flow of a viscous fluid near the forward stagnation point of a two-dimensional symmetric body resulting from a step change in its surface temperature. Later, Rees and Pop [16] extended their work to show the effect of g-jitter on free convection embedded in a porous medium near a stagnation point, then followed by Sharidan et al. [17], studied the effect of g-jitter on the unsteady free convection boundary layer flow of a micropolar fluid near a two-dimensional stagnation point. Motivated by the above studies, objective of the present work is to investigate the g-jitter induced free convection boundary layer flow near a two-dimensional stagnation point in micropolar fluid and considering the analysis on heat and mass transfer. Since the effect of g-jitter is considered, following Rees and Pop [15] and Sharidan et al. [17], the gravitational field is depended on time, where $\bar{g}(\bar{t})$ is the magnitude of the gravity direction in a downward direction and can be defined as,

$$\bar{g}(\bar{t}) = g_0\left\lfloor 1 + a\cos(\pi\bar{\omega}\bar{t})\right\rfloor\mathbf{k} \qquad (1)$$

where g_0 is the time-averaged value of the gravitational acceleration acting along the direction on the unit vector **k** which is oriented in the upward direction**,** a is a scaling parameter, which gives the magnitude of the gravity modulation relative to g_0, t is the time and ω is the frequency of oscillation of the g-jitter flow. If $a << 1$**,** then the forcing may be seen as a perturbation of the mean gravity. Since the governing equations of this problem are non-linear, this kind of forcing leads to the phenomenon of streaming, where a time-periodic forcing with zero means produces a periodic response consisting of a steady-state solution with a non-zero mean and time-dependent fluctuations involving higher harmonics [10].

The coupled nonlinear partial differential equations are solved numerically using a finite-difference scheme, known as the Keller-box method which is described in the book by Cebeci and Bradshaw [18]. The effect of the micropolar parameter, K on the reduced skin friction, heat and mass transfer coefficients are investigated in detail. A comparison with the earlier published result done by Rees and Pop [15] for a Newtonian f1uid (K = 0) is made and found to agree favourably.

2 Governing Equations

Consider the unsteady free convection boundary layer near a two-dimensional symmetric body immersed in a viscous and incompressible micropolar fluid with uniform ambient temperature, T_∞ and concentration, C_∞. Fig. 1 illustrates the physical model and coordinate system of the problem.

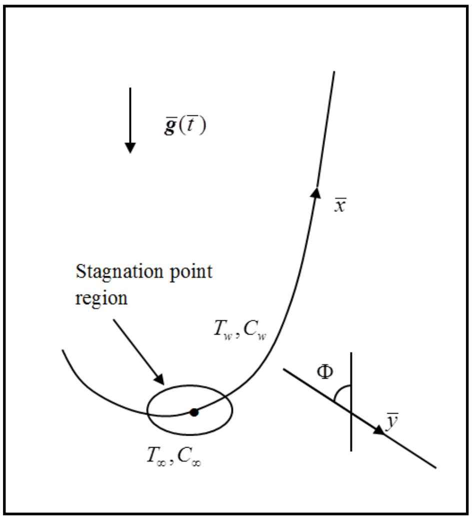

Fig. 1 Physical model and coordinate system

It is assumed that, at time $\bar{t} = 0$, the temperature and concentration of the body surface are suddenly increased to the constant values of T_w and C_w, where $T_w > T_\infty$ and $C_w > C_\infty$. It is further assumed that a time-dependent body force in accordance with Eqn. (1) acts on the fluid and, as a result of volume expansion, fluid motion will exist. Under the usual boundary layer and Boussinesq approximations, the governing equations are given by (See [15]),

Continuity equation:

$$\frac{\partial\bar{u}}{\partial\bar{x}} + \frac{\partial\bar{v}}{\partial\bar{y}} = 0 \qquad (2)$$

Momentum equation:

$$\frac{\partial\bar{u}}{\partial\bar{t}} + \bar{u}\frac{\partial\bar{u}}{\partial\bar{x}} + \bar{v}\frac{\partial\bar{u}}{\partial\bar{y}} = (\upsilon + \frac{\kappa}{\rho})\frac{\partial^2\bar{u}}{\partial\bar{y}^2} + \frac{\kappa}{\rho}\frac{\partial\bar{N}}{\partial\bar{y}} + ..$$
$$\bar{g}(\bar{t})\,\beta_T(T - T_\infty)\bar{S}(\bar{x}) \qquad (3)$$
$$+\bar{g}(\bar{t})\,\beta_C(C - C_\infty)\bar{S}(\bar{x})$$

Microrotation equation:

$$\rho\, j\left(\frac{\partial\bar{N}}{\partial\bar{t}} + \bar{u}\frac{\partial\bar{N}}{\partial\bar{x}} + \bar{v}\frac{\partial\bar{N}}{\partial\bar{y}}\right) = \gamma\,\frac{\partial^2\bar{N}}{\partial\bar{y}^2} - ..$$
$$\kappa\left(2\bar{N} + \frac{\partial\bar{u}}{\partial\bar{y}}\right) \qquad (4)$$

Energy equation:

$$\frac{\partial T}{\partial \bar{t}}+\bar{u}\,\frac{\partial T}{\partial \bar{x}}+\bar{v}\,\frac{\partial T}{\partial \bar{y}}=\alpha\frac{\partial^2 T}{\partial \bar{y}^2} \tag{5}$$

Concentration equation:

$$\frac{\partial C}{\partial \bar{t}}+\bar{u}\,\frac{\partial C}{\partial \bar{x}}+\bar{v}\,\frac{\partial C}{\partial \bar{y}}=D\frac{\partial^2 C}{\partial \bar{y}^2} \tag{6}$$

subject to the following initial and boundary conditions,

$$\begin{aligned}&\bar{t}<0:\bar{u}=\bar{v}=0,\bar{N}=0,\\ &\qquad T=T_\infty,\ C=C_\infty \text{ for any } \bar{x},\bar{y}\\ &\bar{t}\ge 0:\bar{u}=\bar{v}=0,T=T_w,\\ &\qquad C=C_w,\bar{N}=-n\frac{\partial \bar{u}}{\partial \bar{y}} \quad \text{on } \bar{y}=0\\ &\bar{u}\to 0,T\to T_\infty,\ C\to C_\infty,\bar{N}\to 0 \text{ as } \bar{y}\to\infty\end{aligned} \tag{7}$$

where $\bar{x}$ and $\bar{y}$ are the Cartesian coordinates along the surface of the body and normal to it, respectively, $\bar{u}$ and $\bar{v}$ are the velocity components along $\bar{x}$ and $\bar{y}$ – axes, n is a constant and $0 \le n \le 1$, T is the fluid temperature, C is the fluid concentration, D is mass diffusivity, $\bar{N}$ is the microrotation component normal to the plane $(\bar{x},\bar{y})$, j is the microinertia density, $\bar{S}(\bar{x})=\sin\Phi$ denotes a shape function, where Φ is angle between the outward normal from the body surface and the downward vertical and ρ, υ, κ, γ, β_T, and β_C are the density, kinematic viscosity, vortex viscosity, spin gradient viscosity, thermal and concentration expansion coefficients respectively. Following Rees and Bassom [19], the spin gradient viscosity γ is assumed to be a constant given by,

$$\gamma=(\mu+\kappa/2)\,j=\mu(1+K/2)\,j \tag{8}$$

where μ is the dynamic viscosity and $K=\kappa/\mu$ is the material parameter. Eqn. (8) is appealed to allow the field equations to predict the correct behaviour in the limiting case when microstructure effects become negligible, and the microrotation component $\bar{N}$ reduces to the angular velocity. Then, the following non-dimensional variables are introduced,

$$\begin{aligned}&t=Gr^{1/2}\,(\frac{\upsilon}{l^2})\bar{t},\quad x=\frac{\bar{x}}{l},\quad y=Gr^{1/4}\,(\frac{\bar{y}}{l}),\\ &u=Gr^{-1/2}\,(\frac{l}{\upsilon})\bar{u},\ v=Gr^{-1/4}\,(\frac{l}{\upsilon})\bar{v},\\ &\theta=\frac{\bar{T}-T_\infty}{T_w-T_\infty},\quad N=Gr^{-3/4}\,(\frac{l^2}{\upsilon})\bar{N},\\ &\phi=\frac{\bar{C}-C_\infty}{C_w-C_\infty},\omega=Gr^{-1/2}\,(\frac{l^2}{\upsilon})\bar{\omega}\end{aligned} \tag{9}$$

where l is a characteristic length and $Gr=g_0\,\beta_T\,(T_w-T_\infty)l^3/\upsilon^2$ is the Grashof number. By substituting (9) into (2) – (6), the following set of non-dimensional equations are obtained.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{10}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=(1+K)\frac{\partial^2 u}{\partial y^2}+K\frac{\partial N}{\partial y}+..\quad [1+a\cos(\pi\,\omega t)](\theta+\delta\phi)S(x) \tag{11}$$

$$\frac{\partial N}{\partial t}+u\frac{\partial N}{\partial x}+v\frac{\partial N}{\partial y}=(1+\frac{K}{2})\frac{\partial^2 N}{\partial y^2}-..\quad K(2N+\frac{\partial u}{\partial y}) \tag{12}$$

$$\frac{\partial \theta}{\partial t}+u\frac{\partial \theta}{\partial x}+v\frac{\partial \theta}{\partial y}=\frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} \tag{13}$$

$$\frac{\partial \phi}{\partial t}+u\frac{\partial \phi}{\partial x}+v\frac{\partial \phi}{\partial y}=\frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} \tag{14}$$

where $\Pr=\upsilon/\alpha$ is the Prandtl number, $Sc=\upsilon/D$ is Schmidt number and $\delta=\beta_c(C_w-C_\infty)/\beta_T(T_w-T_\infty)$ is the buoyancy ratio.

The initial and boundary conditions become,

$$\begin{aligned}&t<0:\quad u=v=0,\quad \theta=0,\ \phi=0,\\ &\qquad N=0 \quad \text{for any} \quad x,y\\ &t\ge 0:\quad u=v=0,\quad \theta=1,\ \phi=1,\\ &\qquad N=-n\frac{\partial u}{\partial y} \quad \text{on} \quad y=0\\ &u\to 0,\theta\to 0,\phi\to 0,N\to 0 \text{ as } y\to\infty\end{aligned} \tag{15}$$

3 Solution Procedure

In order to solve (10) – (14) for the case of stagnation point, we introduced an appropriate transformation in the following form,

$$\begin{aligned}&\psi=x\,f(t,y),\theta=\theta(t,y),\phi=\phi(t,y)\\ &N=x\,h(t,y),S(x)=x\end{aligned} \tag{16}$$

where ψ is the stream function which is defined as

$$u=\partial\psi/\partial y \text{ and } v=-\partial\psi/\partial x, \tag{17}$$

which is fully satisfied (10). By taking $\tau=\omega t$ and substituting (16) into (11) to (14), the following governing equations are obtained,

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$$(1+K)\frac{\partial^3 f}{\partial y^3}+f\frac{\partial^2 f}{\partial y^2}-(\frac{\partial f}{\partial y})^2+..=\omega\frac{\partial^2 f}{\partial\tau\partial y}$$
$$+K\frac{\partial h}{\partial y}+\left[1+a\cos(\pi\tau)\right](\theta+\delta\phi) \quad (18)$$

$$(1+\frac{K}{2})\frac{\partial^2 h}{\partial y^2}+f\frac{\partial h}{\partial y}-\frac{\partial f}{\partial y}h-..=\omega\frac{\partial h}{\partial\tau}$$
$$-K\left(2h+\frac{\partial^2 f}{\partial y^2}\right) \quad (19)$$

$$\frac{1}{\Pr}\frac{\partial^2\theta}{\partial y^2}+f\frac{\partial\theta}{\partial y}=\omega\frac{\partial\theta}{\partial\tau} \quad (20)$$

$$\frac{1}{Sc}\frac{\partial^2\phi}{\partial y^2}+f\frac{\partial\phi}{\partial y}=\omega\frac{\partial\phi}{\partial\tau} \quad (21)$$

with the initial and boundary conditions (15) become

$$\tau<0: \quad f=\theta=\phi=h=0 \quad \text{for any} \quad y$$
$$\tau\ge 0: \quad f=\frac{\partial f}{\partial y}=0, \quad \theta=1,\ \phi=1, \ \text{on} \quad y=0$$
$$h=-n\frac{\partial^2 f}{\partial y^2} \quad (22)$$

$$\frac{\partial f}{\partial y}\to 0,\theta\to 0,\phi\to 0,h\to 0 \text{ as } y\to\infty$$

The physical quantities of primary interest are wall skin friction, the local Nusselt and Sherwood numbers are defined as,

$$C_f=\frac{\tau_w}{\rho\upsilon^2/l^2}, \quad Nu=\frac{q_w l}{k(T_w-T_\infty)},$$
$$Sh=\frac{m_w l}{D(C_w-C_\infty)} \quad (23)$$

where k is the thermal conductivity and the skin friction τ_w , heat, q_w and mass transfers, m_w are given by

$$\tau_w=\left[(\mu+\kappa)\frac{\partial\bar{u}}{\partial\bar{y}}+\kappa\bar{N}\right]_{\bar{y}=0}, q_w=-k\left(\frac{\partial\bar{T}}{\partial\bar{y}}\right)_{\bar{y}=0}$$
$$m_w=-D\left(\frac{\partial\bar{C}}{\partial\bar{y}}\right)_{\bar{y}=0} \quad (24)$$

Using (9) and (16), we get

$$C_f/Gr^{3/4}=x(1+K-Kn)\frac{\partial^2 f}{\partial y^2}(\tau,0),$$
$$Nu/Gr^{1/4}=-\frac{\partial\theta}{\partial y}(\tau,0)$$
$$Sh/Gr^{1/4}=-\frac{\partial\phi}{\partial y}(\tau,0). \quad (25)$$

4 Results and Discussion

Eqn. (18) to (21) corresponding to boundary conditions (22) are solved numerically using a finite difference scheme known as Keller-box method. This method has been found to be a very suitable in dealing with nonlinear parabolic problems and practically used by many researchers such as Rees and Pop [16], Sharidan et al. [17] and Kasim et al [20]. In all results quoted here were obtained using uniform grids in both the τ and y directions, where the grid sizes are $\Delta\tau=0.01$ and $\Delta y=0.02$. Convergence criterion was set to 10^{-6} which gives accuracy to five decimal places and satisfaction of the outer boundary condition is achieved by considering the boundary layer thickness, $y_\infty=10$.

The detailed results are for the amplitude of modulation a in the range $0\le a\le 1$, frequency of oscillation $\omega=0.2, 1, 5$, micropolar parameter $K=0,$ and 1, buoyancy ratio $\delta=1$, Prandtl number $\Pr=0.7$, and Schmidt number $Sc=0.94$ for both strong concentration $(n=0)$ and weak concentration $(n=1/2)$.

Table 1. Values of the mean heat transfer rate, $\Theta'(0)$ for K=0 (Newtonian fluid) and $n=0$.

	$\Theta'(0)$			
	Rees and Pop [15]		Present	
a	$\omega=0.2$	$\omega=5$	$\omega=0.2$	$\omega=5$
0.0	0.37023	0.37023	0.37022	0.37022
0.2	0.36938	0.37023	0.36963	0.37022
0.4	0.36735	0.37021	0.36788	0.37021
0.6	0.36400	0.37019	0.36483	0.37019
0.8	0.35902	0.37016	0.36020	0.37015
1.0	0.35186	0.37012	0.35344	0.37012

Table 1 represents the direct comparison of the present values for mean heat transfer rate, $\Theta'(0)$ with the numerical results reported earlier by Rees and Pop [15] for the case of Newtonian fluid, $K=0.$ The results obtained shows a very good agreement which can be concluded that the numerical method work efficiently for this present problem. The variation with time of local wall heat transfer is integrated numerically over one period to obtain the values of mean heat transfer rate.

Table 2 presents the values of mean skin friction, $F''(0)$, heat, $\Theta'(0)$ and mass transfer rates, $\Phi^{*\prime}(0)$

for different values of amplitude of modulation *a* for both weak concentration $(n = 1/2)$ and strong concentration $(n = 0)$ respectively. It can be seen from Table 2 that, the range values of mean skin friction, heat and mass transfer rate decrease with an increasing of *a*. These results also show that the values of mean skin friction, heat and mass transfer rate for strong concentration are much lower than those for weak concentration.

The effect of micropolar parameter on the velocity and angular velocity (microrotation) profiles at strong concentration, $(n = 0)$ are presented in Fig. 2 and 3. It is interesting to note that, both velocity and angular velocity decrease near the plate while they increase away from the plate which satisfies the boundary conditions for the increasing of micropolar parameter.

Fig. 4 and 5 respectively show the velocity and angular velocity profiles for different values of *n*. In this paper, the case $n = 0$ corresponds to the boundary condition, where $h(0) = 0$ indicating the no-spin condition and called as strong interaction [7]. Meanwhile, the case $n = 1/2$ corresponds to zero antisymmetric part of the stress tensor and the case $n = 1$ suggested by [21] is used for the modeling of turbulent boundary layer flow. It is observed that the velocity profile increases near the plate but twist the pattern between $2 \le y \le 3$ where the profile start to decrease and become zero far away from the plate. Further, from Fig. 5, it is noted that the angular velocity profile gradually decreases for different values of *n.*

Fig. 6 to 11 illustrate the variation of reduced skin friction, $\partial^2 f(\tau,0)/\partial y^2$, heat transfer coefficient, $-\partial\theta(\tau,0)/\partial y$ and mass transfer coefficient, $-\partial\phi(\tau,0)/\partial y$ for different values of amplitude of modulation a, frequency of oscillation Ω and micropolar parameter K at the fixed values of Prandtl number $\Pr = 0.7$, Schmidt number $Sc = 0.94$ and buoyancy ratio $\delta = 1$. All figures shows that the effect of increasing *a* is giving an almost proportional increase in the variation of $\partial^2 f(\tau,0)/\partial y^2$, $-\partial\theta(\tau,0)/\partial y$, and $-\partial\phi(\tau,0)/\partial y$. It is also observed that, as Ω increases, the range values of $\partial^2 f(\tau,0)/\partial y^2$, $-\partial\theta(\tau,0)/\partial y$, and $-\partial\phi(\tau,0)/\partial y$ are decreased. Finally, the effect of micropolar parameter *K* indicates that as the values of K increases, the values of $\partial^2 f(\tau,0)/\partial y^2$, $-\partial\theta(\tau,0)/\partial y$, and $-\partial\phi(\tau,0)/\partial y$ are decreased. These results are due to the fact that an increase of *K* leads to increase the total viscosity of the fluid flow, thus decreasing the reduced skin friction, heat and mass transfer coefficients.

5 Conclusion

In this paper, the problem of g-jitter induced free convection of heat and mass transfer flow near a two-dimensional stagnation point in micropolar fluid has been numerically investigated. The numerical solutions presented for different values of the governing parameters are obtained by using Keller-box method. Eqn. (18) to (21) corresponding to boundary conditions (22) are solved numerically using a finite difference scheme known as Keller-box method. We have examined the effects of amplitude of modulation, frequency of oscillation and micropolar parameter on the variation of reduced skin friction, heat and mass transfer coefficients. We also investigated the effects of micropolar parameter, *K* and the ratio between the microrotation and skin friction, *n* on the velocity and angular velocity profiles. Comparison of the results show that the present results agree very well with the previous published results reported by Rees and Pop [15] for Newtonian case, $K = 0$.

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APPENDIX

Table 2. Values of the mean skin friction, $F''(0)$ heat, $\Theta'(0)$ and mass transfer rates, $\Phi^{*\prime}(0)$ for $\Omega = 0.2$ and K=1 with different values of n.

a	$F''(0)$		$\Theta'(0)$		$\Phi^{*\prime}(0)$	
	$n=0$	$n=1/2$	$n=0$	$n=1/2$	$n=0$	$n=1/2$
0.0	0.89490	1.05270	0.39331	0.40879	0.45195	0.47037
0.4	0.88981	1.04645	0.39068	0.40601	0.44895	0.46718
0.8	0.87295	1.02574	0.38183	0.39656	0.43885	0.45637
1.0	0.85939	1.00894	0.37373	0.38781	0.42965	0.44641

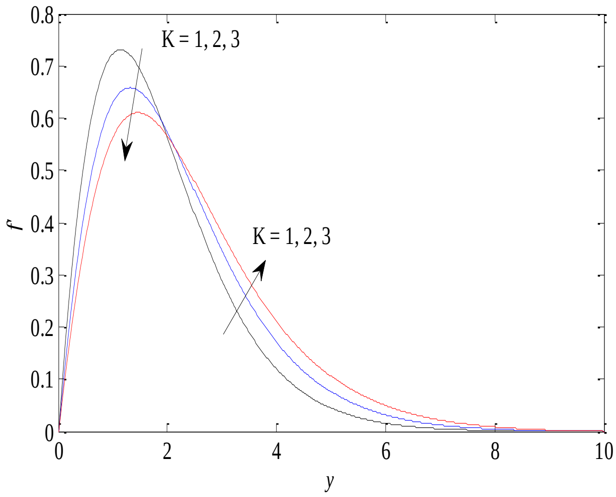

Fig. 2 Velocity profile, $f'(0)$ at $n=0$ and various values of K.

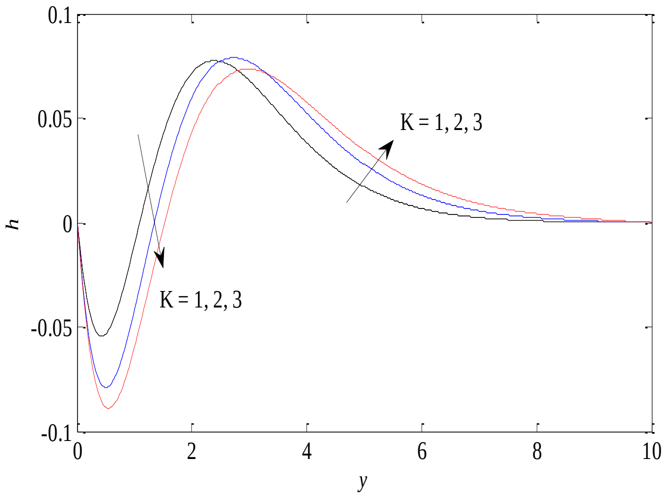

Fig. 3 Angular velocity profile, $h(0)$ at $n=0$ and various values of K.

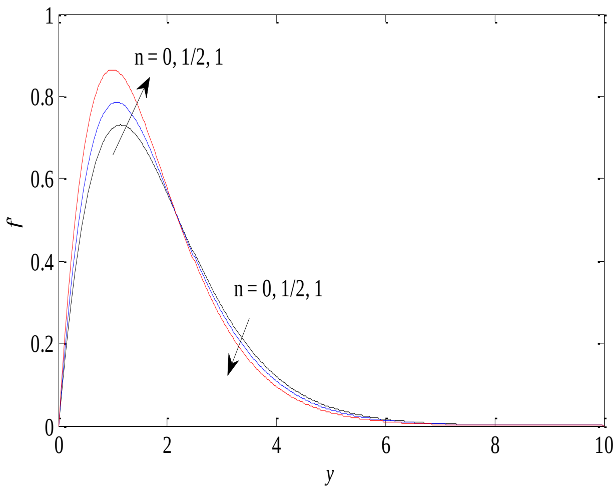

Fig. 4 Velocity profile, $f'(0)$ at $K=1$ and various values of n.

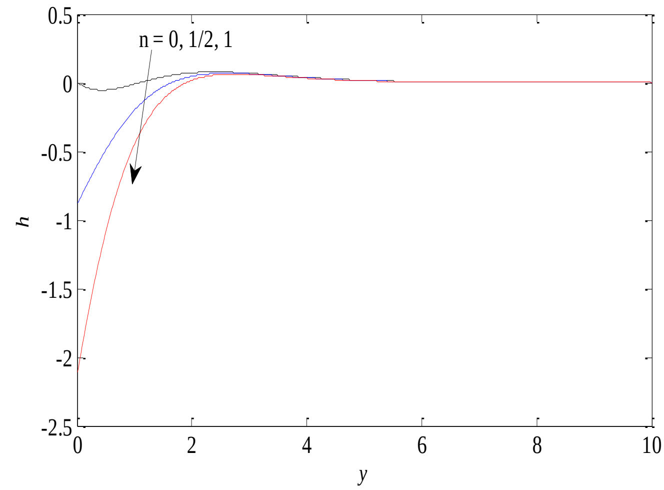

Fig. 5 Angular velocity profile, $h(0)$ at $K=1$ and various values of n.

$$\frac{\partial^2 f}{\partial y^2}(\tau,0)$$

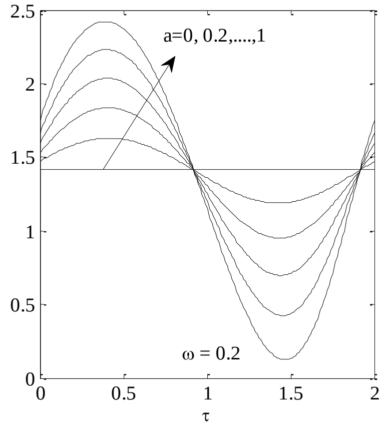

Fig. 6a

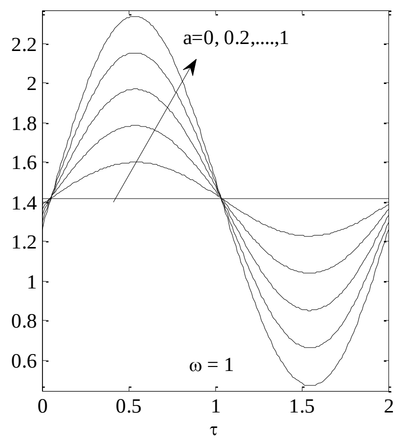

Fig. 6b

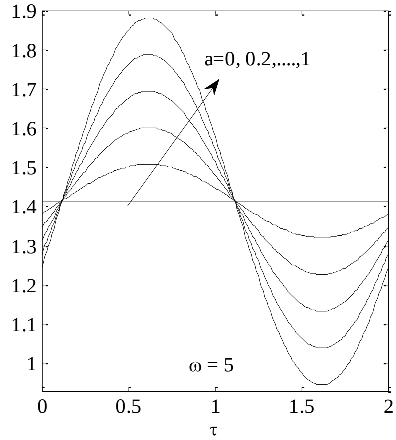

Fig. 6c

Fig. 6 Variations of reduced skin friction with τ for K=0, n=0 and different values of a and ω.

$$-\frac{\partial^2 \theta}{\partial y}(\tau,0)$$

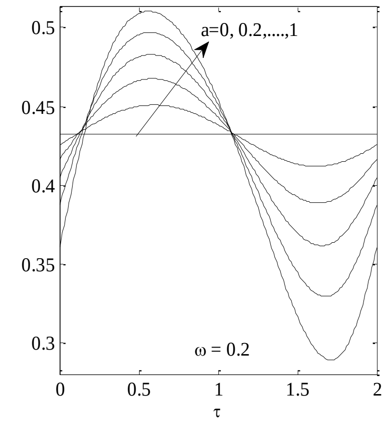

Fig. 7a

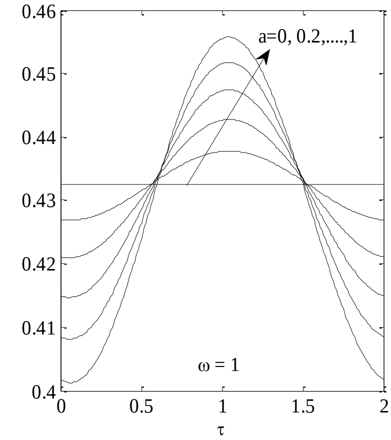

Fig. 7b

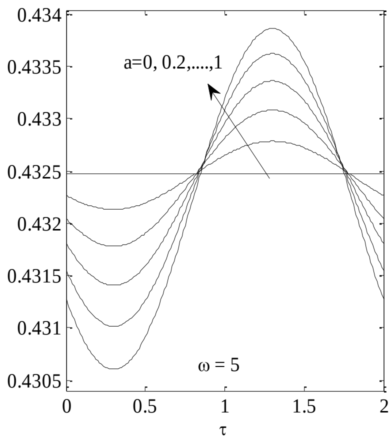

Fig. 7c

Fig. 7 Variations of heat transfer coefficient with τ for K=0, n=0 and different values of a and ω.

$$-\frac{\partial^2 \phi}{\partial y}(\tau,0)$$

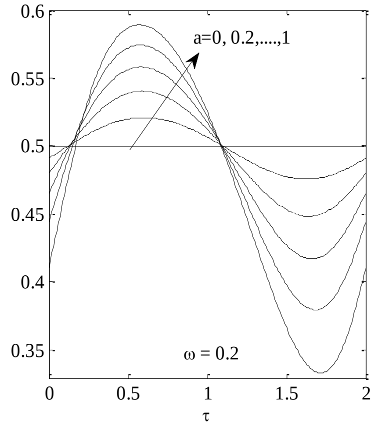

Fig. 8a

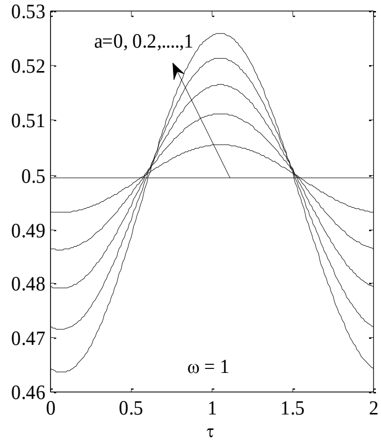

Fig. 8b

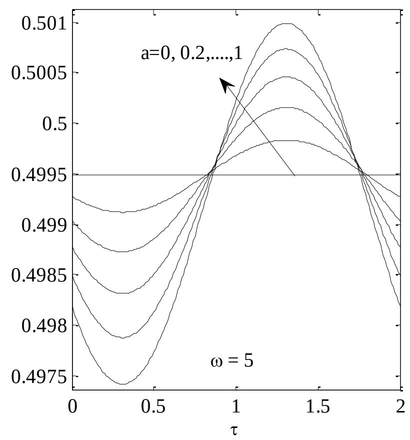

Fig. 8c

Fig. 8 Variations of mass transfer coefficient with τ for K=0, n=0 and different values of a and ω.

$$\frac{\partial^2 f}{\partial y^2}(\tau,0) \qquad -\frac{\partial^2\theta}{\partial y}(\tau,0) \qquad -\frac{\partial^2\phi}{\partial y}(\tau,0)$$

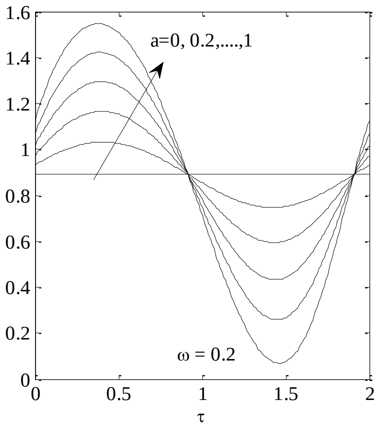

Fig. 9a

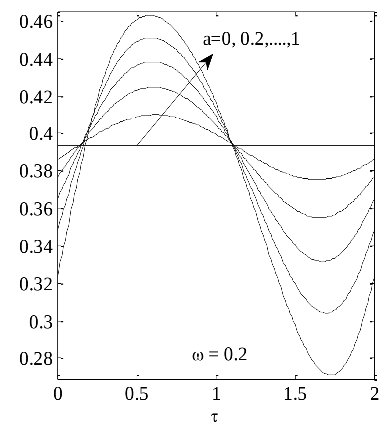

Fig. 10a

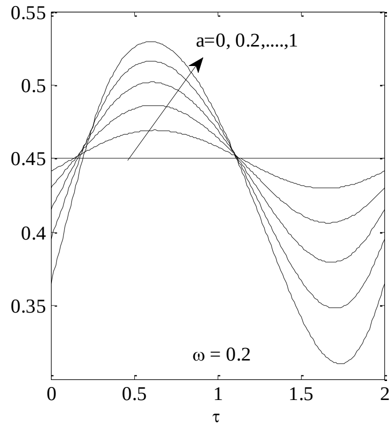

Fig.11

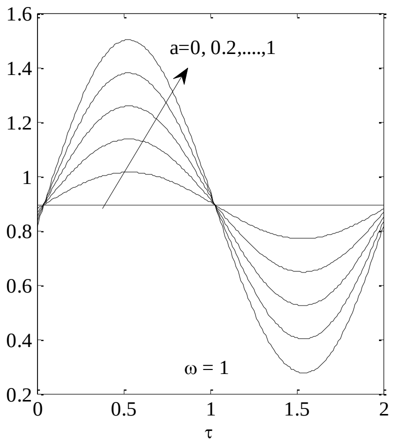

Fig. 9b

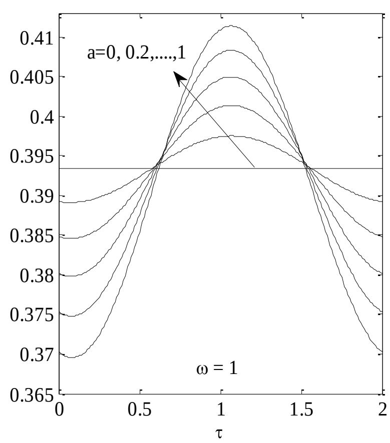

Fig. 10b

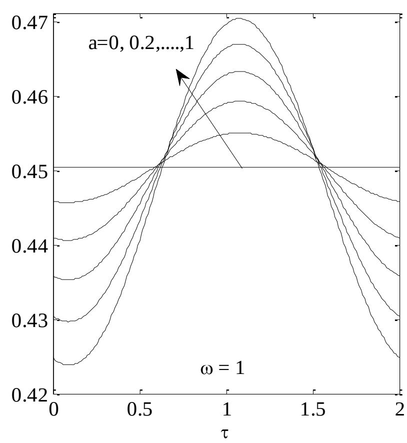

Fig. 11b

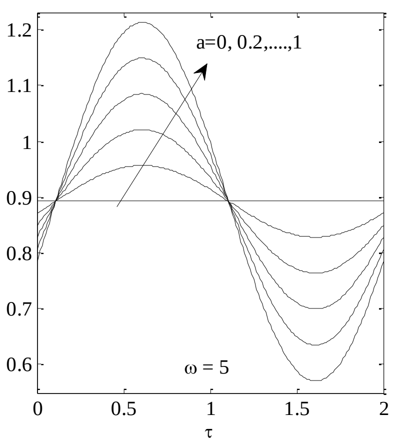

Fig. 9c

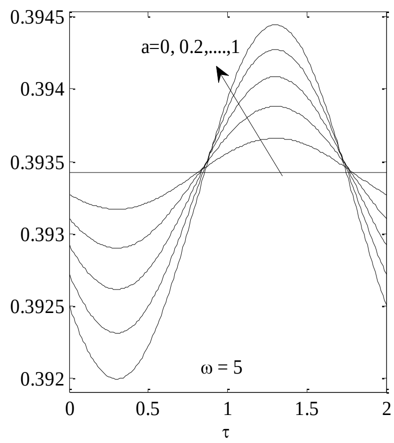

Fig. 10c

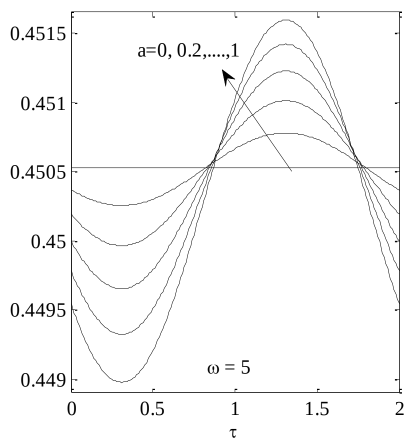

Fig. 11c

Fig. 9 Variations of reduced skin friction with τ for K=1, n=0 and different values of a and ω.

Fig. 10 Variations of heat transfer coefficient with τ for K=1, n=0 and different values of a and ω.

Fig. 11 Variations of mass transfer coefficient with τ for K=1, n=0 and different values of a and ω.

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