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MHD CONVECTIVE FLOW THROUGH A POROUS MEDIUM IN A VERTICAL WAVY CHANNEL WITH HALL EFFECT

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Abstract:
we have considered heat and mass transfer on the MHD free convection flow of second grade fluid through porous medium bounded by an infinite vertical porous rotating plate taking hall current into account. The analytical solutions for the governing equations are found by utilization of Laplace transformation methodology. The velocity, temperature and concentration is analysed graphically, and computational results for the skin friction, and Sherwood number are also obtained.

Keywords: *Hall effects, Heat and mass transfer, MHD flows, porous medium, rotating channels, second grade fluids.*

1. Introduction:

The study of heat and mass transfer with chemical reaction is of great practical importance to engineers and scientists because of its almost universal occurrence in many branches of science and engineering. In particular, the study of chemical reaction, heat and mass transfer with heat radiation is of considerable importance in chemical and hydrometallurgical industries. A reaction is said to be first-order if the rate of reaction is directly proportional to the concentration itself. In many chemical processes, a chemical reaction occurs between a foreign mass and a fluid in which a plate is moving. These processes take place in numerous industrial applications, e.g., polymer production, manufacturing of ceramics or glassware, and food processing Cussler [1]. Chambre and Young [2] analyzed the diffusion of chemically reactive species in a laminar boundary layer flow.

Many researchers have studied MHD free convective heat and mass transfer flow in a porous medium; some of them are Raptis and Kafoussias[3] , Sattar[4] and Kim[5] . Jaiswal and Soundalgekar[6] obtained an approximate solution to the problem of an unsteady flow past an infinite vertical plate with constant suction and embedded in a porous medium with oscillating plate temperature[7-9]. The unsteady flow through a highly porous medium in the presence of radiation was studied by Raptis and Perdikis [10]. Sakiadis [11] investigated the effect of transverse periodic permeability oscillating with time on the heat transfer flow of a viscous incompressible fluid through a highly porous medium bounded by an infinite vertical porous plate, by means of series solution method.

The second graded fluid preserve many fluids these are diluted polymer solution, slurry flow, as well as industrial oil, in addition to a lot of flow problems by a choice of ge- ometry as well as dissimilar mechanical and/or thermal boundary cir- cumstances have been deliberated. Tan and Masuoka [12] found the Stokes first problems for the second graded fluids and Rashidi et al. [13] discussed by the unsteady compressible flows of the second order fluids. Hayat et al. [14] explored by the unsteady stagnation point flow of second grade fluids with changeable free stream.The magnetohydrodynamic (MHD) is a subdivision of fluid dynamics and this studied the association of the electrically conducting fluids in the magnetic field. Many of investigative efforts in the MHD has been proceed extensively for the duration of the preceding little decades subsequent to the established work of Hartmann [15] in fluid metalized ducts flow under external magnetic field. There are most applications for the parabolic movement for instance solar cooker, solar concentrator and parabolic through stellar collector. The parabolic concentrator model solar cookers have the wide range of applications for example baking, roast as well as distillations. Solar concentrator model had those applications into growing rates of evaporations in dissipate stream, in food dispensations, for producing consumption water from salt water as well as seawater. Murthy et al. [16] discussed by the evaluations of thermal performances of temperature exchangers units for parabolic

Motivated by the current study set out to examine the effects of heat sources and chemical reactions in a rotating system while accounting for hall current on the unsteady MHD free convection flow of an incompressible electrically conducting second grade fluid through a porous medium enclosed by an infinite vertical porous surface.

2. Formulation of the problem

We consider the unsteady MHD free convection flow of an electrically conducting viscous incompressible second grade fluid bounded by a vertical porous surface in a rotating system in the presence of heat source and chemical reaction subjected to a uniform transverse magnetic field of strength B_0 normal to plate and taking hall current into account. The temperature on the surface varies with the time about a non-zero constant mean while the temperature of free stream is taken to be constant. We consider that the vertical infinite porous plate rotates with the constant angular velocity about an axis is perpendicular to the vertical plane surface.

We choose a Cartesian co-ordinate system $O(x, y, z)$ such that *x*, *y* axes respectively are in the vertical upward and perpendicular directions on the plane of the vertical porous surface $z = 0$, while z-axis normal to it. The interaction of Coriolis force with the free convection sets up a secondary flow in addition to primary flow and hence the flow becomes three dimensional. With the above frame of reference and assumptions, all the physical variables are functions of *z* and *t* alone. In the equation of motion, along x-direction the x-component current density $B_0 J_y$ and the x-component current density $-B_0 J_x$.

The constitutive equation for the stress T in an incompressible fluid of second grade is given by

$$T(t) = -pI + \mu A_1 + \alpha_1 A_2 + \alpha_2 A_1 \quad (2.1)$$

Where, μ is the dynamic viscosity α_1, α_2 are the normal stress moduli and the kinematical tensors

$$A_1 = (gradV) + (gradV)^T, \ A_2 = \frac{DA_1}{Dt} + A_1 (gradV) + (gradV)^T A_1 \quad (2.2)$$

Where, *V* is the velocity, *grad* the gradient operator and *D/Dt* the material time derivative.

The unsteady hydro magnetic flow in a rotating co-ordinate system is governed by the equation of motion, continuity equation and the Maxwell equations in the form.

$$\rho\left(\frac{\partial V}{\partial t} + (V.\nabla)V + 2\Omega \times V + \Omega \times (\Omega \times r)\right) = \nabla.T + J \times B \quad (2.3)$$

$$\nabla.V = 0 \quad (2.4)$$

$$\nabla . B = 0 \tag{2.5}$$

$$\nabla \times B = \mu_m J \tag{2.6}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{2.7}$$

Where, J is the current density, B is the total magnetic field, E is the total electric field, μ_m is the magnetic permeability and r is radial co-ordinate given by $r^2 = x^2 + y^2$. When the strength of the magnetic field is very large, the generalized ohm's law is modified to include the hall current so that

$$J + \frac{\omega_e \tau_e}{B_O}\left(J \times B\right) = \sigma\left[E + V \times B + \frac{1}{e\eta_e}\nabla P_e\right] \tag{2.8}$$

Where ω_e is the cyclotron frequency of the electrons, τ_e is the electron collision time, σ is the electrical conductivity, e is the electron charge and P_e is the electron pressure. The ion-slip and thermo electric effects are not included in equation (2.8). Further it is assumed that $\omega_e \tau_e \sim 0$ (1) and $\omega_i \tau_i << 1,$ where ω_i and τ_i are the cyclotron frequency and collision time for ions respectively. The unsteady hydro magnetic flow in a rotating system is governed by the equation of motion for momentum, the conservation of mass, energy and the equation of mass transfer, under usual Boussinesq approximation, are given by

$$\frac{\partial w}{\partial z} = 0 \tag{2.9}$$

$$\frac{\partial u}{\partial t} + w\frac{\partial u}{\partial z} - 2\Omega v = \nu\frac{\partial^2 u}{\partial z^2} + \frac{\alpha_1}{\rho}\frac{\partial^3 u}{\partial z^2 \partial t} + B_0 J_y - \frac{\nu}{K_1}u + g\beta(T - T_\infty) + g\beta^*(C - C_\infty) \tag{2.10}$$

$$\frac{\partial v}{\partial t} + w\frac{\partial v}{\partial z} + 2\Omega u = \nu\frac{\partial^2 v}{\partial z^2} + \frac{\alpha_1}{\rho}\frac{\partial^3 v}{\partial z^2 \partial t} - B_0 J_x - \frac{\nu}{K_1}v \tag{2.11}$$

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial z} - \frac{\nu}{k}w \tag{2.12}$$

$$\frac{\partial T}{\partial t} + w\frac{\partial T}{\partial z} = \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial z^2} + S_1(T - T_\infty) \tag{2.13}$$

$$\frac{\partial C}{\partial t} + w\frac{\partial C}{\partial z} = D\frac{\partial^2 C}{\partial z^2} - K_C(C - C_\infty) \tag{2.14}$$

where, (u, v) is the velocity components along x and y directions, T is the temperature of the fluid, C is the species concentration, α_1 is the normal stress modulus, ρ is the density of the fluid, σ is the electrical conductivity of the fluid, K_1 is the permeability of the porous medium, B_0 is the uniform magnetic field of strength, ν is the coefficient of kinematic viscosity, k is the thermal conductivity of the fluid, C_p is the specific heat of the fluid at constant pressure, β is the volumetric coefficient of the thermal expansion, β^* is the volumetric coefficient of the thermal expansion with concentration, g is the acceleration due to gravity, D is the thermal diffusivity of the fluid, S_1 is the heat source/sink parameter and K_C is the chemical reaction parameter.

In equation (2.8) the electron pressure gradient, the ion-slip and thermo-electric effects are neglected. We also assume that the electric field *E=0* under assumptions reduces to

$$J_x + m\, J_y = \sigma B_0 v \tag{2.15}$$

$$J_y - m\, J_x = -\sigma B_0 u \tag{2.16}$$

Where $m = \tau_e \omega_e$ is the hall parameter.

On solving equations (2.15) and (2.16) we obtain

$$J_x = \frac{\sigma B_0}{1+m^2}(v+mu) \quad (2.17)$$

$$J_y = \frac{\sigma B_0}{1+m^2}(mv-u) \quad (2.18)$$

Using the equations (2.17) and (2.18), the equations of motion with reference to a rotating frame are given by

$$\frac{\partial u}{\partial t} + w\frac{\partial u}{\partial z} - 2\Omega v = \nu\frac{\partial^2 u}{\partial z^2} + \frac{\alpha_1}{\rho}\frac{\partial^3 u}{\partial z^2 \partial t} + \frac{\sigma B_0^2}{1+m^2}(mv-u) - \frac{\nu}{K_1}u + g\beta(T-T_\infty) + g\beta^*(C-C_\infty) \quad (2.19)$$

$$\frac{\partial v}{\partial t} + w\frac{\partial v}{\partial z} + 2\Omega u = \nu\frac{\partial^2 v}{\partial z^2} + \frac{\alpha_1}{\rho}\frac{\partial^3 v}{\partial z^2 \partial t} - \frac{\sigma B_0^2}{1+m^2}(v+mu) - \frac{\nu}{K_1}v \quad (2.20)$$

The corresponding boundary conditions are

$$u = v = 0,\ T = T_w + \varepsilon(T_w - T_\infty)e^{i\omega t},\ C = C_w + \varepsilon(C_w - C_\infty)e^{i\omega t} \text{ at } z = 0 \quad (2.21)$$

$$u = v = 0, T = T_\infty, C = C_\infty \text{ at } z = \infty \quad (2.22)$$

Where $\varepsilon << 1$ and ω is the frequency of oscillation. There will be always some fluctuation in the temperature, the plate temperature is assumed to vary harmonically with time. It varies from $T_w \pm \varepsilon(T_w - T_\infty)$ as t varies from 0 to $\pi/2\omega$. Now there may also occur some variation in suction at the plate due to the variation of the temperature, here we assume that, the frequency of suction and temperature variation are same.

Integrating the equation (2.9), we get

$$w(t) = -w_0(1+\varepsilon A e^{i\omega t}) \quad (2.23)$$

Where A is the suction parameter, w_0 is the constant suction velocity and ε is the small positive number such that $\varepsilon A \le 1$. The equation (2.12) determines the pressure distribution along the axis of rotation and the absence of $\frac{\partial p}{\partial y}$ in the equation (2.11) implies that there is a net cross flow in the $y-$direction. We choose, $q = u + iv$ and taking into consideration (2.23), the momentum equation (2.19) and (2.20) can be written as

$$\frac{\partial q}{\partial t} - w_0(1+\varepsilon A e^{i\omega t})\frac{\partial q}{\partial z} + 2i\Omega q = \nu\frac{\partial^2 q}{\partial z^2} + \frac{\alpha_1}{\rho}\frac{\partial^3 q}{\partial z^2 \partial t} - \frac{\sigma B_0^2}{\rho(1-im)}q - \frac{\nu}{K_1}q + g\beta(T-T_\infty) + g\beta^*(C-C_\infty) \quad (2.24)$$

Introducing the following non-dimensional quantities:

$$z^* = \frac{w_0 z}{\nu},\ q^* = \frac{q}{w_0},\ T^* = \frac{T-T_\infty}{T_w-T_\infty},\ C^* = \frac{C-C_\infty}{C_w-C_\infty},\ \omega^* = \frac{\nu\omega}{w_0^2},\ t^* = \frac{t w_0^2}{\nu}$$

Making use of non-dimensional quantities (dropping asterisks), the equation (2.24), (2.13) and (2.14) can be written as

$$\frac{\partial q}{\partial t} - (1+\varepsilon A e^{i\omega t})\frac{\partial q}{\partial z} + 2iRq = \frac{\partial^2 q}{\partial z^2} + \alpha\frac{\partial^3 q}{\partial z^2 \partial t} - \left(\frac{M^2}{1-im} + \frac{1}{K}\right)q + G_r T + G_m C \quad (2.25)$$

$$\frac{\partial T}{\partial t} - (1+\varepsilon A e^{i\omega t})\frac{\partial T}{\partial z} = \frac{1}{\Pr}\frac{\partial^2 T}{\partial z^2} + ST \quad (2.26)$$

$$\frac{\partial C}{\partial t} - (1+\varepsilon A e^{i\omega t})\frac{\partial C}{\partial z} = \frac{1}{Sc}\frac{\partial^2 C}{\partial z^2} - K_C C \quad (2.27)$$

Where,

$M^2 = \frac{\sigma B_0^2 \nu}{\rho w_0^2}$ is the Hartmann number (Magnetic field parameter), $K = \frac{K_1 w_0^2}{\nu^2}$ is the Porosity parameter, $R = \frac{\Omega\nu}{w_0^2}$ is the Rotation parameter, $\alpha = \frac{\alpha_1 w_0^2}{\rho\nu^2}$ is the second grade fluid parameter, $G_r = \frac{g\beta\nu(T_w - T_\infty)}{w_0^3}$ is the thermal Grashof number, $G_m = \frac{g\beta^* \nu (C_w - C_\infty)}{w_0^3}$ is the mass Grashof number, $\Pr = \frac{\rho \nu C_p}{k}$ is Prandtl parameter, $S = \frac{S_1 \nu}{w_0}$ is the Source parameter, $K_C = \frac{K_C \nu}{w_0^2}$ chemical reaction parameter, $m = \tau_e \omega_e$ is the hall parameter and $Sc = \frac{\nu}{D}$ is the Schmidt number.

Equating the harmonic and non-harmonic terms, we get

$$\frac{d^2 q_0}{dz^2} + \frac{dq_0}{dz} - \left(2iR + \frac{M^2}{1 - im} + \frac{1}{K} \right) q_0 = -G_r T_0 - G_m C_0 \tag{2.28}$$

$$(1 + \alpha i \omega) \frac{d^2 q_1}{dz^2} + \frac{dq_1}{dz} - \left((2R + \omega) i + \frac{M^2}{1 - im} + \frac{1}{K} \right) q_1 = -G_r T_1 - G_m C_1 - A \frac{dq_0}{dz} \tag{2.29}$$

$$\frac{d^2 T_0}{dz^2} + \Pr \frac{dT_0}{dz} + S \Pr T_0 = 0 \tag{2.30}$$

$$\frac{d^2 T_1}{dz^2} + \Pr \frac{dT_1}{dz} - (i\omega - S) \Pr T_1 = -A \Pr \frac{dT_0}{dz} \tag{2.31}$$

$$\frac{d^2 C_0}{dz^2} + Sc \frac{dC_0}{dz} - Sc K_C C_0 = 0 \tag{2.32}$$

$$\frac{d^2 C_1}{dz^2} + Sc \frac{dC_1}{dz} - (i\omega + K_C) Sc C_1 = -A Sc \frac{dC_0}{dz} \tag{2.33}$$

The corresponding boundary conditions

$$\left. \begin{array}{l} q_0 = 0, T_0 = 1, C_0 = 1 \\ q_1 = 0, T_1 = 1, C_1 = 1 \end{array} \right\} \text{ at } z = 0 \tag{2.34}$$

$$\left. \begin{array}{l} q_0 = T_0 = C_0 = 0 \\ q_1 = T_1 = C_1 = 0 \end{array} \right\} \text{ at } z = \infty \tag{2.35}$$

Hence the expression for the transient velocity profiles for $\omega t = \pi / 2$ are given by

$$u\left(z, \frac{\pi}{2\omega} \right) = w_0 \left(u_0(z) - \varepsilon v_1(z) \right) \tag{2.36}$$

$$v\left(z, \frac{\pi}{2\omega} \right) = w_0 \left(v_0(z) + \varepsilon u_1(z) \right) \tag{2.37}$$

3.Skin friction:

The non-dimensional skin friction at the plate $z = 0$ in term of amplitude and phase angle is given by

$$\tau = \left(\frac{dq}{dz} \right)_{z=0} = \left(\frac{dq_0}{dz} \right)_{z=0} + \varepsilon \left(\frac{dq_1}{dz} \right)_{z=0} e^{i\omega t}$$

$$= C_5 b_1 + C_2 b_2 + C_3 a_6 + \varepsilon \left(a_8 C_{17} + a_2 C_{12} + C_5 C_{13} + a_4 C_{14} + C_2 C_{15} + a_6 C_{16} \right) e^{i\omega t} \tag{2.38}$$

The τ_{xz} and τ_{yz} components of skin friction at the plate are given by

$$\tau_{xz} = \left(\frac{du_0}{dz} \right)_{z=0} - \varepsilon \left(\frac{dv_1}{dz} \right)_{z=0} \text{ and } \tau_{yz} = \left(\frac{dv_0}{dz} \right)_{z=0} + \varepsilon \left(\frac{du_1}{dz} \right)_{z=0}$$

4.Rate of heat transfer (Nusselt number):

The rate of heat transfer co-efficient at the plate $z = 0$ in term of amplitude and phase angle is given by

$$Nu = \left(\frac{dT}{dz} \right)_{z=0} = \left(\frac{dT_0}{dz} \right)_{z=0} + \varepsilon \left(\frac{dT_1}{dz} \right)_{z=0} e^{i\omega t} = C_5 + \varepsilon \left(a_2 + \frac{A \Pr C_5}{C_6} (a_2 - C_5) \right) e^{i\omega t} \tag{2.39}$$

5.Rate of mass transfer (Sherwood number):

The rate of mass transfer co-efficient at the plate $z = 0$ in term of amplitude and phase angle is given by

$$Sh = \left(\frac{dC}{dz}\right)_{z=0} = \left(\frac{dC_0}{dz}\right)_{z=0} + \varepsilon\left(\frac{dC_1}{dz}\right)_{z=0} e^{i\omega t} = C_2 + \varepsilon\left(a_4 + \frac{A\,ScC_2}{C_3}(a_4 - C_2)\right)e^{i\omega t} \quad (2.40)$$

6.Analysis of the numerical results.

The closed form solutions for the velocity $q = u + iv$, temperature θ and concentration C are obtained making use of perturbation technique. The velocity expression consists of steady state and oscillatory state. It reveals that, the steady part of the velocity field has three layer characters while the oscillatory part of the fluid field exhibits a multi layer character.It is noticed that, from the Figures 1(a-h) the magnitude of the velocity *u* reduces with increasing the intensity of the magnetic field (Hartmann number M) while it enhances with increasing second grade fluid parameter α or permeability of porous medium *K* or hall parameter *m* throughout the fluid region. The magnitude of the velocity component *v* enhances with increasing *M* or second grade fluid parameter α or permeability of porous medium *K* or hall parameter *m*. The application of the transverse magnetic field plays the important role of a resistive type force (Lorentz force) similar to drag force (that acts in the opposite direction of the fluid motion) which tends to resist the flow thereby reducing its velocity. The resultant velocity q enhances with increasing α, *K* and *m*; and reduces with increasing *M*. We observe that lower the permeability of porous medium lesser the fluid speed in the entire fluid region. Further, it is to observed that from Figures 2 (a-h) the velocity *u* reduces and *v* enhances with increasing Schmidt number *Sc*, first the velocity *u* increases and then experiences retardation where as *v* reduces in the entire fluid region with increasing chemical reaction parameter Kc. With increasing Prandtl number Pr the velocity *u* reduces and *v* enhances in the complete flow field. This implies that an increase in Prandtl number Pr leads to fall the thermal boundary layer flow. This is because fluids with large have low thermal diffusivity which causes low heat penetration resulting in reduced thermal boundary layer. Likewise the velocity *u* enhances and *v* decreases with increasing the frequency of oscillation ω and time *t*. The resultant velocity reduces with increasing Kc or Sc and increases with increasing Pr and time *t*.

This is scrutinized from Table .1 that, it is notified that, for together ramped wall temperature and isothermal plate, the stress components τx as well as τy enhances by an increasing in second graded fluid parameter α, chemical reacting parameter Kr, temperature generations and/or absorptions H and thermal radiation parameter R, as well as it reduces by an increasing in the permeability parameter K, thermal-diffusion (Soret) parameters Sr, thermal Grashof numbers Gr and mass Grashof quantity Gm. This is also found that by an increasing in the intensity of the magnetic fields then the stress components τx retards and the component τy boosting up for together ramped wall and isothermal plate. Finally, the Sherwood number Sh is reduced with an increasing in the Soret number Sr as well as Schmidt number, and it is increasing with an increasing in chemically reacting parameter Kr and certain instant of time for together ramped wall temperature and an isothermal plate (Table .2).

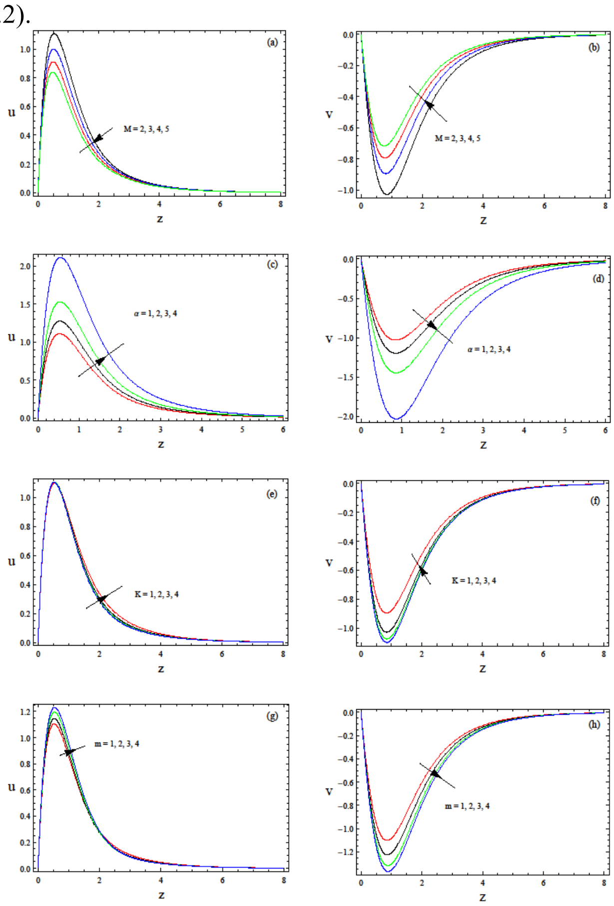

Fig. 1. The velocity profiles for the components *u* and *v* for M, α, K and *m* with $A = 0.05$; $\omega = 5\pi/2$; $\varepsilon = 0.001$, $t = 0.2$

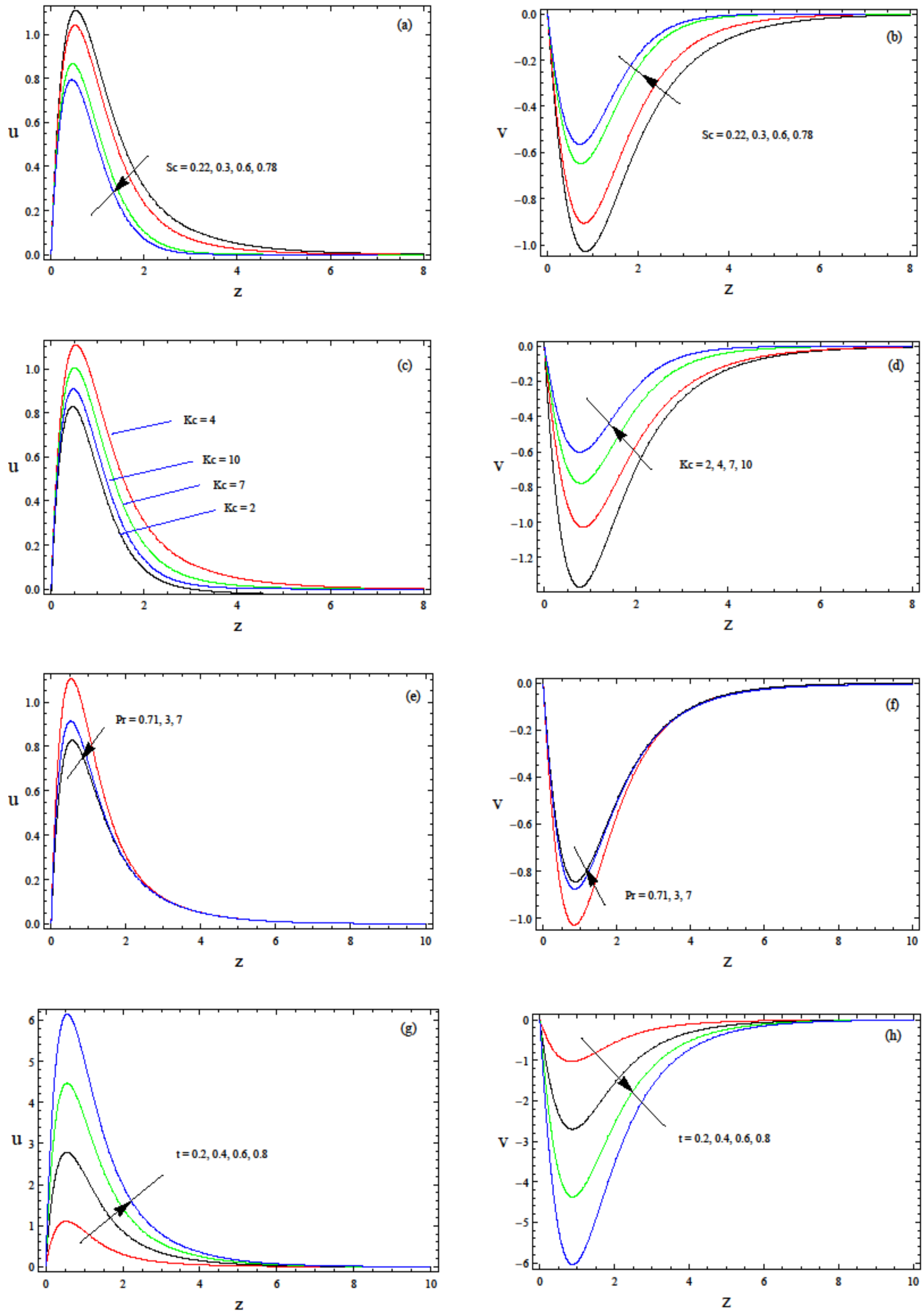

Fig. 2. The velocity profiles for the components *u* and *v* for Sc, Kc, Pr and t with $A = 0.05$; $\omega = 5\pi/2$; $\varepsilon = 0.001$, $t = 0.2$

Table.1 The Shear stresses

M	K	α	K_r	S_r	G_r	G_m	H	R	Ramped Temperature		Isothermal Plate	
0.5	0.5	0.1	2	0.1	5	2	2	2	τ_x	τ_y	τ_x	τ_y
0.8									1.836214	0.047785	1.899789	0.97589
1									1.417058	0.058898	1.610469	1.005547
	1								1.073592	0.065578	1.380014	1.109554
	1.5								1.738796	0.025478	1.724635	0.909969
		1							1.509478	0.014502	1.579789	0.798559
		1.5							2.406466	0.058895	2.013966	1.108748
			3						3.539896	0.085547	2.155254	1.286589
			4						2.139895	0.055874	2.253801	1.175478
				0.5					2.772747	0.087748	3.240479	1.575041

				1					1.743745	0.021411	1.350884	0.656952
					8				1.553985	0.014115	0.605856	0.416658
					10				1.73611	0.025041	1.877147	0.944587
						5			1.507522	0.018874	1.855145	0.918847
						8			1.780547	0.036306	1.887265	0.967895
							-5		1.673954	0.021447	1.876458	0.944014
							5		1.743665	0.032256	1.840595	0.878748
								5	2.13965	0.058874	2.024854	1.078849
								8	1.909452	0.055289	2.013859	1.175954

Table.2 The Sherwood number(Pr=0.710,R=2.0,H=-2.0)

S_r	K_r	S_c	t	Ramped Temperature	Isothermal Temperature
0.1	2	0.22	0.2	0.563478	0.647278
0.5				0.480254	0.564054
1				0.425854	0.509654
	3			0.625785	0.709585
	4			0.703699	0.787499
		0.3		0.536895	0.620695
		0.6		0.503548	0.587348
			0.5	0.633897	0.717697

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