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THERMAL EFFECTS ON MHD STOKES' SECOND PROBLEM FOR COUPLE STRESS FLUID THROUGH A POROUS MEDIUM

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ABSTRACT

In this paper, the thermal effects on MHD stokes's second problem for couple stress fluid through a porous medium is investigated. The effects ofvarious emerging parameters on the velocity field and temperature field arediscussed in detail through graphs.

Keywords: *Couple stress fluid, MHD, Thermal effect.*

1. INTRODUCTION

The flow induced by a suddenly accelerating plate on the fluid above it, usually referred to as Stokes' first problem (Stokes, 1851), and the flow due to an oscillating flat plate, usually referred to as Stokes' second problem (see Raleigh, 1911) are amongst a handful of unsteady flows of a Navier–Stokes fluid for which one can obtain an exact solution. Such exact solutions serve a dual purpose, that of providing an explicit solution to a problem that has physical relevance and as a means for testing the efficiency of complex numerical schemes for flows in complicated flow domains. The Stokes' second problem describes the oscillatory flat plate in a semi-infinite flow domain with a specific frequency. Tanner (1962) has investigated the exact solution to this Stokes' first problem for a Maxwell fluid. The impulsive motion of a flat plate in a viscoelastic fluid was analyzed by Taipel (1981). Exact solution for unsteady flow of non-Newtonian fluid due to an oscillating wall was presented by Rajagopal (1982). Prezoisi and Joseph (1987) have discussed the Stokes first problem for viscoelastic fluids. Erdogan (1995) has investigated the unsteady flow of viscous fluid due to an oscillating plane wall by using Laplace transform technique. Puri and Kythe (1998) have discussed an unsteady flow problem which deals with non-classical heat conduction effects and the structure of waves in Stokes' second problem. Much work has been published on the flow of fluid over an oscillating plate for different constitutive models (Zeng and Weinbaum, 1995; Asghar et al., 2002; Ibrahem et al., 2006). The theory of couple stresses in fluids, developed by Stokes (1966), represents the simplest generalization of the classical theory and allows for polar effects such as the presence of couple stresses and body couples. Stokes' first and second problems for an incompressible couple stress fluid under isothermal conditions were studied by Devakar and Iyengar (2008).

There has been an increase in interest in the effect of porous media, because of their extensive practical applications in geophysics, thermal insulation in buildings, petroleum resources, packed-bed reactors and sensible heat-storage beds. Many studies related to non-Newtonian fluids saturated in a porous medium have been carried out. Dharmadhikari and Kale (1985) studied experimentally the effect of non-Newtonian fluids in a porous medium. Chen and Chen (1988) investigated the free convection flow along a vertical plate embedded in a porous medium. Rees (1996) analyzed the effect of inertia on free convection over a horizontal surface embedded in a porous medium. Nakayama (1991) investigated the effect of buoyancy-induced flow over a non-isothermal body of arbitrary shape in a fluid-saturated porous medium. A ray-tracing method for evaluating the radiative heat transfer in a porous medium was examined by Argento (1996).

Past few decades the study of magnetohydrodynamics flow of electrically conducting fluids in electric and magnetic fields are of considerable interest in modern metallurgical and metal working process. The Hartmann flow is a classical problem that has important applications in MHD power generators and pumps, accelerators, aerodynamic heating, electrostatic precipitation, polymer technology, the petroleum industry, purification of crude oil and design of various heat exchangers. Ramachandra Rao and Deshikachar (1986) have investigated the MHD oscillatory flow of blood through channels of variable cross section. The effect of transverse magnetic field in physiological type of flow, through a uniform circular pipe was studied by Ramachandra Rao and Deshikachar (1988). It has been established that the biological systems in general are greatly affected by the application of external magnetic field. Vajravelu and

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Rivera (2003) have analyzed the hydromagnetic flow at an oscillating plate. The pulsatile flow of couple stress fluid through a porous medium with periodic body acceleration and magnetic field was investigated by Rathod and Tanveer (2009). Reddappa et al. (2009) have investigated the non-classical heat conduction effects in Stokes' second problem of a micropolar fluid under the influence of a magnetic field.

In view of these, we investigated the magnetic field and thermal effects on Stoke's second problem for couple stress fluid through a porous medium. The expressions for the velocity field and the temperature field are obtained analytically. The effects of various emerging parameters on the velocity field and temperature field are studied in detail with the help of graphs.

2. FORMULATION OF THE PROBLEM

The equations of motion that characterize couple stress fluid flow are similar to the Navier- Stokes equations and are given by:

$$\frac{d\rho}{dt} + \rho\,\mathrm{div}(q) = 0 \tag{2.1}$$

$$\rho\frac{dq}{dt} = \rho f + \begin{bmatrix} \frac{1}{2}\mathrm{curl}(\rho c) + div\left(\tau^{(s)}\right) \\ +\frac{1}{2}\mathrm{curl}\left(\mathrm{div}(M)\right) \end{bmatrix} + J\times B - \frac{\mu}{k}q - \rho\left[1-\alpha\left(\theta-\theta_\infty\right)\right]g\delta_{i1} \tag{2.2}$$

where ρ is the density of the fluid, α - the co-efficient of thermal expansion, g - the acceleration due to gravity, $B\left(=B_0+B_1\right)$ - total magnetic field, B_1 is the induced magnetic field assumed negligible, $\tau^{(s)}$ is the symmetric part of the force stress diad, μ is the viscosity of the fluid, k is the permeability of the porous medium, M is the couple stress diad and f, c are the body force per unit mass and body couple per unit mass respectively.

The constitutive equations concerning the force stress t_{ij}, and the rate of deformation tensor d_{ij} are given by:

$$t_{ij} = -p\delta_{ij} + \lambda\,\mathrm{div}(q)\delta_{ij} + 2\mu d_{ij} - \frac{1}{2}\varepsilon_{ijk}\left[m_{,k} + 4\eta\omega_{k,rr} + \rho c_k\right] \tag{2.3}$$

The couple stress tensor m_{ij} that arises in the theory has the linear constitutive relation

$$m_{ij} = \frac{1}{3}m\delta_{ij} + 4\eta\omega_{j,i} + 4\eta^{'}\omega_{i.j} \tag{2.4}$$

In the above $\omega = \frac{1}{2}\mathrm{curl}q$ is the spin vector, $\omega_{i,j}$ is the spin tensor, m is the trace of couple stress tensor m_{ij}, p is the fluid pressure and ρc_k is the body couple vector. Comma in the suffixes denotes covenant differentiation and $\omega_{k,rr}$ stands for $\omega_{k,11}+\omega_{k,22}+\omega_{k,33}$. The quantities λ and μ, are the viscosity coefficients and η, $\eta^{'}$ are the couple stress viscosity coefficients. These material constants are constrained by the inequalities

$$\mu \ge 0, \qquad 3\lambda + 2\mu \ge 0, \qquad \eta \ge 0, \qquad \left|\eta^{'}\right| \le \eta \tag{2.5}$$

There is a length parameter $l = \sqrt{\eta/\mu}$, which is a characteristic measure of the polarity of the fluid model and this parameter is identically zero in the case of non-polar fluids.

After neglecting body forces and body couples, the equations governing the couple stress fluid dynamics as given by Stokes (1966) are

$$\mathrm{div}q = 0 \tag{2.6}$$

$$\rho\left[\frac{\partial q}{\partial t} + (q.\nabla q)\right] = -\nabla p - \begin{bmatrix} \mu\,\mathrm{curl}\left(\mathrm{curl}(q)\right) - \\ \mathrm{curl}\left(\mathrm{curl}\left(\mathrm{curl}\left(\mathrm{curl}(q)\right)\right)\right) \end{bmatrix} + J\times B - \frac{\mu}{k}q + \alpha g\left(\theta-\theta_\infty\right) \tag{2.7}$$

Neglecting the displacement currents, the Maxwell equations and the Ohm's law are:

$$\operatorname{div} B = 0, \ \operatorname{curl} B = \mu_m J, \ \operatorname{curl} E = -\frac{\partial B}{\partial t}, \quad J = \sigma\left(E + q \times B\right) \tag{2.8}$$

where σ is the electrical conductivity, μ_m is the magnetic permeability and $\overline{E}$ is the electric field. The imposed and induced electrical fields are assumed to be negligible. Under the assumption of low magnetic Reynolds number, $\overline{J} \times \overline{B}$ reduces to

$$J \times B = -\sigma \mu_e^2 B_0^2 q \tag{2.9}$$

We consider the unsteady flow of an incompressible, couple stress fluid through a porous medium which fills the half space $y > 0$ above a flat (solid) plate occupying xz-plane. Initially, we assume (has both fluid and plate are at rest. A uniform magnetic field B_0 is applied transverse direction to the flow. It is assumed that the transversely applied magnetic field and magnetic Reynolds number are very small and hence the induced magnetic field is negligible as in Cowling (1971). At time $t = 0+$, whether we allow the plate to start with a constant velocity *U* along x-axis or oscillate with velocity $U \cos \omega t$ the flow occurs only in x - direction. Therefore, the velocity is expected to be in the form $q = \left(u\left(y,t\right), 0, 0\right)$ and it automatically satisfies the continuity Eq. (2.6).

Under these assumptions the Eq. (2.7) becomes

$$\rho \frac{\partial u}{\partial t} = \mu \frac{\partial^2 u}{\partial y^2} - \eta \frac{\partial^4 u}{\partial y^4} - \sigma \mu_e^2 B_0^2 u - \frac{\mu}{k} u + \alpha g\left(\theta - \theta_\infty\right) \tag{2.10}$$

The energy equation (MCF model) is given by (Ibrahem et al., 2006)

$$\tau \theta_{tt} + \theta_t = \frac{\chi}{\rho c_p} \theta_{yy} \tag{2.11}$$

where ω_{ij} is the vorticity, χ the thermal conductivity, θ the temperature, and τ the thermal relaxation time.

Introducing the non-dimensional variables

$$\bar{u} = \frac{u}{U}, \bar{y} = \frac{y}{l}, \bar{t} = \frac{U}{l} t, \ \bar{\theta} = \frac{\theta - \theta_0}{\theta_w - \theta_0}, \ l^2 = \frac{\eta}{\mu}, R = \frac{\rho U l}{\mu} \tag{2.12}$$

into Equations (2.10) and (2.11), we get (after dropping bars)

$$R \frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} - \frac{\partial^4 u}{\partial y^4} - \left(H^2 + \frac{1}{Da}\right) u + G\theta \tag{2.13}$$

$$\lambda p \theta_{tt} + p \theta_t = \theta_{zz} \tag{2.14}$$

here $p = \dfrac{v \rho c_p}{\chi}$, $\lambda = \dfrac{\tau U_0^2}{v} = C_p$.

The non-dimensional boundary conditions are

$$\begin{aligned}
&\theta\left(y,t\right) = e^{i\omega t} && \text{at} && y = 0 \\
&\theta(y,t) \to 0 && \text{as} && y \to \infty \\
&u(y,t) = e^{i\omega t} && \text{at} && y = 0 \\
&\frac{\partial^2 u}{\partial y^2} = 0 && \text{at} && y = 0 \\
&u(y,t) \to 0 && \text{as} && y \to \infty
\end{aligned} \tag{2.15}$$

3. SOLUTION

To solve the nonlinear system (2.13) and (2.14) with the boundary conditions (2.15), we assume that

$$u(y,t)=U(y)e^{i\omega t},\ \theta(y,t)=\Theta(y)e^{i\omega t} \tag{3.1}$$

If we substitute by Eq. (3.1) in Equations (2.13) and (2.14) and the boundary conditions (2.15), we get

$$R\frac{\partial^4 U}{\partial y^4}-\frac{\partial^2 U}{\partial y^2}+\left(iR\omega+\frac{1}{Da}+H^2\right)U=G\Theta \tag{3.2}$$

$$\Theta''+(\lambda p\omega^2-i\omega p)\Theta=0 \tag{3.3}$$

The corresponding boundary conditions are

$$\Theta(0)=1,\ \Theta(\infty)=0,\ U(0)=1,\ U''(0)=0,\ \ U(\infty)=0 \tag{3.4}$$

Solving the Equations (3.2) and (3.3) using the boundary conditions Eq. (3.4), we get

$$\Theta(y)=e^{-my} \tag{3.5}$$

$$U(y)=c_1e^{-m_1y}+c_2e^{-m_2y} \tag{3.6}$$

where $m=\sqrt{-\lambda p\omega^2+i\omega p}$, $c_1=\frac{m_2^{\ 2}}{m_2^{\ 2}-m_1^{\ 2}}$, $c_2=-\frac{m_1^{\ 2}}{m_2^{\ 2}-m_1^{\ 2}}$, $m_1=\sqrt{\frac{1-r}{2}}$, $m_2=\sqrt{\frac{1+r}{2}}$

and $r=\sqrt{1-4\left(H^2+\frac{1}{Da}\right)^2-4iR\omega}$.

The solution of Equations (2.13) and (2.14) are given by

$$\theta(y,t)=e^{-(my-i\omega t)} \tag{3.7}$$

$$U(y,t)=c_1e^{-(m_1y-i\omega t)}+c_2e^{-(m_2y-i\omega t)} \tag{3.8}$$

4. DISCUSSION OF THE RESULTS

Fig. 1 depicts the variation of velocity $\mathrm{Re}\,u$ with y for different values of Darcy number Da with $\lambda=0.005$, $p=1$, $H=1$ $\omega=10$, $\mathrm{R}=0.5$, $t=0.1$ and $G=5$. It is found that, the velocity $\mathrm{Re}\,u$ osscilates with y. Further it is found that, the velocity $\mathrm{Re}\,u$ initially increases and then decreases with increasing Da.

The variation of velocity $|u|$ with y for different values of Darcy number Da with $\lambda=0.005$, $p=1$, $H=1$ $\omega=10$, $\mathrm{R}=0.5$, $t=0.1$ and $G=5$ is shown in Fig. 2. It is noted that, the velocity $|u|$ increases with an increase in Da.

Fig. 3 shows the variation of velocity $\mathrm{Re}\,u$ with y for different values of Hartmann number H with $\lambda=0.005$, $p=1$, $\omega=10$, $Da=0.1$, $\mathrm{R}=0.5$, $t=0.1$ and $G=5$. It is observed that, the velocity $\mathrm{Re}\,u$ first decreases and then increases with increasing M .

The variation of velocity $|u|$ with y for different values of Hartmann number H with $\lambda=0.005$, $p=1$, $\omega=10$, $\mathrm{R}=0.5$, $Da=0.1, t=0.1$ and $G=5$ is shown in Fig. 4. It is found that, the absolute velocity $|u|$ decreases with an increase in M .

Fig. 5 depicts the variation of velocity $\mathrm{Re}\,u$ with y for different values of Grshof number G with $\lambda = 0.005$, $p = 1$, $\omega = 10$, $\mathrm{R} = 0.5$, $Da = 0.1$, $t = 0.1$ and $H = 1$. It is noted that, the $\mathrm{Re}\,u$ initially decreases and thwen increases with increasing G.

The variation of velocity $|u|$ with y for different values of Grshof number G with $\lambda = 0.005$, $p = 1$, $\omega = 10$, $\mathrm{R} = 0.5$, $Da = 0.1$, $t = 0.1$ and $H = 1$ is depicted in Fig. 6. It observed that, the absolute velocity $|u|$ first increases and then decreases with an increase in G.

Fig. 7 illustrates the variation of velocity $\mathrm{Re}\,u$ with y for different values of couple stress Reynolds number R with $\lambda = 0.005$, $p = 1$, $\omega = 10$, $G = 5$, $t = 0.1$ and $M = 1$. As R increases, it is seen that the velocity $\mathrm{Re}\,u$ first decreases and then increases.

The variation of velocity $|u|$ with y for different values of couple stress Reynolds number R with $\lambda = 0.005$, $p = 1$, $\omega = 10$, $Da = 0.1$, $G = 5$, $t = 0.1$ and $H = 1$ is illustrated in Fig. 8. It is noted that, the absolute velocity $|u|$ decreases with increasing R.

Fig. 9 shows the variation of velocity $\mathrm{Re}\,u$ with y for different values of p with $\lambda = 0.005$, $R = 0.5$, $\omega = 10$, $G = 5$, $Da = 0.1$, $t = 0.1$ and $H = 1$. It is observed that, the the velocity $\mathrm{Re}\,u$ first increases and then decreases with an increase in p.

The variation of velocity $|u|$ with y for different values of p with $\lambda = 0.005$, $R = 0.5$, $\omega = 10$, $Da = 0.1$, $G = 5$, $t = 0.1$ and $H = 1$ is shown in Fig. 10. It is found that, the absolute velocity $|u|$ initially increases and then decreases with increasing p.

Fig. 11 depicts the variation of velocity $\mathrm{Re}\,u$ with y for different values of λ with $\lambda = 1$, $R = 0.5$, $\omega = 10$, $Da = 0.1$, $G = 5$, $t = 0.1$ and $H = 1$. It is noted that, the velocity $\mathrm{Re}\,u$ fisrt increases and then decreases with an increase in λ.

The variation of velocity $|u|$ with y for different values of λ with $\lambda = 1$, $R = 0.5$, $\omega = 10$, $Da = 0.1$, $G = 5$, $t = 0.1$ and $H = 1$ is depicted in Fig. 12. It is observed that, the absolute velocity $|u|$ increases with increasing λ.

Fig. 13 illustrates the variation of temperature $\mathrm{Re}\,\theta$ with y for different values of p with $\lambda = 0.005$ and $\omega = 10$. It is found that, the temperature $\mathrm{Re}\,\theta$ initially increases and then decreases with increase in p.

The variation of temperature $|\theta|$ with y for different values of p with $\lambda = 0.005$ and $\omega = 10$ is shown in Fig. 14. It is noted that, the absolute temperature $|\theta|$ decreases with increasing p.

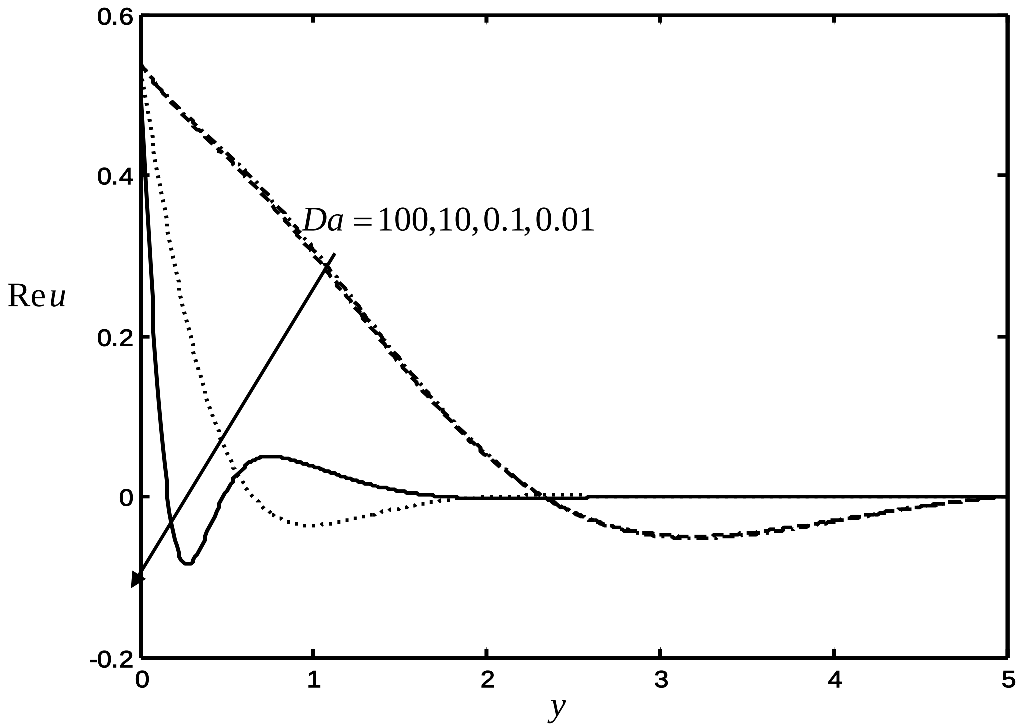

Fig. 1 The variation of velocity $\mathrm{Re}\,u$ with y for different values of Darcy number Da with $\lambda = 0.005$, $p = 1$, $H = 1$ $\omega = 10$, $\mathrm{R} = 0.5$, $t = 0.1$ and $G = 5$.

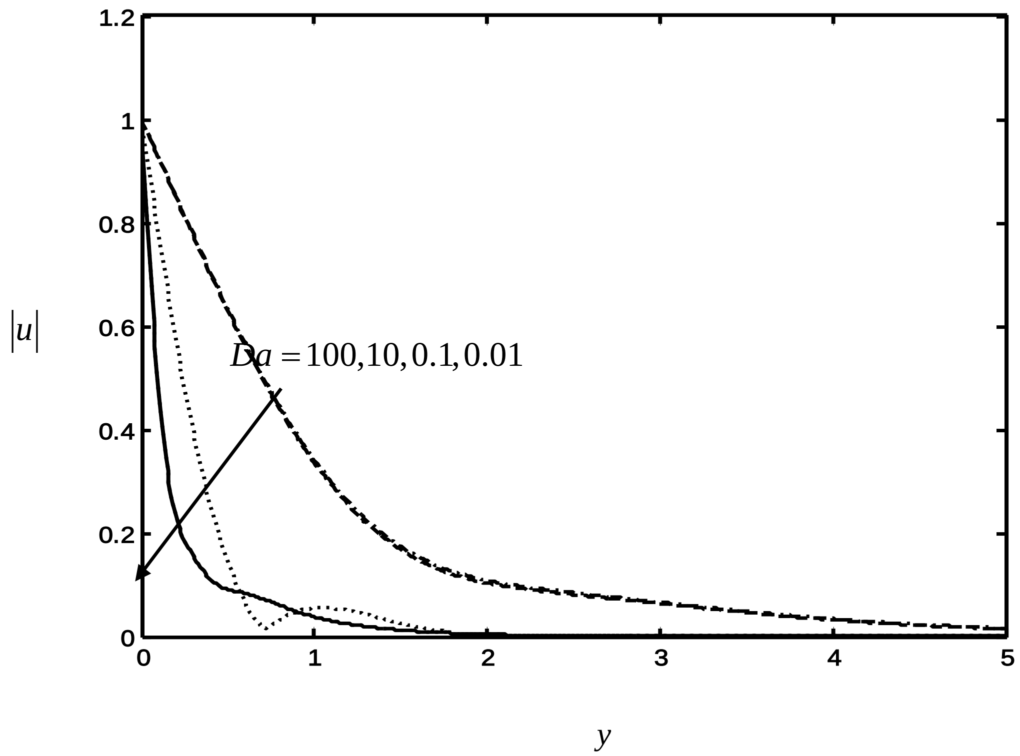

Fig. 2 The variation of velocity $|u|$ with y for different values of Darcy number Da with $\lambda = 0.005$, $p = 1$, $H = 1$ $\omega = 10$, $\mathrm{R} = 0.5$, $t = 0.1$ and $G = 5$.

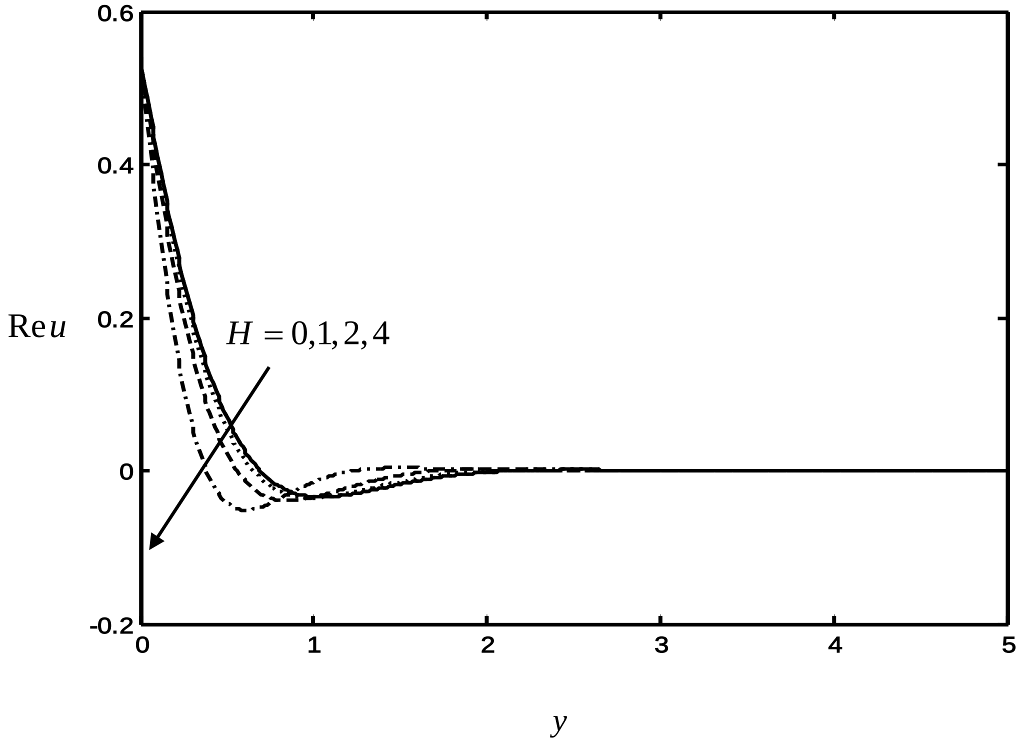

Fig. 3 The variation of velocity Reu with y for different values of Hartmann number H with $\lambda = 0.005$, $p = 1$, $Da = 0.1$, $\omega = 10$, $\mathrm{R} = 0.5$, $t = 0.1$ and $G = 5$.

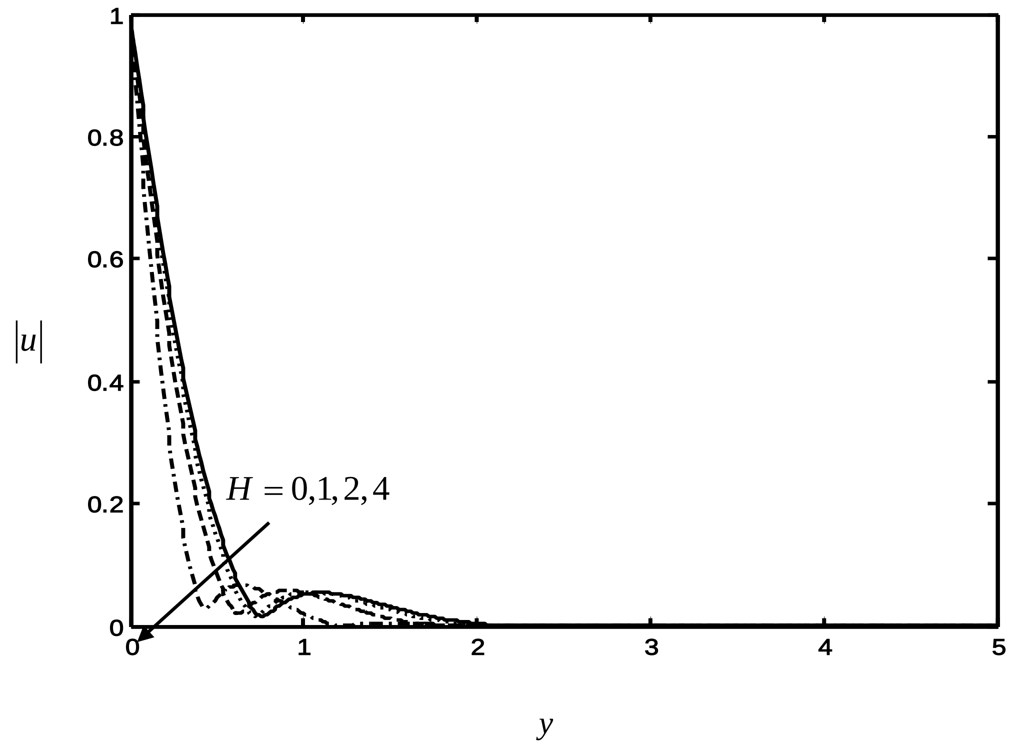

Fig. 4 The variation of velocity $|u|$ with y for different values of Hartmann number H with $\lambda = 0.005$, $p = 1$, $Da = 0.1$, $\omega = 10$, $\mathrm{R} = 0.5$, $t = 0.1$ and $G = 5$.

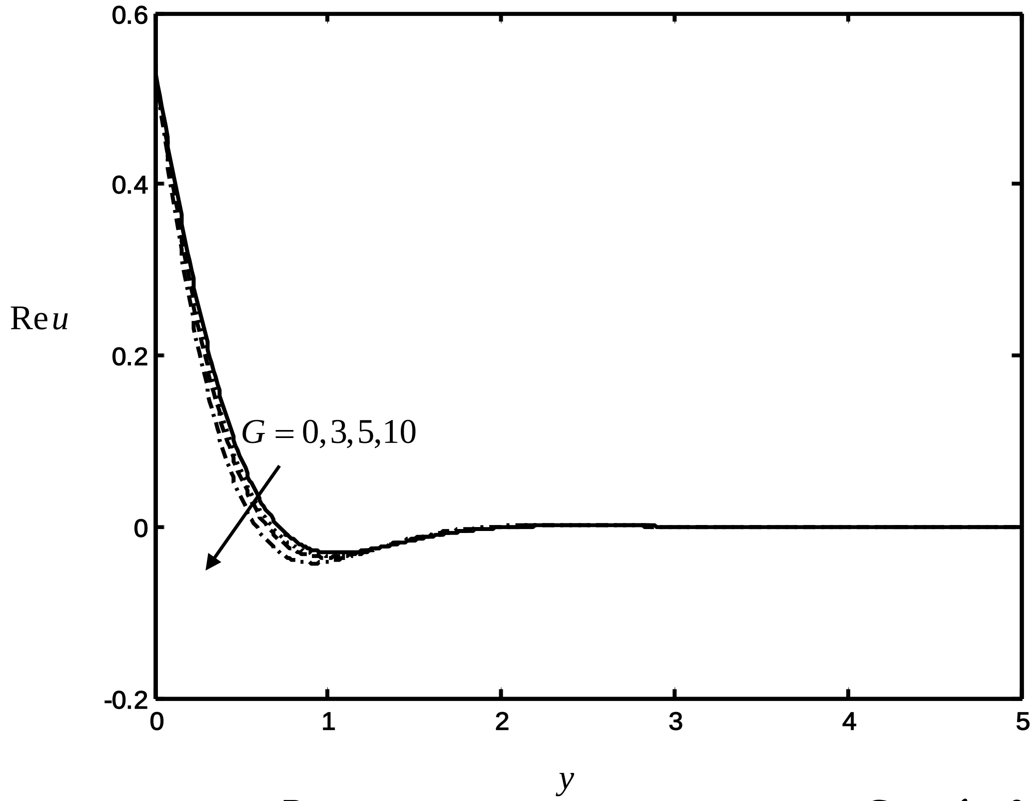

Fig. 5 The variation of velocity $\mathrm{Re}\,u$ with y for different values of Grshof number G with $\lambda = 0.005$, $p = 1$, $\omega = 10$, $\mathrm{R} = 0.5$, $Da = 0.1$, $t = 0.1$ and $H = 1$.

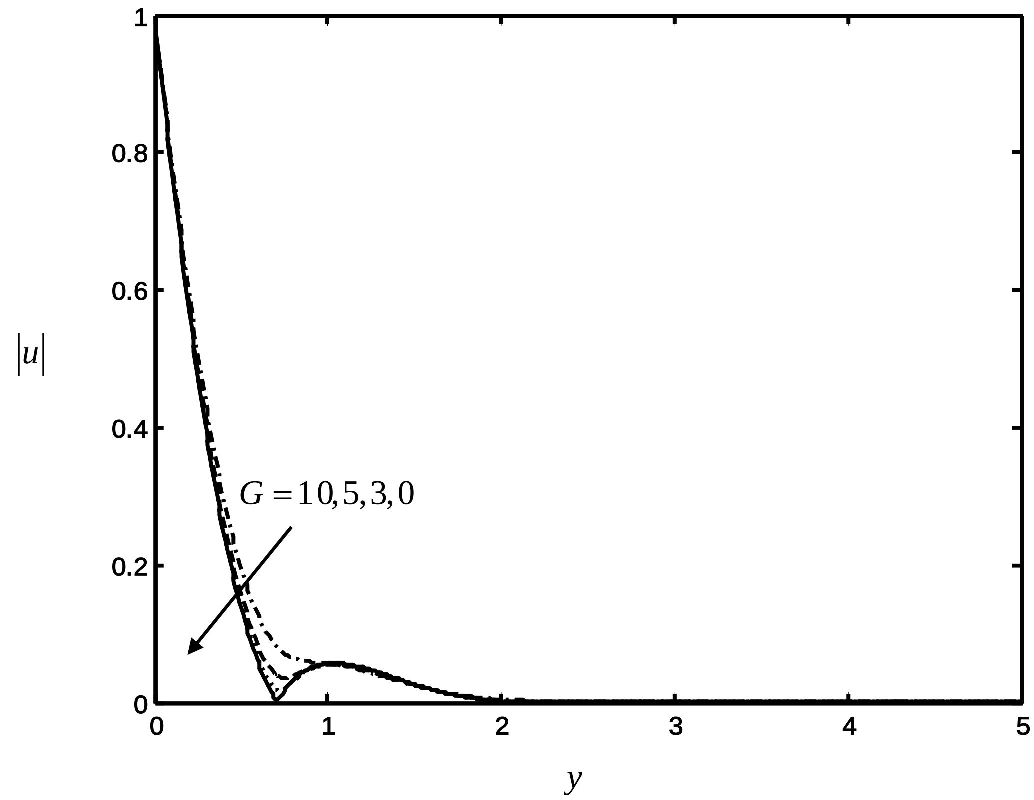

Fig. 6 The variation of velocity $|u|$ with y for different values of Grshof number G with $\lambda = 0.005$, $p = 1$, $\omega = 10$, $\mathrm{R} = 0.5$, $Da = 0.1$, $t = 0.1$ and $H = 1$.

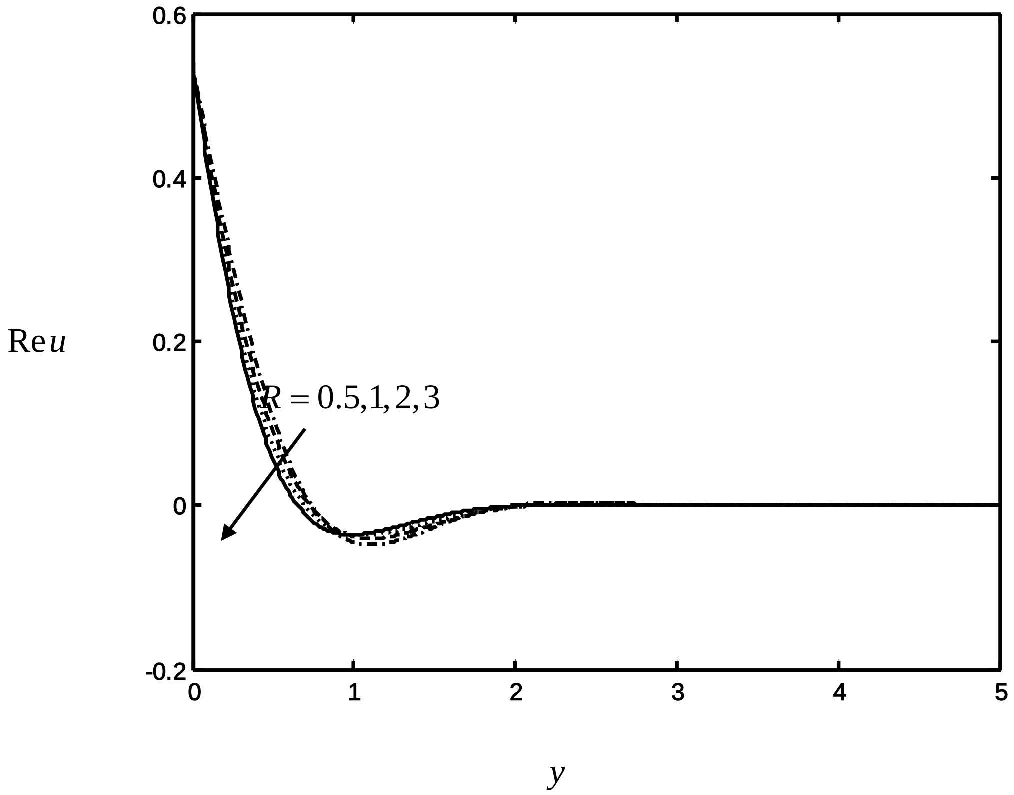

Fig. 7 The variation of velocity $\mathrm{Re}\,u$ with y for different values of Reynolds number R with $\lambda = 0.005$, $p = 1$, $\omega = 10$, $G = 5$, $Da = 0.1$, $t = 0.1$ and $H = 1$.

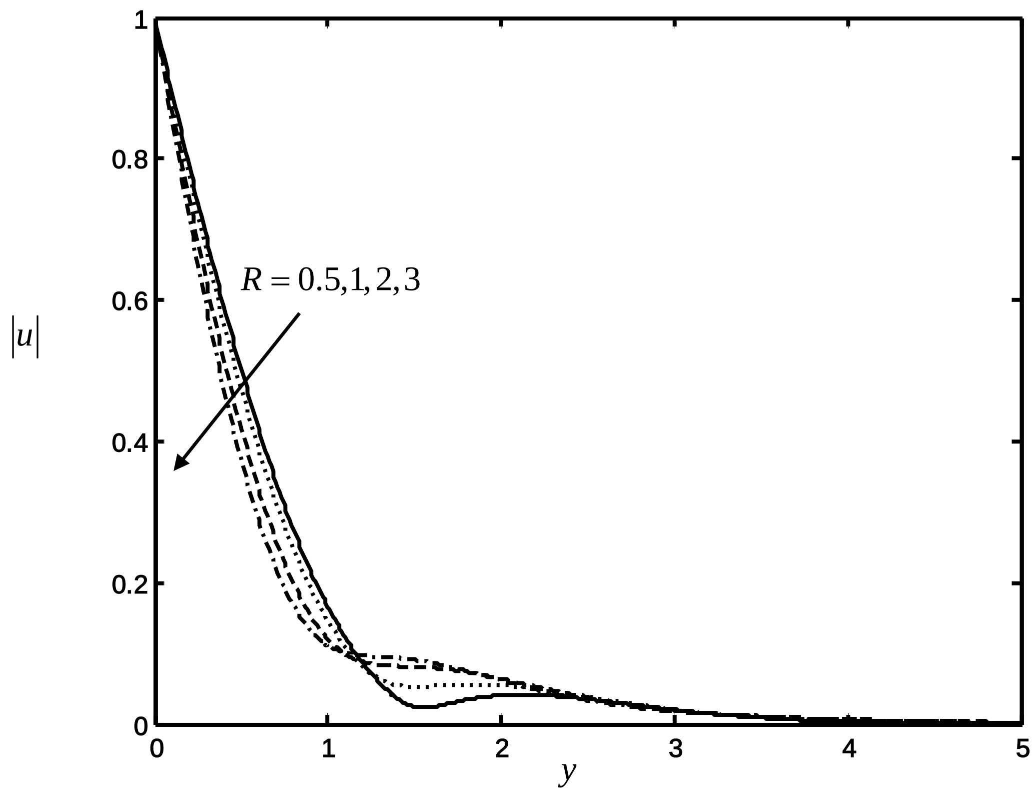

Fig. 8 The variation of velocity $|u|$ with y for different values of Reynolds number R with $\lambda = 0.005$, $p = 1$, $\omega = 10$, $G = 5$, $Da = 0.1$, $t = 0.1$ and $H = 1$.

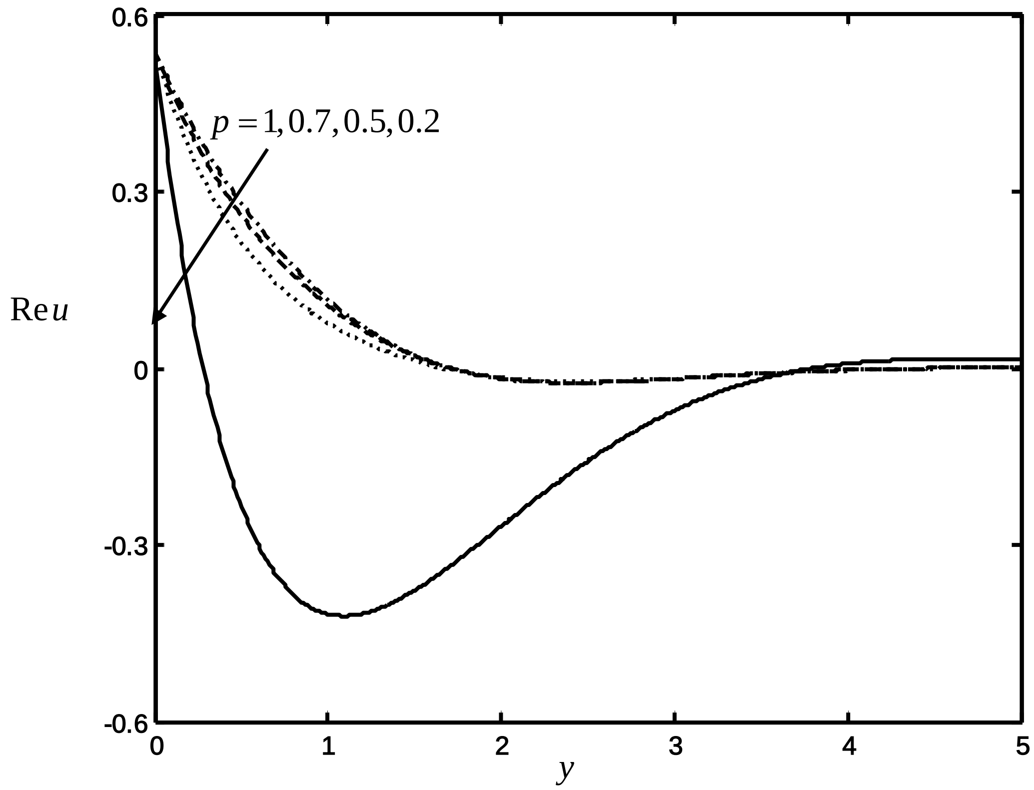

Fig. 9 The variation of velocity Reu with y for different values of p with $\lambda = 0.005$, $R = 0.5$, $\omega = 10$, $Da = 0.1$, $G = 5$, $t = 0.1$ and $H = 1$.

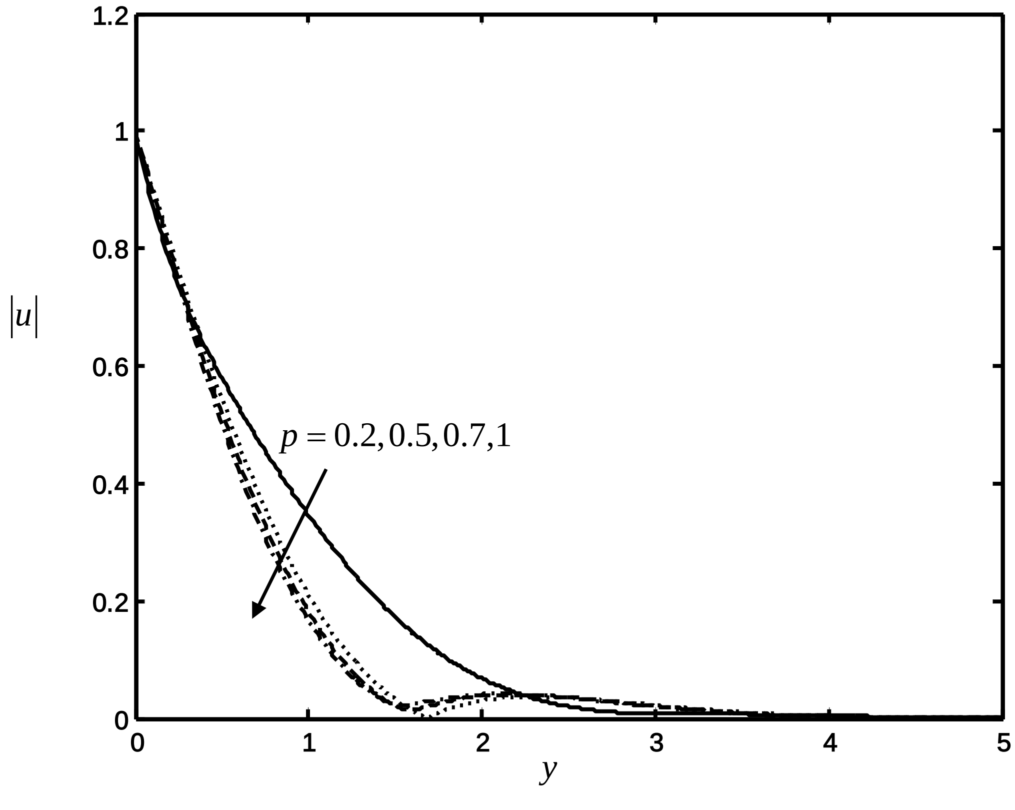

Fig. 10 The variation of velocity $|u|$ with y for different values of p with $\lambda = 0.005$, $R = 0.5$, $\omega = 10$, $Da = 0.1$, $G = 5$, $t = 0.1$ and $H = 1$.

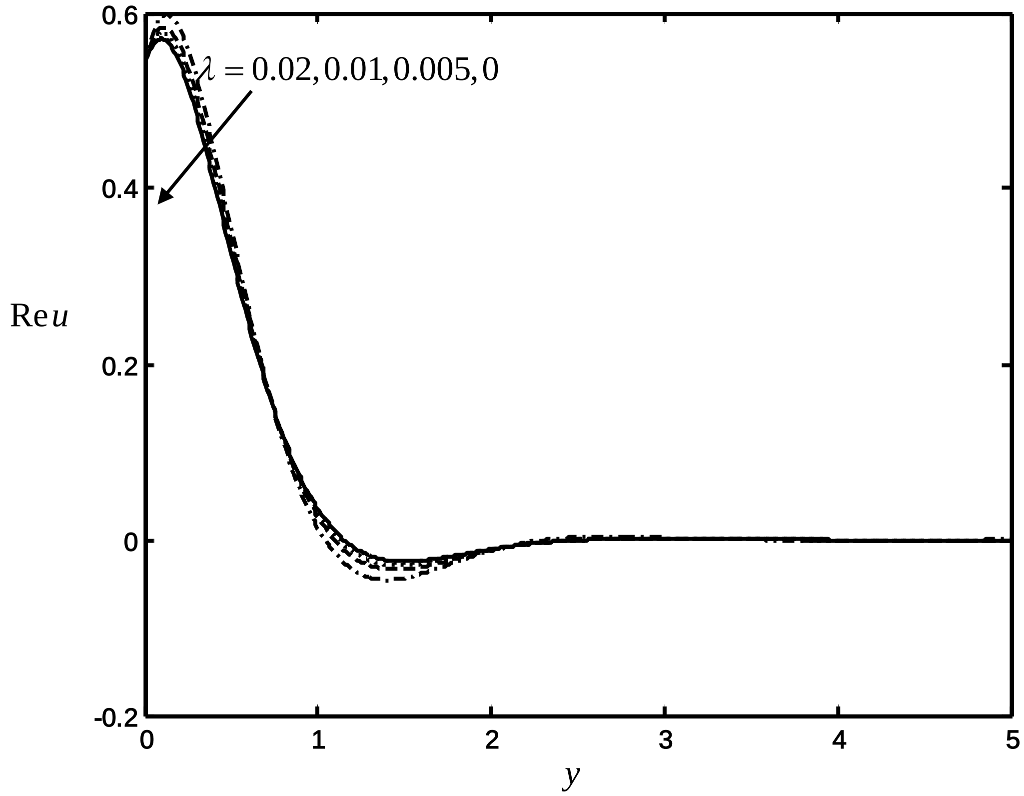

Fig. 11 The variation of velocity Reu with y for different values of λ with $\lambda = 1$, $R = 0.5$, $\omega = 10$, $Da = 0.1, G = 5$, $t = 0.1$ and $M = 1$.

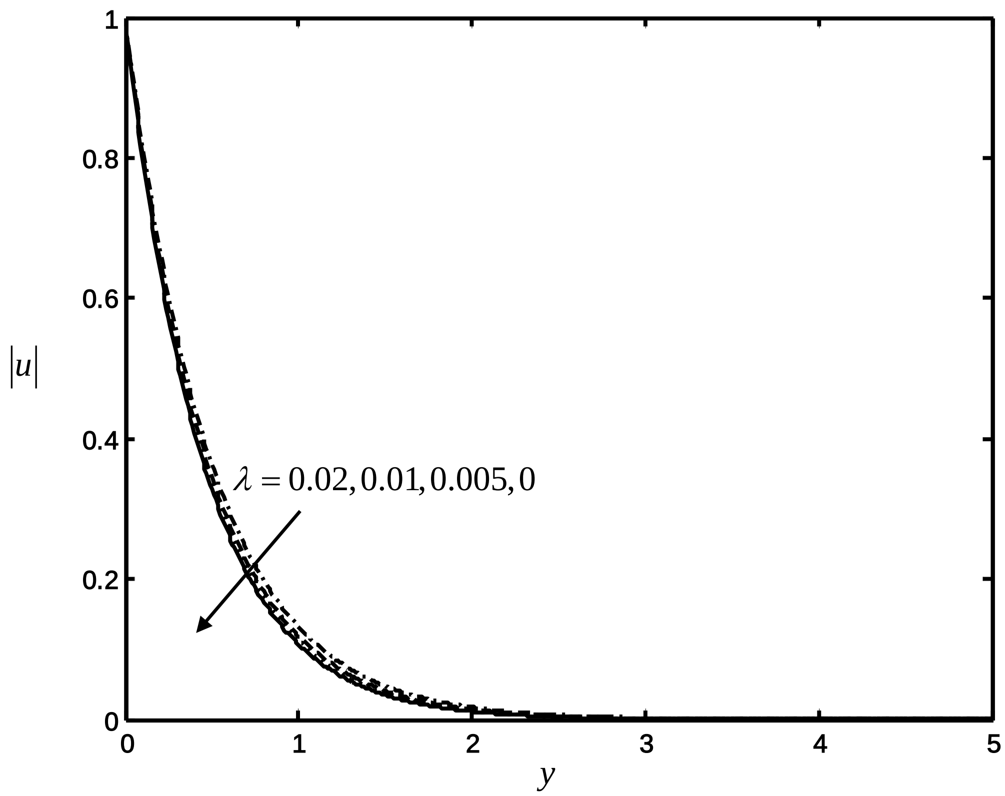

Fig. 12 The variation of velocity $|u|$ with y for different values of λ with $\lambda = 1$, $R = 0.5$, $\omega = 10$, $Da = 0.1, G = 5$, $t = 0.1$ and $M = 1$.

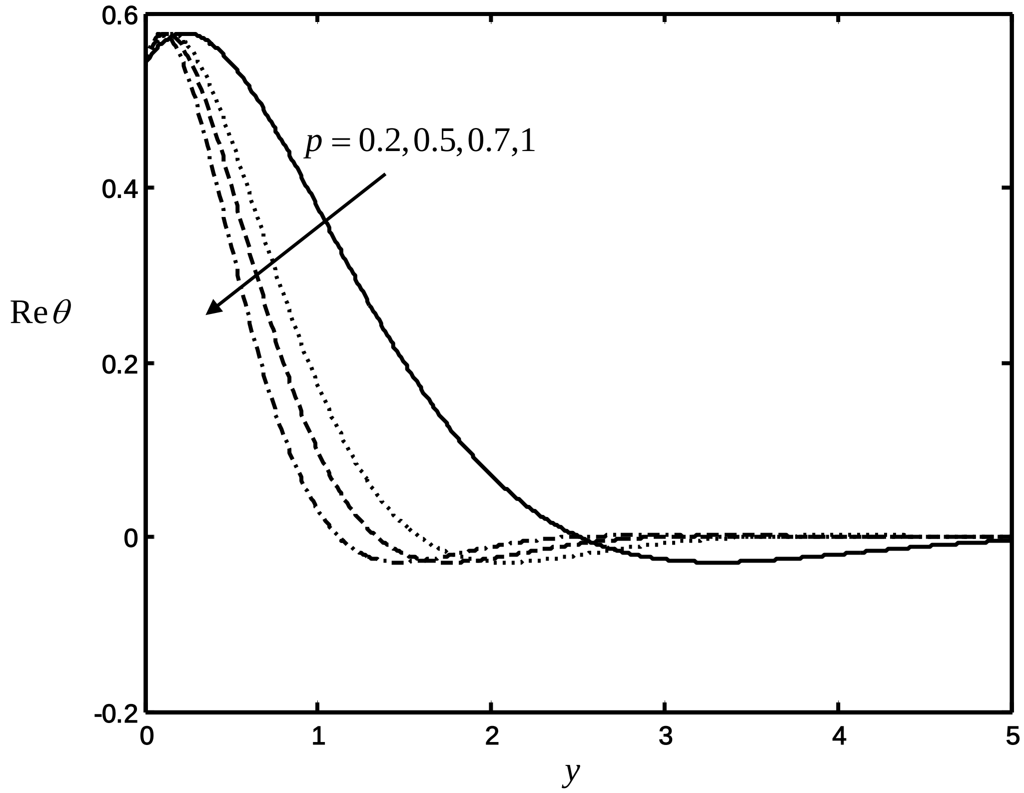

Fig. 13 The variation of temperature $\mathrm{Re}\,\theta$ with y for different values of p with $\lambda = 0.005$ and $\omega = 10$.

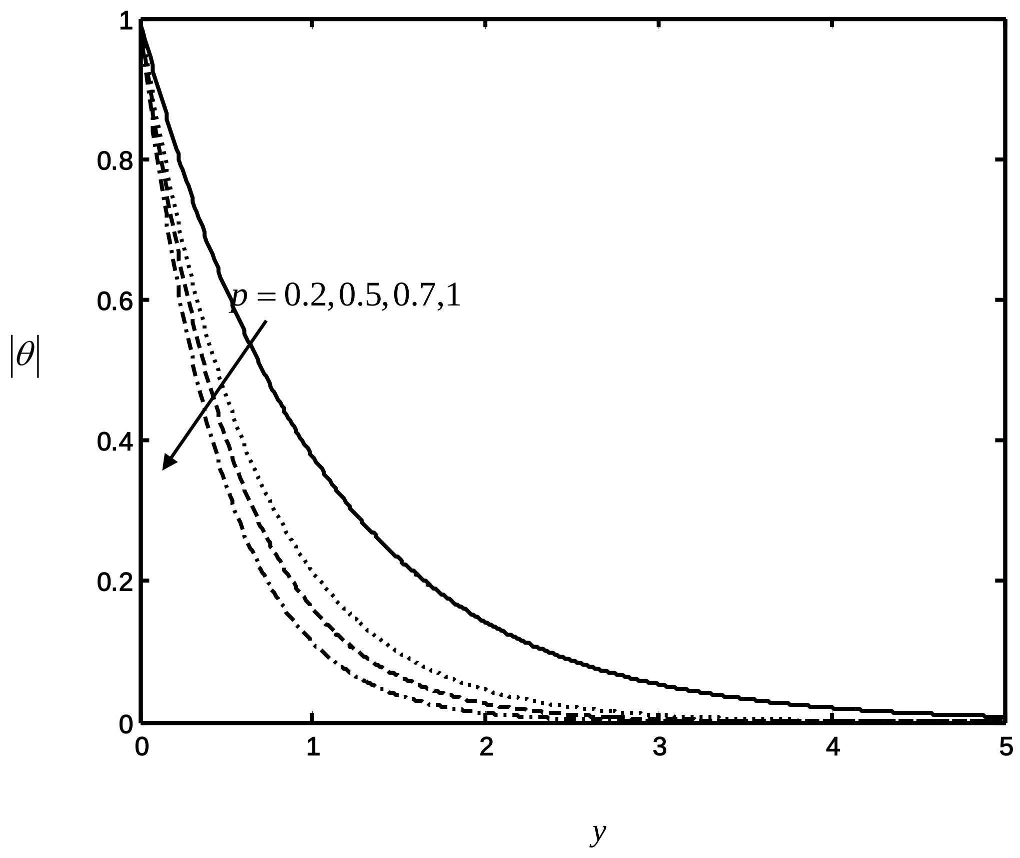

Fig. 14 The variation of temperature $|\theta|$ with y for different values of p with $\lambda = 0.005$ and $\omega = 10$.

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