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# OSCILLATORY FLOW OF A FLUID THROUGH A POROUS MEDIUM IN A POROUS CHANNEL UNDER THE EFFECT OF INCLINED MAGNETIC FIELD

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## ABSTRACT

*In this paper an investigation of unsteady free convective flow of an incompressible viscous electrically conducting fluid through a porous medium under the action of an inclined magnetic field between two heated vertical porous plates. The governing equations of the flow field are solved by a regular perturbation method for small elastic parameter. The expressions for the velocity, temperature, have been derived analytically and also its behaviour is computationally discussed with reference to different flow parameters with the help of graphs. The heat flux in terms of the Nusselt number is also obtained and discussed its behaviour.*

**KEY WORDS**: *MHD, Magnetic field, Porous medium, Perturbation method*

## 1. INTRODUCTION

In recent years, the study of oscillatory flow of an electrically conducting fluid through a porous channel saturated with porous medium is important in many physiological flows and engineering applications such as magneto-hydrodynamic (MHD) generators, arterial blood flow, petroleum engineering and many more. Several researchers have studied the flow and heat transfer in oscillatory fluid problems. Makinde and Mhone [1] (2005) investigated the forced convective MHD oscillatory fluid flow through a channel filled with porous medium. The effect of slip on the free convective oscillatory flow through vertical channel with periodic temperature and dissipative heat was studied by Mehmood and Ali [2] (2007). Chauchan and Kumar [3] (2011) have investigated the steady flow and heat transfer in a composite vertical channel. MHD Poiseuille flow between two infinite parallel porous plates in an inclined magnetic field was analyzed by Manyonge et al.[4] (2012). The unsteady MHD poiseuille flow between two infinite parallel plates in an inclined magnetic field with heat transfer has been studied by Idowu et al [5] (2014). Simon (2014) have studied the effect of heat of transfer on unsteady MHD couette flow between two infinite parallel porous plates with an inclined magnetic field.

In all the above studies, the channel walls are assumed to be impermeable. This assumption is not valid in studying flows such as blood flow in miniature level where digested food particles are diffused into the bloodstream through the wall of the blood capillary. Hence, there have been several studies on the convective heat transfer through porous channel owing to several other important suction/ injection controlled applications. Ajibade and Jha [6] (2010) have investigated the effects of suction and injection on hydrodynamics of oscillatory fluid through parallel plates. Adesanya and Makinde [7] (2012) investigated the effect of radiative heat transfer on the pulsatile couple stress fluid flow with time dependent boundary condition on the heated plate. It is well known that the no-slip condition is not realistic in some flows involving Nanochannel, micro-channel and flows over coated plates with hydrophobic substances. In view of this, Adesanya and Gbadeyan [8] (2010) have studied the flow and heat transfer of steady non-Newtonian fluid flow noting the fluid slip in the porous channel. Recently, the effect on suction/injection on the slip flow of oscillatory hydromagnetic fluid through a channel filled with saturated porous medium was investigated by Falade et al.[9] (2017). Recently Raghunath and Siva Prasad [10] [2018) have investigated Heat and mass transfer on MHD flow of Non-Newtonian fluid over an infinite vertical porous plate. Raghunath and Siva [11] (2018) Prasad Indigested Heat and mass transfer on Unsteady MHD flow of a second grade fluid through porous medium between two vertical plates.

In view of these, we studied the unsteady free convective flow of an incompressible viscous electrically conducting fluid through a porous medium under the action of an inclined magnetic field between two heated vertical porous plates. The governing equations of velocity and temperature fields with appropriate boundary conditions are solved analytically. The effects of various physical parameters on the velocity and temperature fields are discussed in detail with the help of graphs.

## 2. MATHEMATICAL FORMULATION

We consider the free convective unsteady MHD flow of a viscous incompressible electrically conducting fluid between two heated vertical parallel porous plates filled with porous medium. Let $x$ -axis be taken along the vertically upward direction through the central line of the channel and the $y$ -axis is perpendicular to the x-axis. The plates of the channel are kept at $y = \pm h$ distance apart. A uniform magnetic field $B_0$ acts at an angle $\alpha$ $\left(0 \le \alpha \le \frac{\pi}{2}\right)$, to the $y$ -axis $u$ is the velocity in the direction of flow of fluid, along the $x$ -axis and $v$ is the velocity along the $y$ -axis. Consequently, $u$ is a function of $y$ and $t$, but $v$ is independent of $y$ . The fluid is assumed to be of low conductivity, such that the induced magnetic field is negligible. In order to derive the equations of the problem, we assume that the fluid is finitely conducting and the viscous dissipation the Joule heats are neglected. The polarization effect is also neglected.

The equations governing the flow field are given by

$$\frac{\partial u}{\partial t} - v_0 \frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{dp}{dx} + \nu \frac{\partial^2 u}{\partial y^2} - \left(\frac{\nu}{k} + \frac{\sigma B_0^2}{\rho}\cos^2\alpha\right)u + g\beta(T - T_0) \tag{2.1}$$

$$\frac{\partial T}{\partial t} - v_0 \frac{\partial T}{\partial y} = \frac{K}{\rho c_p}\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho c_p}\frac{\partial q}{\partial y} \tag{2.2}$$

here $\rho$ is the density of the fluid, $B_0$ is the magnetic field strength, $\sigma$ is the electrical conductivity of the fluid, $\nu$ is the co-efficient of kinematic viscosity, $k$ is the permeability of the porous medium. $K$ is the thermal conductivity of the fluid, $c_p$ is the specific heat at constant pressure, $\beta$ is the co-efficient of thermal expansion, $g$ is the acceleration due to gravity, $T$ is the temperature of the fluid and $q$ is the radiative heat flux. Following Cogley et al. (1968), it is assumed that the fluid is optically thin with a relatively low density and the radiative heat flux is given by

$$\frac{\partial q}{\partial y} = 4\alpha_1^{\,2}(T_0 - T) \tag{2.3}$$

here $\alpha_1$ is the mean radiation absorption coefficient.

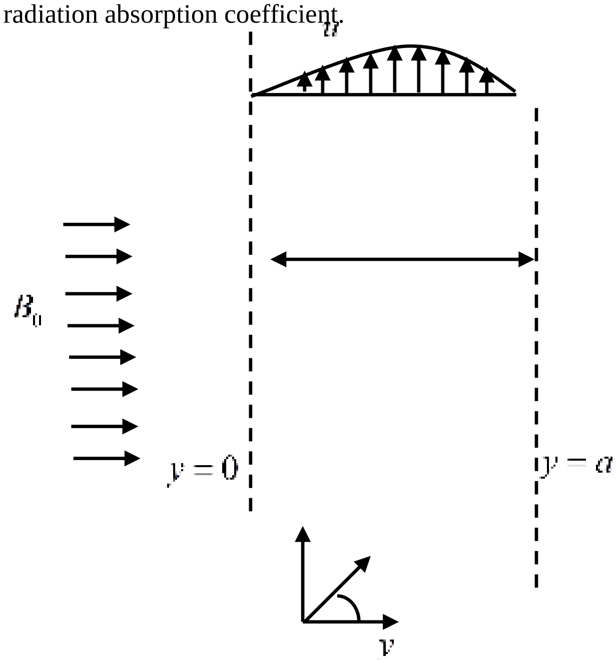


**Fig. 1** The physical model

The boundary conditions for the problem are:

$$u = \frac{\sqrt{k}}{\alpha_s}\frac{\partial u}{\partial y}, T = T_0 \quad \text{at} \quad y = 0$$

$$u = 0, T = T_1 \quad \text{at} \quad y = a \tag{2.4}$$

The non-dimensional variables are

$$\bar{u} = \frac{au}{\nu}, \bar{y} = \frac{y}{a}, \bar{T} = \frac{T - T_0}{T_1 - T_0}, \bar{t} = \frac{\nu t}{a^2}, \mathrm{Pr} = \frac{\mu c_p}{K}, \gamma = \frac{\sqrt{k}}{a\alpha_s}, M = B_0 a\sqrt{\frac{\sigma}{\mu}}$$

$$Da = \frac{k}{a^2}, \; s = \frac{v_o h}{\nu}, \; R = \frac{4\alpha_1^{\,2} h^2}{\mu c_p} \tag{2.5}$$

Using the non-dimensional variables (2.5) in to the equations (2.1) and (2.2), we obtain

$$\frac{\partial u}{\partial t} - s\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} - N^2 u + GrT \tag{2.6}$$

$$\frac{\partial T}{\partial t} - s\frac{\partial T}{\partial y} = \frac{1}{\mathrm{Pr}}\frac{\partial^2 T}{\partial y^2} + RT \tag{2.7}$$

Here $N=\sqrt{\frac{1}{Da}+M^2\cos^2\alpha}$ .

Under the above non-dimensional quantities, the corresponding boundary conditions reduces to

$u=\gamma\frac{\partial u}{\partial y}, T=0$ at $y=0$

$u=0, T=1$ at $y=a$ (2.8)

## 1. SOLUTION OF THE PROBLEM

Following Makinde and Mhone (2005), we assume that an oscillatory pressure gradient, such that solutions of the dimensionless Eqs. (2.6) - (2.8) is in the following form: $-\frac{dp}{dx}=\lambda e^{i\omega t}$ (3.1)

$$u=u_o\left(y\right)e^{i\omega t} \quad (3.2)$$

$$T=T_0\left(y\right)e^{i\omega t} \quad (3.3)$$

Substituting Equations (3.1) - (3.3) into the Equations (2.6) – (2.8) and solving the resultant Equations, we obtain

$$u=\left(c_1e^{m_3y}+c_2e^{m_4y}+b_1+b_2e^{m_1y}+b_3e^{m_2y}\right)e^{i\omega t} \quad (3.4)$$

and

$$T=\left(a_1e^{m_1y}+a_2e^{m_2y}\right)e^{i\omega t} \quad (3.5)$$

Here $m_1=\frac{-s\Pr+\sqrt{\left(s\Pr\right)^2-4\Pr\left(R-i\omega\right)}}{2}$ , $m_2=\frac{-s\Pr-\sqrt{\left(s\Pr\right)^2-4\Pr\left(R-i\omega\right)}}{2}$,

$m_3=\frac{-s+\sqrt{s^2+4\left(M^2\cos^2\alpha+\frac{1}{Da}+i\omega\right)}}{2}$ , $m_4=\frac{-s-\sqrt{s^2+4\left(M^2\cos^2\alpha+\frac{1}{Da}+i\omega\right)}}{2}$,

$a_1=\frac{1}{e^{m_1}-e^{m_2}}$ , $a_2=\frac{1}{e^{m_2}-e^{m_1}}$, $b_1=\frac{\lambda}{M^2\cos^2\alpha+\frac{1}{Da}+i\omega}$ ,

$b_2=\frac{-a_1Gr}{m_1^2+sm_1-\left(M^2\cos^2\alpha+\frac{1}{Da}+i\omega\right)}$ , $b_3=\frac{-a_2Gr}{m_2^2+sm_2-\left(M^2\cos^2\alpha+\frac{1}{Da}+i\omega\right)}$ ,

$d_1=b_1+b_2+b_3$ , $d_2=\gamma\left(m_1b_2+m_2b_3\right)$, $d_3=b_1+b_2e^{m_1}+b_3e^{m_2}$,

$c_1=\frac{c_2\left(m_4\gamma-1\right)+d_2-d_1}{1-m_3\gamma}$ and $c_2=-\frac{m\left(d_3+\frac{(d_2-d_1)e^{m_3}}{1-m_3\gamma}\right)}{\left(e^{m_4}+\frac{(m_4\gamma-1)}{1-m_3\gamma}\right)}$ .

The rate of heat transfer coefficient in terms of Nusselt number $Nu$ at the plate $y=1$ of the channel is given by

$$Nu = \left.\frac{\partial \theta}{\partial y}\right|_{y=0} = (m_1 a_1 + m_2 a_2) e^{i\omega t} \tag{3.6}$$

As $\alpha \to 0$ our results coincides with the results of Falade et al. (2017).

## 2. RESULTS AND DISCUSSIONS

Fig. 2 depicts the variation of velocity $u$ with inclination angle $\alpha$ for $\Pr=1$, $M=1$, $Da=1$, $s=1$, $\alpha=\frac{\pi}{6}$, $Gr=1$, $\lambda=1, \omega=\pi$, $\gamma=0.1$, $R=1$ and $t=0$. It is found that, the velocity $u$ increases with an increase in the inclination angle $\alpha$. The variation of velocity $u$ with Hartmann number $M$ for $\Pr=1$, $Da=1$, $s=1$, $\alpha=\frac{\pi}{6}$, $Gr=1$, $\lambda=1, \omega=\pi$, $\gamma=0.1$, $R=1$ and $t=0$ is shown in Fig. 3. It is observed that an increase in the Hartmann number $M$ decreases the velocity $u$. Further it is observed that, the maximum fluid velocity occurs in the absence of magnetic field. Fig. 4 shows the variation of velocity $u$ with Darcy number $Da$ for $\Pr=1$, $M=1$, $s=1$, $\alpha=\frac{\pi}{6}$, $Gr=1$, $\lambda=1$, $\omega=\pi$, $\gamma=0.1$, $R=1$ and $t=0$. It is noted that, as the permeability of the medium increases there is increase in the fluid velocity since obstacles placed on the flow path reduce as $Da$ increases allowing for free flow thus increasing the velocity $u$ .The variation of velocity $u$ with Navier slip parameter $\gamma$ for $\Pr=1$, $M=1$, $Da=1$, $s=1$, $\alpha=\frac{\pi}{6}$, $Gr=1, \lambda=1$, $\omega=\pi$, $R=1$ and $t=0$ is depicted in Fig. 5. It is found that, as the Navier slip parameter increases at the cold wall, there is a resultant rise in the velocity $u$ at the cold wall itself.

Fig. 6 illustrates the variation of velocity $u$ with pressure gradient parameter $\lambda$ for $\Pr=1$, $M=1$, $Da=1$, $s=1$, $\gamma=0.1$, $\alpha=\frac{\pi}{6}$, $Gr=1$, $\omega=\pi$, $R=1$ and $t=0$. It is observed that, the velocity $u$ increases with increasing $\lambda$. The variation of velocity $u$ with $Gr$ for $\Pr=1$, $M=1$, $Da=1$, $s=1$, $\gamma=0.1$, $\alpha=\frac{\pi}{6}$, $\lambda=1$, $\omega=\pi$, $R=1$ and $t=0$ is presented in Fig. 7. It is noted that, the velocity $u$ increases with an increase in Gr.Fig. 8 shows the variation of velocity $u$ with Prandtl number $\Pr$ for $M=1$, $Da=1$, $s=1$, $\alpha=\frac{\pi}{6}$, $Gr=1$, $\omega=\pi$, $\gamma=0.1$, $R=1$ and $t=0$. It is found that, the velocity $u$ decreases with increasing $\Pr$ .The variation of velocity $u$ with radiation parameter $R$ for $M=1$, $Da=1$, $s=1$, $\alpha=\frac{\pi}{6}$, $Gr=1$, $\omega=\pi$, $\gamma=0.1$, $R=1$ and $t=0$ is shown in Fig. 9. It is noticed that, an increase in the thermal radiation parameter $R$ increases the velocity $u$ owing to internal heat generation that enhances the fluid flow. Fig. 10 depicts the variation of velocity $u$ with oscillating parameter $\omega$ for $M=1$,

$Da=1$, $s=1$, $\alpha=\frac{\pi}{6}$, $Gr=1$, $\gamma=0.1$, $R=1$ and $t=0$. It is found that, the velocity $u$ decreases with an increase in $\Pr$. The variation of velocity $u$ with the suction/injection parameter $s$ for $M=1$, $Da=1$, $\omega=\pi$, $\alpha=\frac{\pi}{6}$, $Gr=1$, $\lambda=1$, $\gamma=0.1$, $R=1$ and $t=0$ is depicted in Fig. 11. It is observed that, the result shows that as the suction/ injection parameter $s$ increases there is an increase in the fluid velocity $u$ towards the cold wall, whereas as the suction/ injection parameter $s$ increases there is decrease in the fluid velocity towards the heated wall. Fig. 12 illustrates the variation of temperature $T$ with the radiation parameter $R$ for $\Pr=1, s=1, \omega=\pi$ and $t=0$. It is found that, as the radiation increases there is an increase in the fluid temperature $T$. The variation of temperature $T$ with suction/ injection parameter $s$ for $\Pr=1, R=1, \omega=\pi$ and $t=0$ is shown in Fig. 13. It is noticed that, as injection increases on the heated plate, fluid temperature increases within the channel and the linearity observed at $s=0$ has given way to concave distribution. The concavity with increase in the suction/injection parameter is as a result of the direction of heat flow from the heated plate towards the cold plate. Fig. 14 shows the variation of temperature $T$ with the Prandtl number $\Pr$ for $R=1, s=1, \omega=\pi$ and $t=0$. It is noted that, the temperature $T$ increases with increasing $\Pr$. The variation of temperature $T$ with the frequency of oscillation $\omega$ for $R=1, s=1, \Pr=1$ and $t=0$ is shown in Fig. 15. It is found that, an increase in the frequency of oscillation $\omega$ decreases the fluid temperature $T$ within the channel. Table-1 shows the effects of $\Pr$, $s$, $R$ and $\omega$ on Nusselt number $Nu$ for $t=0$. It is found that, the $Nu$ increases with increasing $\Pr$, $s$ and $R$, where as it decreases with increasing $\omega$.

## 5. CONCLUSIONS

In this chapter, we studied the unsteady free convective flow of an incompressible viscous electrically conducting fluid through a porous medium under the action of an inclined magnetic field between two heated vertical porous plates. The governing equations of velocity and temperature fields with appropriate boundary conditions are solved analytically. The expressions for velocity and temperature are obtained by using analytic method. It is found that the velocity increases with increasing $\alpha, Da, \gamma, \lambda, Gr, R$ and $s$, while it decreases with increasing $M, \Pr$ and $\omega$; the temperature increases with increasing $R, s$ and $\Pr$ where as it decreases with increasing $\omega$. Also it is found that, the $Nu$ increases with increasing $\Pr$, $s$ and $R$, where as it decreases with increasing $\omega$.

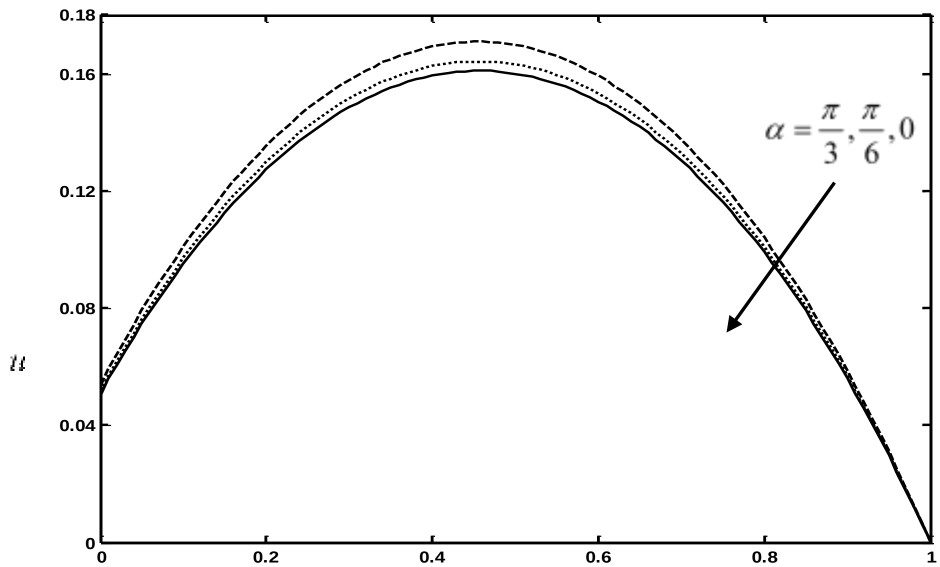


**Fig. 2** The variation of velocity $u$ with inclination angle $\alpha$ for $\Pr = 1$, $M = 1$, $Da = 1$, $s = 1$, $\alpha = \frac{\pi}{6}$, $Gr = 1$, $\lambda = 1$, $\omega = \pi$, $\gamma = 0.1$, $R = 1$ and $t = 0$.

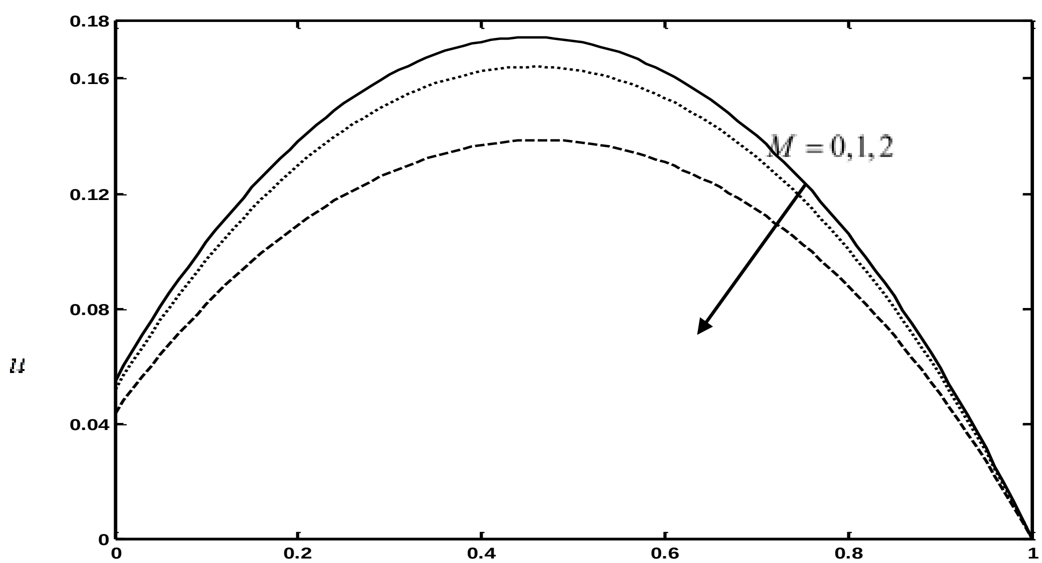


**Fig. 3** The variation of velocity $u$ with Hartmann number $M$ for $\Pr = 1$, $Da = 1$, $s = 1$, $\alpha = \frac{\pi}{6}$, $Gr = 1$, $\lambda = 1$, $\omega = \pi$, $\gamma = 0.1$, $R = 1$ and $t = 0$

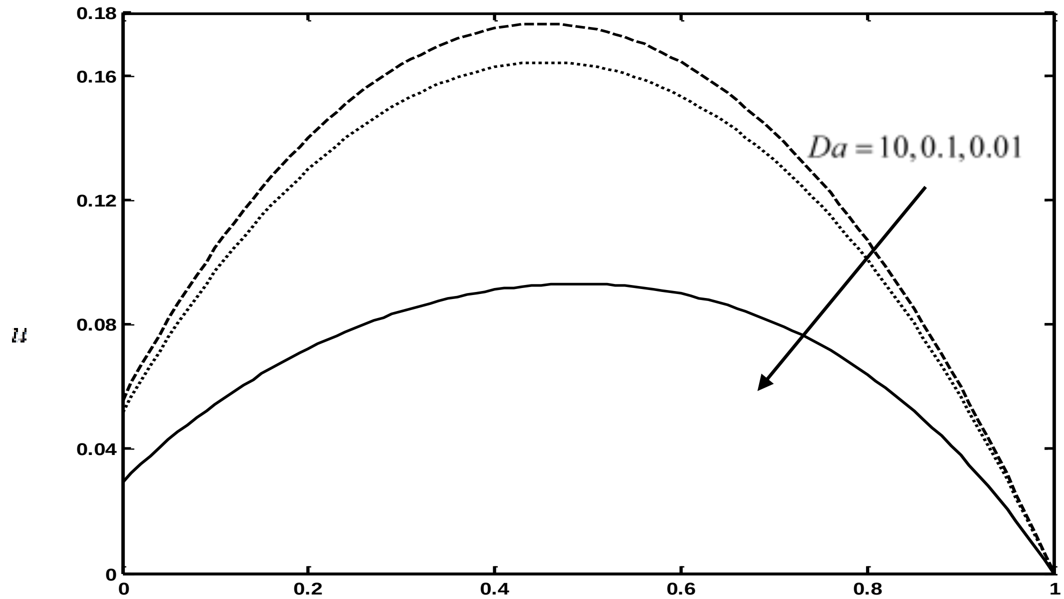


**Fig. 4** The variation of velocity $u$ with Darcy number $Da$ for $\Pr = 1$, $M = 1$, $s = 1$, $\alpha = \frac{\pi}{6}$, $Gr = 1$, $\lambda = 1$, $\omega = \pi$, $\gamma = 0.1$, $R = 1$ and $t = 0$.

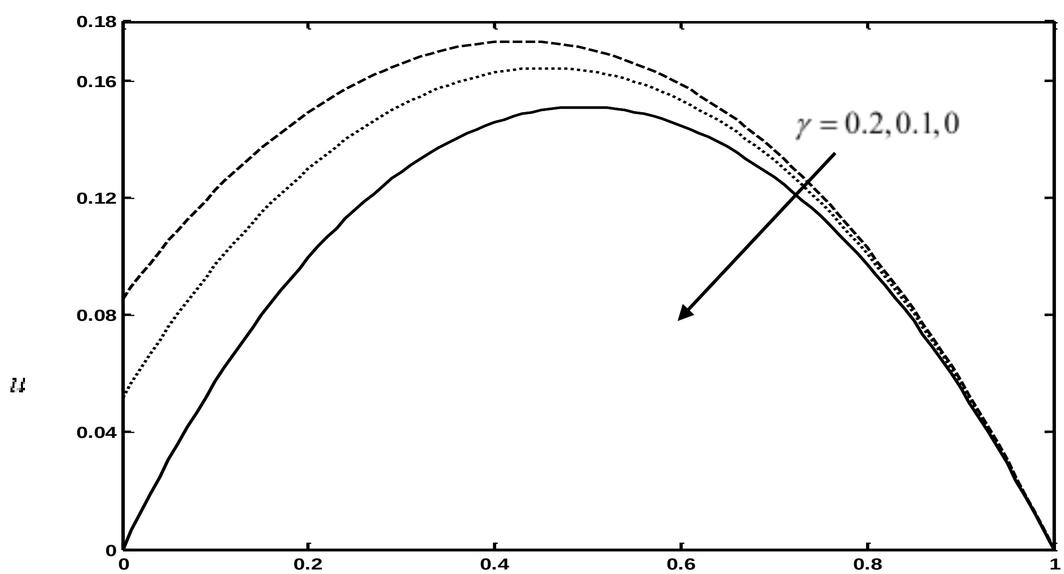


**Fig. 5** The variation of velocity $u$ with $\gamma$ for $\Pr = 1$, $M = 1$, $Da = 1$, $s = 1$, $\alpha = \frac{\pi}{6}$, $Gr = 1$, $\lambda = 1$, $\omega = \pi$, $R = 1$ and $t = 0$

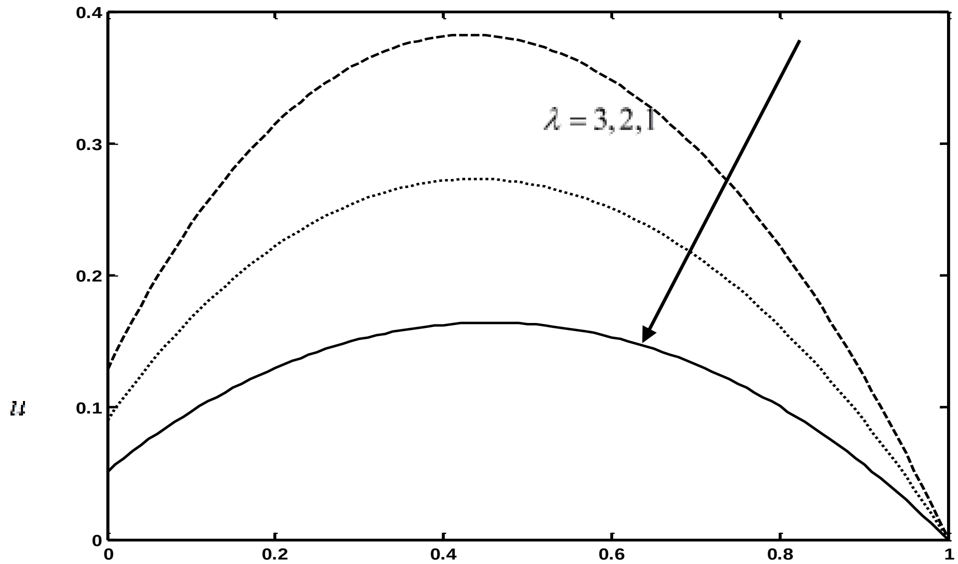


**Fig. 6** The variation of velocity $u$ with λ for $\Pr = 1,\ M = 1,\ Da = 1,\ s = 1,\ \gamma = 0.1,$

$$\alpha = \frac{\pi}{6},\ Gr = 1,\ \omega = \pi,\ R = 1 \text{ and } t = 0.$$

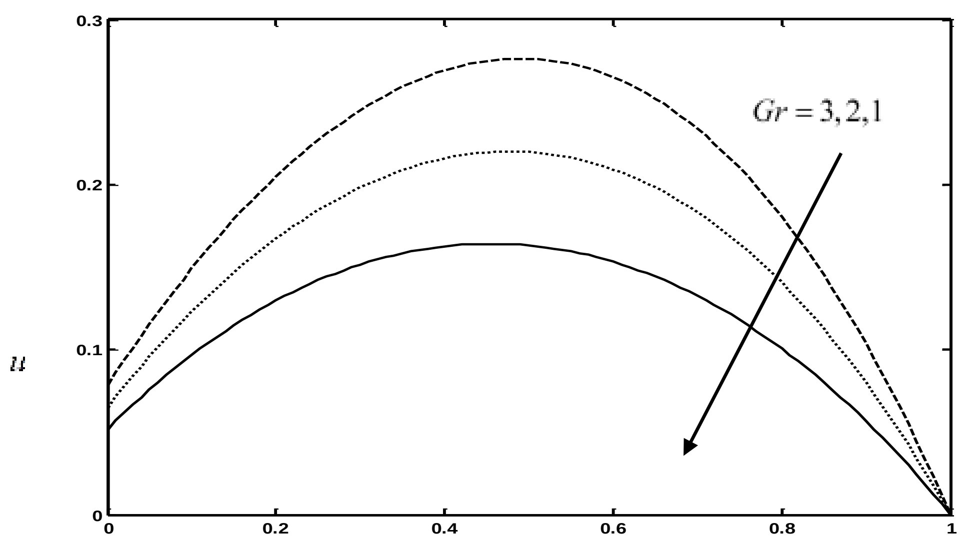


**Fig. 7** The variation of velocity $u$ with $Gr$ for $\Pr = 1,\ M = 1,\ Da = 1,\ s = 1,\ \gamma = 0.1,$

$$\alpha = \frac{\pi}{6},\ \lambda = 1,\ \omega = \pi,\ R = 1 \text{ and } t = 0$$

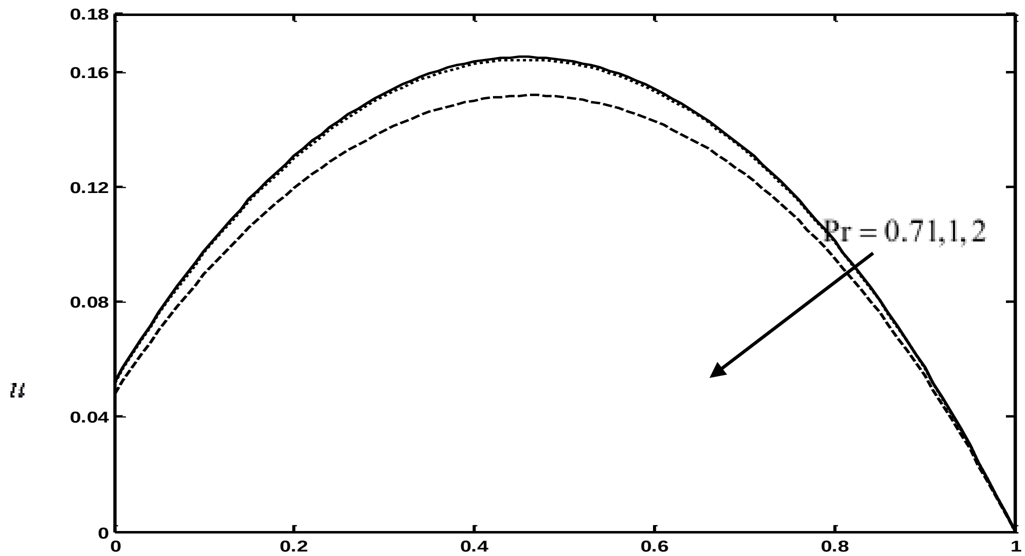


**Fig. 8** The variation of velocity $u$ with Prandtl number $\Pr$ for $M=1,\ Da=1,$

$s=1,\ \alpha=\dfrac{\pi}{6},\ Gr=1,\ \lambda=1,\ \omega=\pi,\ \gamma=0.1,\ R=1$ and $t=0$.

$y$

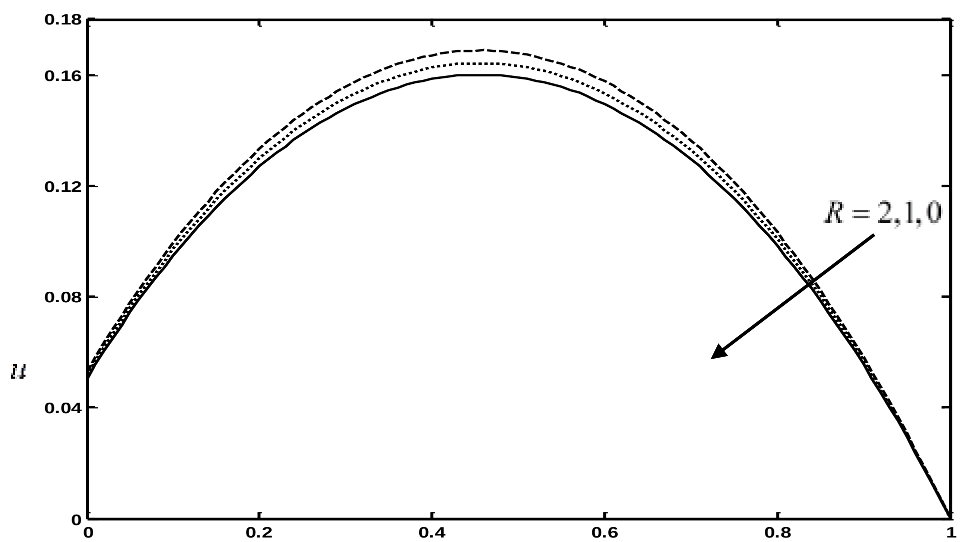


**Fig. 9** The variation of velocity $u$ with radiation parameter $R$ for $M=1,\ Da=1,$

$s=1,\ \alpha=\dfrac{\pi}{6},\ Gr=1,\ \omega=\pi,\ \lambda=1\ ,\gamma=0.1,\ R=1$ and $t=0$

$y$

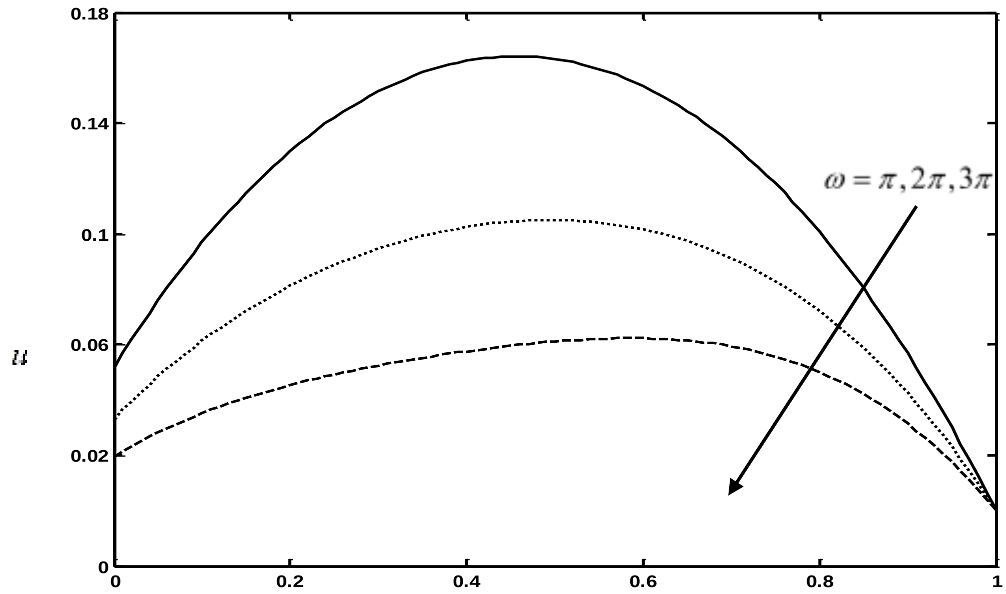


**Fig. 10** The variation of velocity $u$ with oscillating parameter ω for $M = 1,\ Da = 1,$

$s = 1,\ \alpha = \frac{\pi}{6},\ Gr = 1,\ \lambda = 1,\ \gamma = 0.1,\ R = 1$ and $t = 0$.

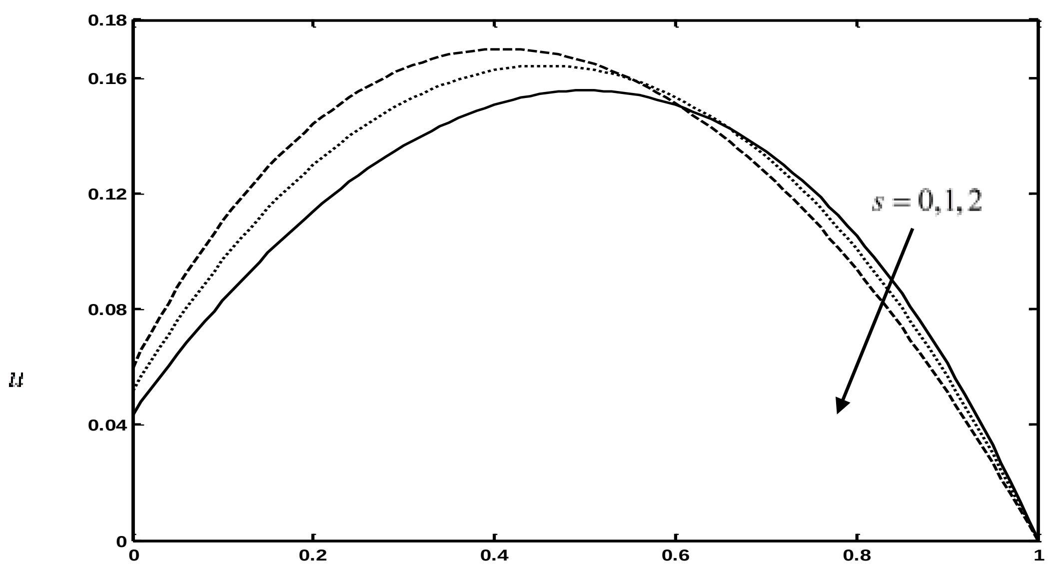


**Fig. 11** The variation of velocity $u$ with suction/injection parameter $s$ for $M = 1,\ Da = 1,$

$\omega = \pi,\ \alpha = \frac{\pi}{6},\ Gr = 1,\ \lambda = 1,\ \gamma = 0.1,\ R = 1$ and $t = 0$.

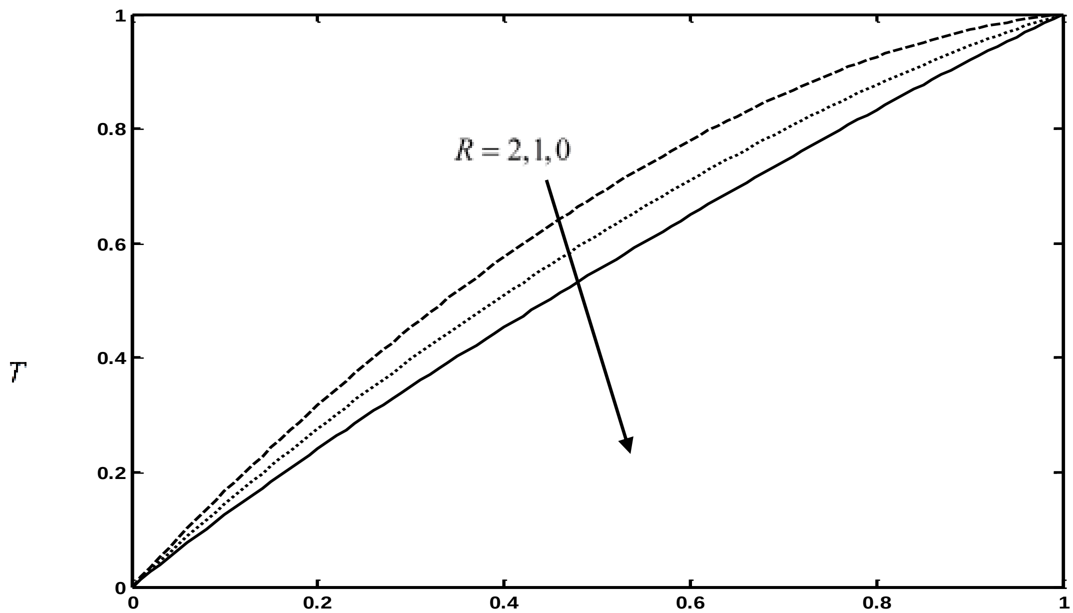


**Fig. 12** The variation of temperature $T$ with $R$ for $\Pr = 1, s = 1, \omega = \pi$ and $t = 0$.

$y$

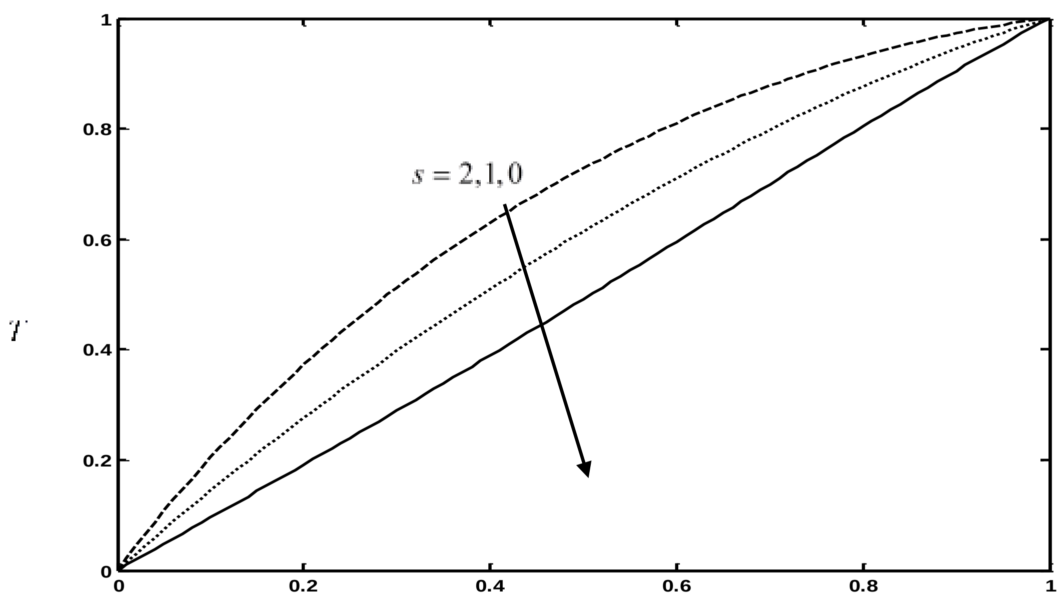


**Fig. 13** The variation of temperature $T$ with $s$ for $\Pr = 1, R = 1, \omega = \pi$ and $t = 0$.

$y$

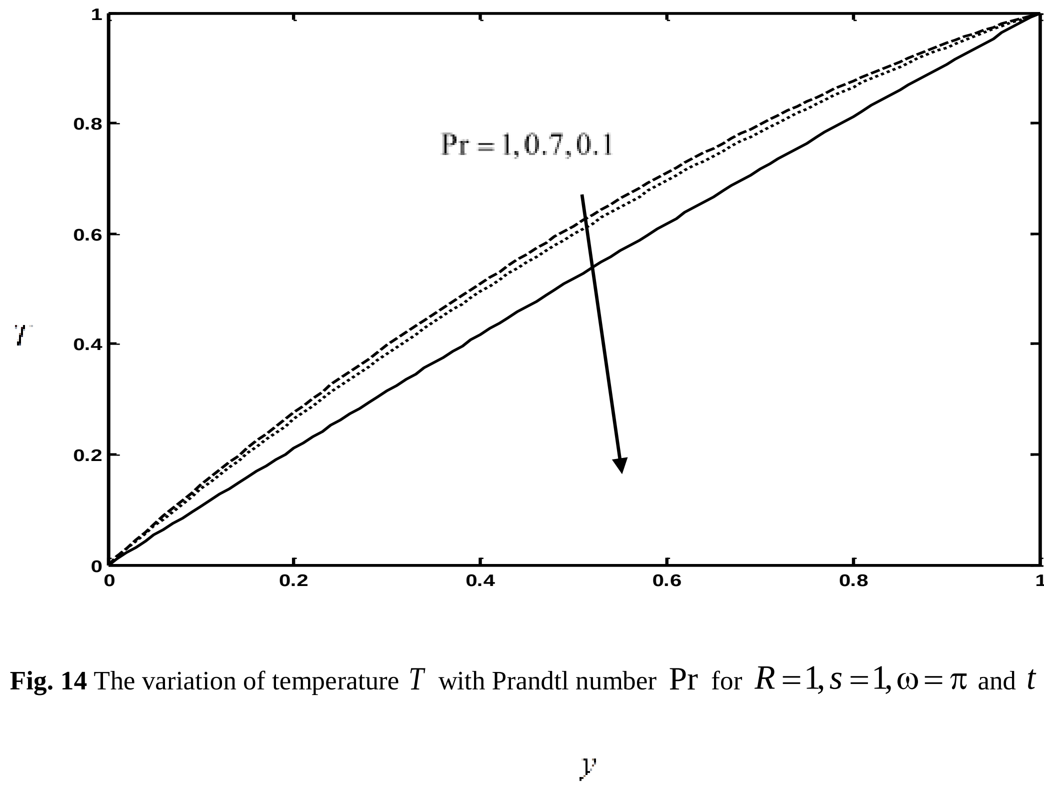


**Fig. 14** The variation of temperature $T$ with Prandtl number $\Pr$ for $R=1, s=1, \omega=\pi$ and $t=0$.

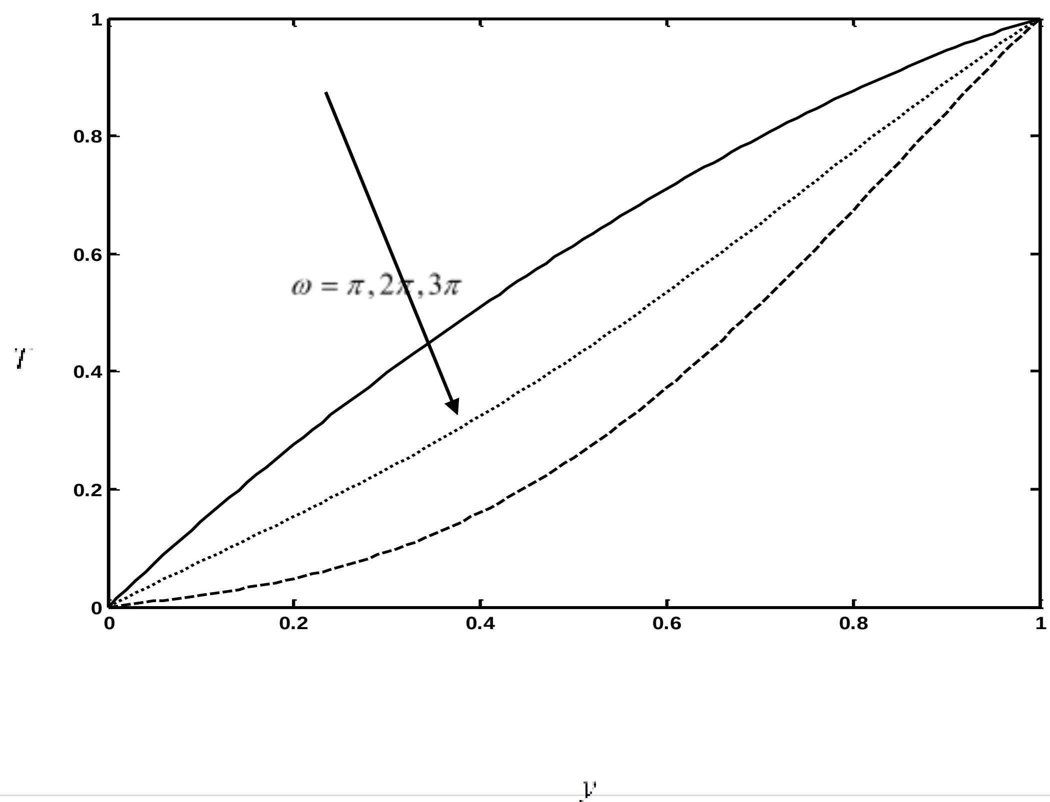

**Fig. 15** The variation of temperature $T$ with oscillating parameter $\omega$ for $R=1, s=1, \Pr=1$ and $t=0$.

**Table-1:** Effects of $\Pr$, $s$, $R$ and $\omega$ on Nusselt number $Nu$ for $t=0.$

| $\Pr$ | s | R | $\omega$ | $Nu$ |
|---|---|---|---|---|
| **0.7** | **1** | **1** | $\pi$ | **1.4134** |
| **1** | **1** | **1** | $\pi$ | **1.5145** |
| **1** | **2** | **1** | $\pi$ | **2.2471** |
| **1** | **1** | **2** | $\pi$ | **1.7483** |
| **1** | **1** | **1** | $2\pi$ | **0.7989** |

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