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Research Article

Heat Transfer Analysis for Viscous Fluid Flow with the Newtonian Heating and Effect of Magnetic Force in a Rotating Regime

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In this article, an unsteady free convection flow of MHD viscous fluid over a vertical rotating plate with Newtonian heating and heat generation is analyzed. The dimensionless governing equations for temperature and velocity fields are solved using the Laplace transform technique. Analytical solutions are obtained for the temperature and components of velocity fields. The obtained solutions satisfy the initial and boundary conditions. Some physical aspects of flow parameters on the fluid motion are presented graphically.

1. Introduction

Free convection flow of Newtonian and non-Newtonian fluids has many applicable usages in processing industry and heat transfer processes. A number of such investigations have been contributed by many researchers of the respective subject. Uddin et al. [1] discussed the free convection flow of fluid over the moving plate. Mahapart et al. [2] considered the effect of magnetic field over the natural convection flow past a horizonal plate. Babaelahi et al. [3] established analytical results for mixed convection flow. Farhad et al. [4] considered MHD rotating flow by imposing slip condition and Hall current through a porous medium. Jana et al. [5] analyzed flow of viscous fluid through a porous medium in a rotating system. Mohammad et al. [6] investigated the results for flow of nanofluid over rotating plates. Hussain et al. [7] discussed heat and mass transfers at the boundary of flow domain for free convection flow of viscous fluid. Islam et al. [8] discussed free convection flow with variable properties in steady-state situation. Alam et al. [9] analyzed the free convection flow by considering Joule heating and heat generation. Mohamed et al. [10] discussed the unsteady free convection flow of second-grade fluid in rotating frame with ramped wall temperature. Krishna and Reddy [11] considered the chemical reaction and Hall current effect for the free convection flow and established analytical results for concentration, temperature, and velocity fields.

Rotational flow is an essential aspect in several physical flow phenomena and has useful applications in many fields of engineering. Raghunath et al. [12] investigated the free convection flow over the rotating surface. Sharma et al. [13] discussed the effect of chemical reaction and magnetic field on the rotating fluid flow. Vasu et al. [14] explained heat and mass transfer flow by imposing the constant thermal and chemical conditions on boundary. Muthucumarasway et al. [15] discussed the free convection flow of fluid with isothermal conditions. Some other studies regarding rotating fluid flow with heat and mass transfers flow are presented in [16–19]. In the present article, it is assumed that heat transfer from the surface is proportional to the local surface temperature; formally this concept is known as Newtonian heating and was intimated by Merkin [20]. Some more investigations regarding Newtonian heating are found in [21–26].

Our focal intension of present study is to construct a flow model of rotating viscous fluid over a moving flat plate in the presence of magnetic field with the effect of heat generation subject to Newtonian heating. The prescribed rotating flow model is described by the set of partial differential equations as the governing equations. The nondimensional governing equations are solved by the Laplace transform method, and transformed explicit expressions for temperature and velocity components are established. Moreover, the influence of parameters of interest is highlighted in the graphical form. Heat transfer at boundary is quantified in terms of Nusselt number and presented in the tabular form.

2. Mathematical Formulation of Problem

Consider an incompressible viscous fluid lying near the vertical rotating plate. The plate is situated in the xy-plane and z-axis is normal to the plane of plate. Initially, plate and fluid both are at rest with the constant temperature T_∞. A magnetic field of constant magnitude β_0 is applied normally to the xy-plane as shown in Figure 1. And the fluid and the plate rotate with a constant angular velocity $\Omega\hat{k}$ about z-axis taken normal to the plate. Initially, the plate and the fluid are at rest with constant temperature. After passing some time, plate starts to move with time depending on velocity and temperature is raised directly proportional to the temperature at the wall. Heat transfer takes place from plate to fluid according to the Newtonian heating. Under the usual Boussinesq approximation, the governing equations of flow model take the following form [19]:

$$\frac{\partial u(z,t)}{\partial t} - 2\Omega v(z,t) = g\beta_T(T - T_\infty) + \nu\frac{\partial^2 u(z,t)}{\partial z^2} - \frac{\sigma\beta_0^2 u(z,t)}{\rho}, \tag{1}$$

$$\frac{\partial v(z,t)}{\partial t} + 2\Omega u(z,t) = \nu\frac{\partial^2 v(z,t)}{\partial z^2} - \frac{\sigma\beta_0^2 v(z,t)}{\rho}, \tag{2}$$

$$\frac{\partial T(z,t)}{\partial t} = \frac{k}{\rho c_p}\frac{\partial^2 T(z,t)}{\partial z^2} + Q_0(T - T_\infty), \tag{3}$$

with suitable initial and boundary conditions

$$\begin{gathered} u(z,0) = 0, v(z,0) = 0, T(z,0) = T_\infty, \quad z \ge 0, \\ u(0,t) = U_0 f(t), v(0,t) = 0, \left.\frac{\partial T(z,t)}{\partial z}\right|_{z=0} = -\frac{h}{k}T(0,t), \\ u(\infty,t) = 0, v(\infty,t) = 0, T(\infty,t) = T_\infty, \quad t > 0, \end{gathered} \tag{4}$$

where Ω is the angular velocity of the fluid, ν is the kinematic viscosity, $u(z,t)$ is the velocity component along x-axis and $v(z,t)$ is the velocity component along y-axis, ρ is the density of the fluid, T is the temperature of the fluid, β is the coefficient of volume expansion, g is the gravitational acceleration, T_∞ is the temperature at infinity, Q_0 is the heat generation parameter, k is the thermal conductivity, β_0 is the external magnetic field, and σ is the current density.

Now, introducing the following nondimensional variables and parameters:

$$\begin{aligned} u &= U_0 u^\bullet, \\ v &= U_0 v^\bullet, \\ t^\bullet &= \frac{tU_0^2}{\nu}, \\ T^\bullet &= \frac{T - T_\infty}{T_\infty}, \\ z^\bullet &= \frac{zU_0}{\nu}, \end{aligned} \tag{5}$$

into equations (1)–(4) after dropping dot notation, we obtain the following dimensionless model:

$$\frac{\partial u(z,t)}{\partial t} - 2\mathrm{Ek}v(z,t) = \mathrm{Gr}T + \frac{\partial^2 u(z,t)}{\partial z^2} - \mathrm{M}u(z,t), \tag{6}$$

$$\frac{\partial v(z,t)}{\partial t} + 2\mathrm{Ek}u(z,t) = \frac{\partial^2 v(z,t)}{\partial z^2} - Mv, \tag{7}$$

$$\frac{\partial T(z,t)}{\partial t} = \frac{1}{\mathrm{Pr}}\frac{\partial^2 T(z,t)}{\partial z^2} - QT(z,t), \tag{8}$$

with nondimensional initial and boundary conditions

$$\begin{gathered} u(z,0) = 0, v(z,0) = 0, T(z,0) = 0, \quad z \ge 0, \\ u(0,t) = f(t), v(0,t) = 0, \left.\frac{\partial T(z,t)}{\partial z}\right|_{z=0} = -\mathrm{hs}(T(0,t) + 1), \\ u(\infty,t) = 0, v(\infty,t) = 0, T(\infty,t) = 0, \end{gathered} \tag{9}$$

where

$$\begin{aligned} \mathrm{Ek} &= \frac{\nu\Omega}{U_0^2}, \\ \mathrm{Pr} &= \frac{C_p\mu}{k}, \\ \mathrm{Q} &= \frac{\nu Q_0}{U_0^2}, \\ M &= \frac{\beta_0^2\sigma\nu}{\rho U_0^2}, \\ \mathrm{Gr} &= \frac{\nu g\beta_T T_\infty}{U_0^3}, \\ \mathrm{hs} &= \frac{\nu h}{U_0 k}, \end{aligned} \tag{10}$$

are Ekman number, Prandtl number, heat absorption parameter, magnetic field parameter, Grashof number, and Newtonian heating parameter, respectively.

Introduce the complex velocity field $F(z,t) = u + \imath v$, where the function $F(z,t)$ is the solution of the following problem:

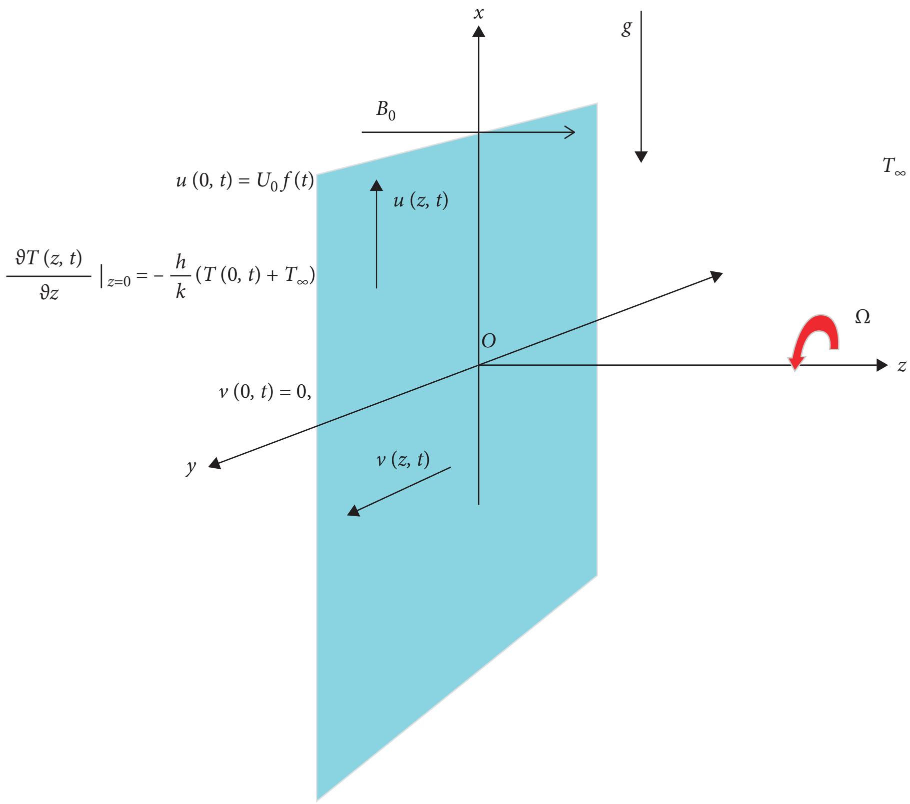


FIGURE 1: Coordinate system and flow geometry.

$$\frac{\partial F(z,t)}{\partial t} + 2\mathrm{Ek}F(z,t) = \frac{\partial^2 F(z,t)}{\partial z^2} - MF(z,t) + \mathrm{Gr}T(z,t), \tag{11}$$

$$F(z,0) = 0, F(0,t) = f(t), F(\infty,t) = 0. \tag{12}$$

3. Solution of Problem

We solve the dimensionless model of equations (6)–(12) by Laplace transform.

3.1. Calculation of Temperature. Applying Laplace transform to equation (8) and keeping in mind the conditions of equation (9), we get

$$\frac{\partial^2 \overline{T}(z,q)}{\partial z^2} + \mathrm{Pr}Q\overline{T}(z,q) - \mathrm{Pr}q\overline{T}(z,q) = 0. \tag{13}$$

Equation (13) satisfies the following transformed conditions:

$$\frac{\partial \overline{T}(z,q)}{\partial z}\Big|_{z=0} = -\mathrm{hs}\left[\overline{T}(0,q) + \frac{1}{q}\right], \quad \overline{T}(\infty,q) = 0. \tag{14}$$

Solution of equation (13) subject to the boundary conditions (14) is obtained as follows:

$$\overline{T}(z,q) = \frac{\mathrm{hs}}{q\left(\sqrt{\mathrm{Pr}(q-Q)} - \mathrm{hs}\right)} e^{-z\sqrt{\mathrm{Pr}(q-Q)}}. \tag{15}$$

In order to invert the Laplace transform, equation (15) can be written in suitable form as

$$\overline{T}(z,q) = \frac{\mathrm{hs}}{\sqrt{\mathrm{Pr}}} \frac{1}{(q-Q)\left(\sqrt{(q-Q)} - (\mathrm{hs}/\mathrm{Pr})\right)} e^{-z\sqrt{\mathrm{Pr}}\sqrt{(q-Q)}} - Q\frac{1}{q}\frac{\mathrm{hs}}{\sqrt{\mathrm{Pr}}} \frac{1}{(q-Q)\left(\sqrt{(q-Q)} - (\mathrm{hs}/\mathrm{Pr})\right)} e^{-z\sqrt{\mathrm{Pr}}\sqrt{(q-Q)}}. \tag{16}$$

Applying the inverse Laplace transform to equation (16), we obtain the following velocity in t-domain:

$$T(z,t) = \mathrm{erfc}\left(\frac{z\sqrt{\mathrm{Pr}}}{2\sqrt{t}}\right)e^{Q} - \mathrm{erfc}\left(\frac{\mathrm{hs}}{\sqrt{\mathrm{Pr}}}\sqrt{t} + \frac{z\sqrt{\mathrm{Pr}}}{2\sqrt{t}}\right)e^{-z\mathrm{hs}+\left(\left((\mathrm{hs})^2 t\right)/\mathrm{Pr}\right)+Qt} - Q\int_0^t \left[\mathrm{erfc}\left(\frac{z\sqrt{\mathrm{Pr}}}{2\sqrt{\tau}}\right)e^{Q} - \mathrm{erfc}\left(\frac{\mathrm{hs}}{\sqrt{\mathrm{Pr}}}\sqrt{\tau} + \frac{z\sqrt{\mathrm{Pr}}}{2\sqrt{\tau}}\right)e^{-z\mathrm{hs}+\left(\left((\mathrm{hs})^2 t\right)/\mathrm{Pr}\right)+Q\tau}\right]d\tau. \tag{17}$$

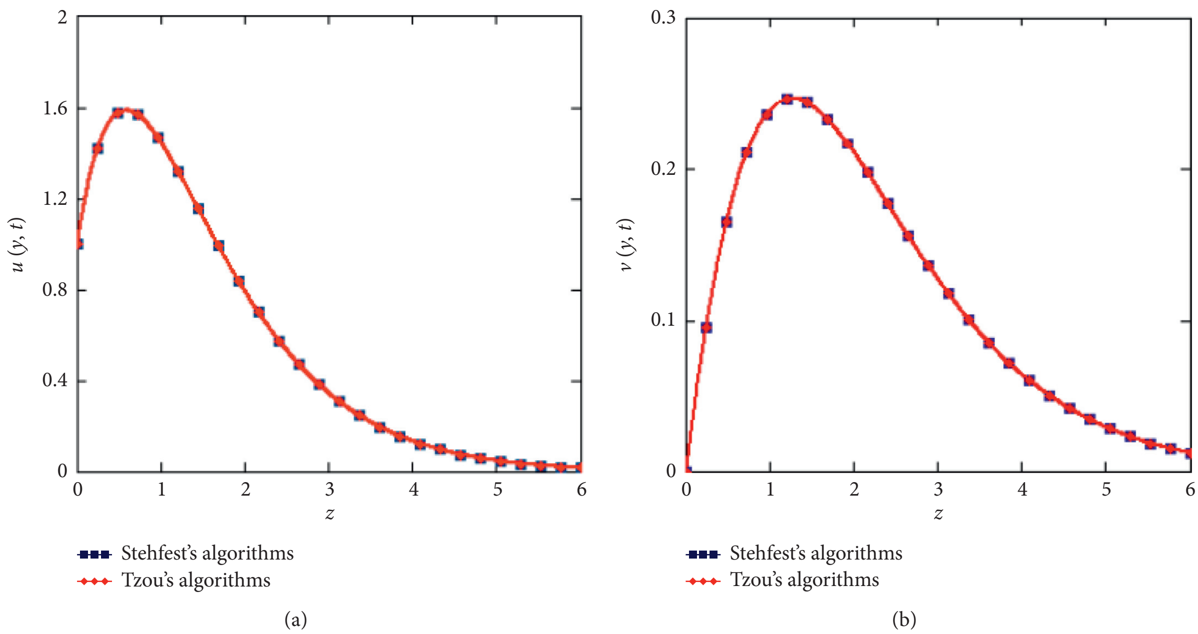


FIGURE 2: Inversion of real and imaginary components of velocity.

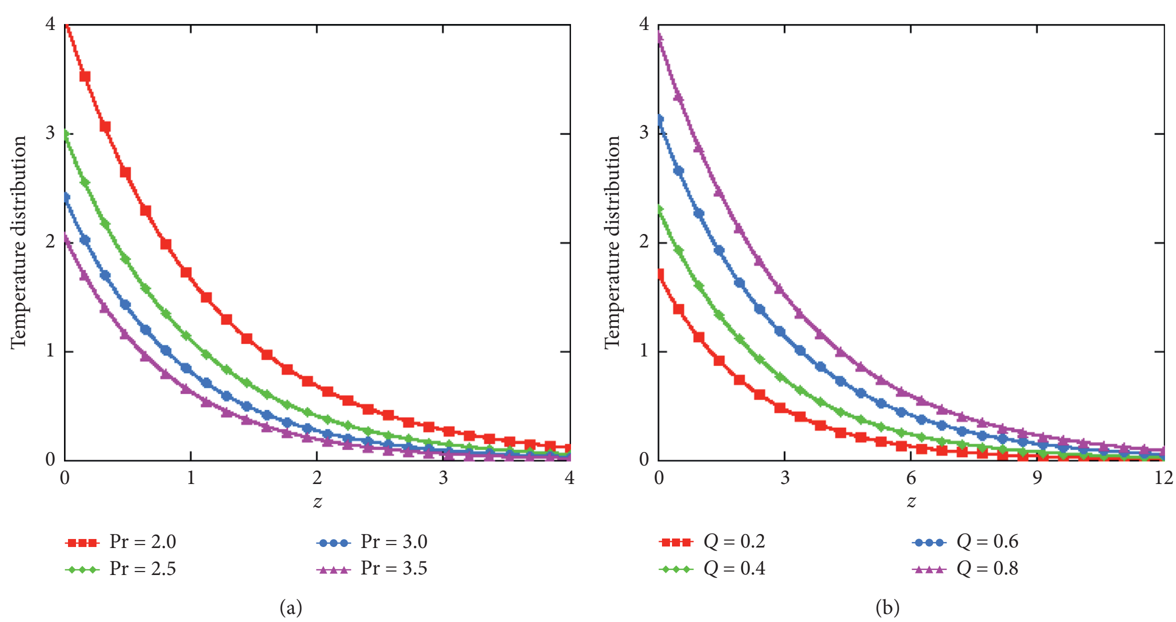


FIGURE 3: Temperature profiles versus z subject to variation of Pr and Q.

3.2. Nusselt Number. The local coefficient of the rate of heat transfer is defined in terms of Nusselt number and defined by the following relation:

$$\mathrm{Nu} = \left.\frac{\partial T(z,t)}{\partial z}\right|_{y=0} = -\frac{\partial}{\partial y} L^{-1}\left[\overline{T}(y,q)\right] = -L^{-1}\left[\frac{\partial \overline{T}(y,q)}{\partial y}\right],$$

$$\mathrm{Nu} = -\frac{\mathrm{hs}\sqrt{\Pr(q-Q)}}{q\left(\sqrt{\Pr(q-Q)} - \mathrm{hs}\right)}. \tag{18}$$

3.3. Velocity Calculation. Applying Laplace transform to equation (11) and keeping in mind the condition of equation (12), we get

$$\frac{\partial^2 \overline{F}(z,q)}{\partial z^2} - (q + M - 2l\mathrm{Ek})\overline{F}(z,q) = -\mathrm{Gr}\, T(z,q). \tag{19}$$

Equation (19) satisfies the following transformed conditions:

$$\overline{F}(0,q) = f(q), \overline{F}(\infty,q) = 0. \tag{20}$$

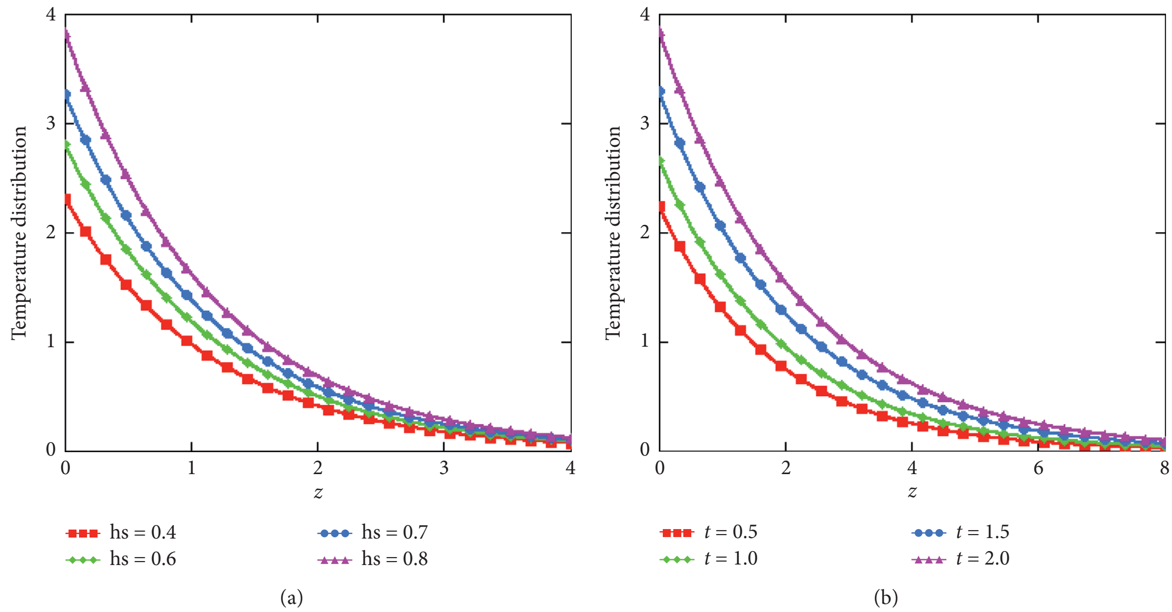


FIGURE 4: Temperature profiles versus z subject to variation of hs and t.

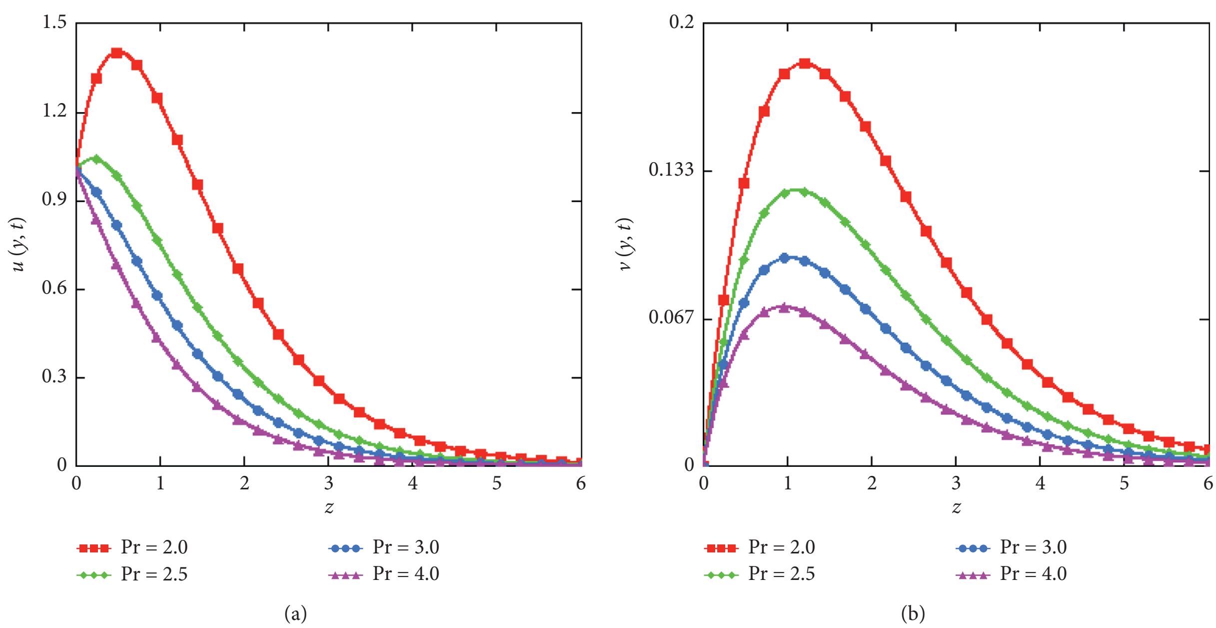
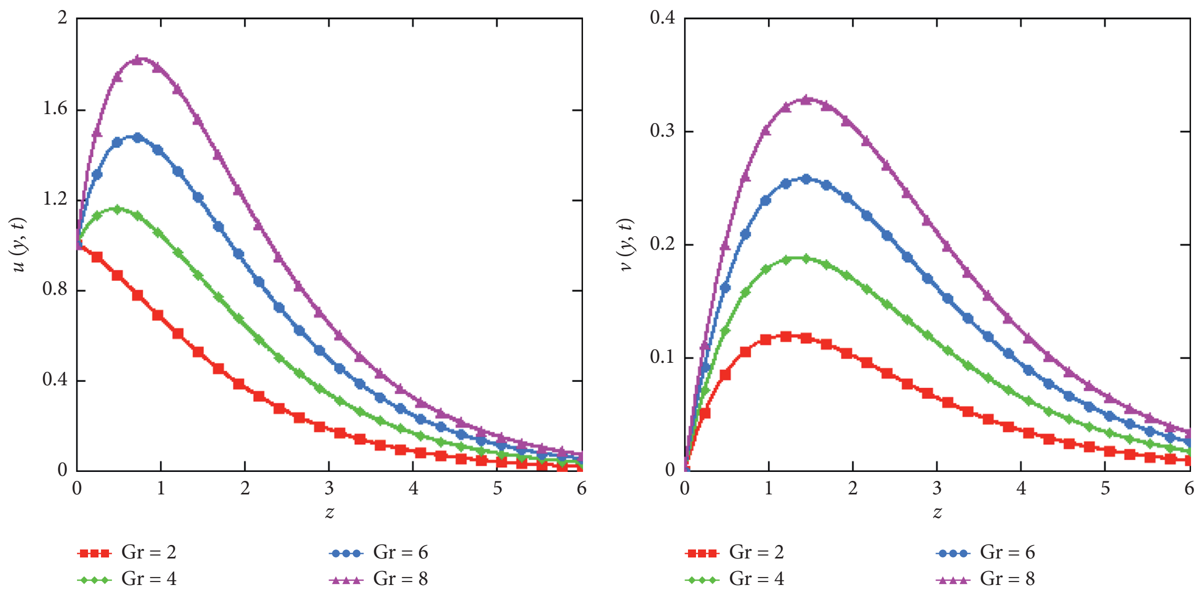


FIGURE 5: Velocity profiles versus z subject to variation of Pr.

Solution of equation (19) subject to transformed conditions (20) is

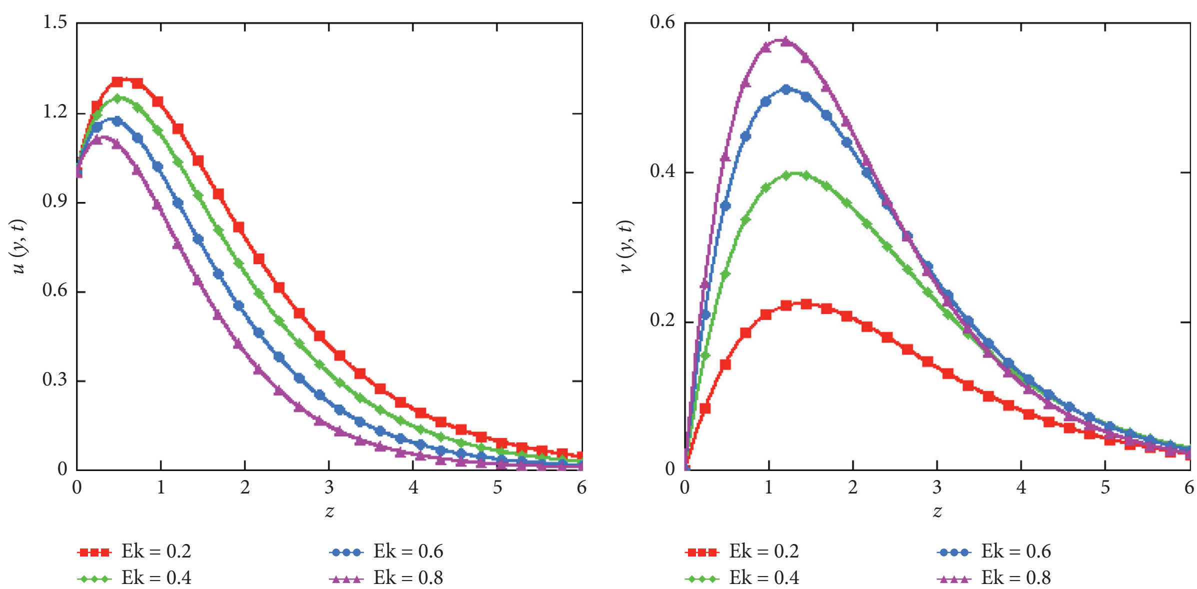
$$\overline{F}(z,q) = f(q)e^{-z\sqrt{q+M-2l\mathrm{Ek}}} + \frac{\mathrm{hsGr}\left(e^{-z\sqrt{q+M-2l\mathrm{Ek}}} - e^{-z\sqrt{\Pr(q-Q)}}\right)}{(\Pr-1)\left(q-\left((\Pr Q+M-2l\mathrm{Ek})/(\Pr-1)\right)\right)\left(\sqrt{\Pr(q-Q)}-\mathrm{hs}\right)(q)}. \tag{21}$$



(a)

(b)

FIGURE 6: Velocity profiles versus z subject to variation of Gr.



(a)

(b)

FIGURE 7: Velocity profiles versus z subject to variation of Ek.

Real and imaginary parts are follows:

$$u(z,q) = f(q)e^{-zl}\cos zm + \frac{z_1 z_3 + z_2 z_4}{z_3^2 + z_4^2}, \tag{22}$$

$$v(z,q) = -f(q)e^{-zl}\cos zm + \frac{z_2 z_3 - z_1 z_4}{z_3^2 + z_4^2}, \tag{23}$$

where

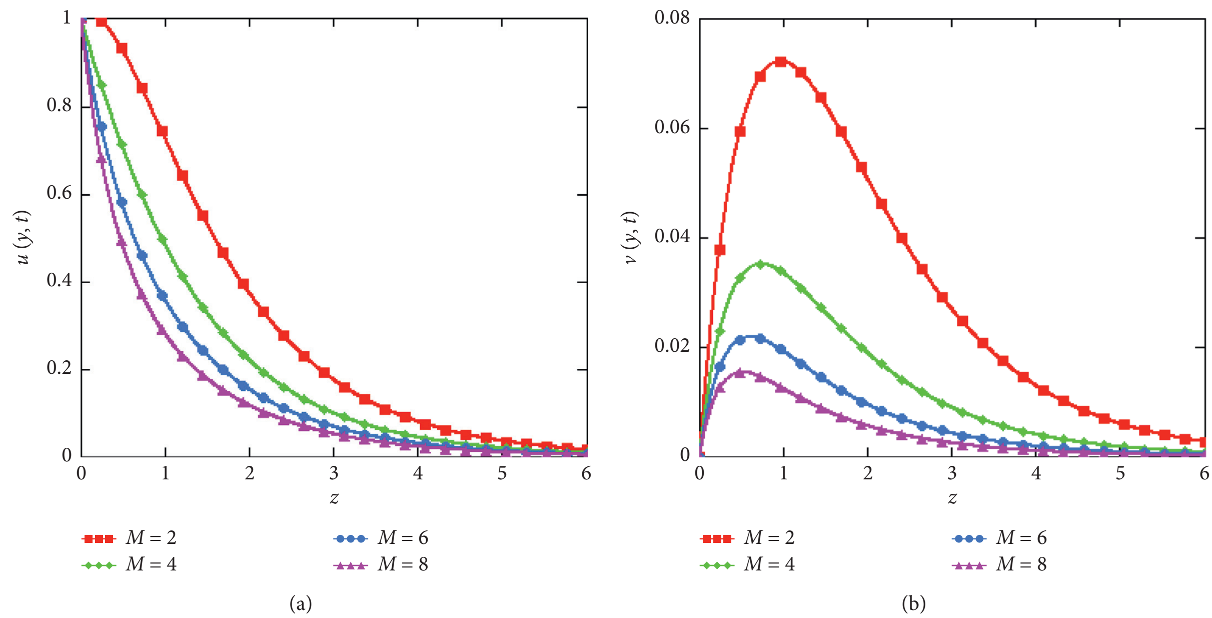


FIGURE 8: Velocity profiles versus z subject to variation of M.

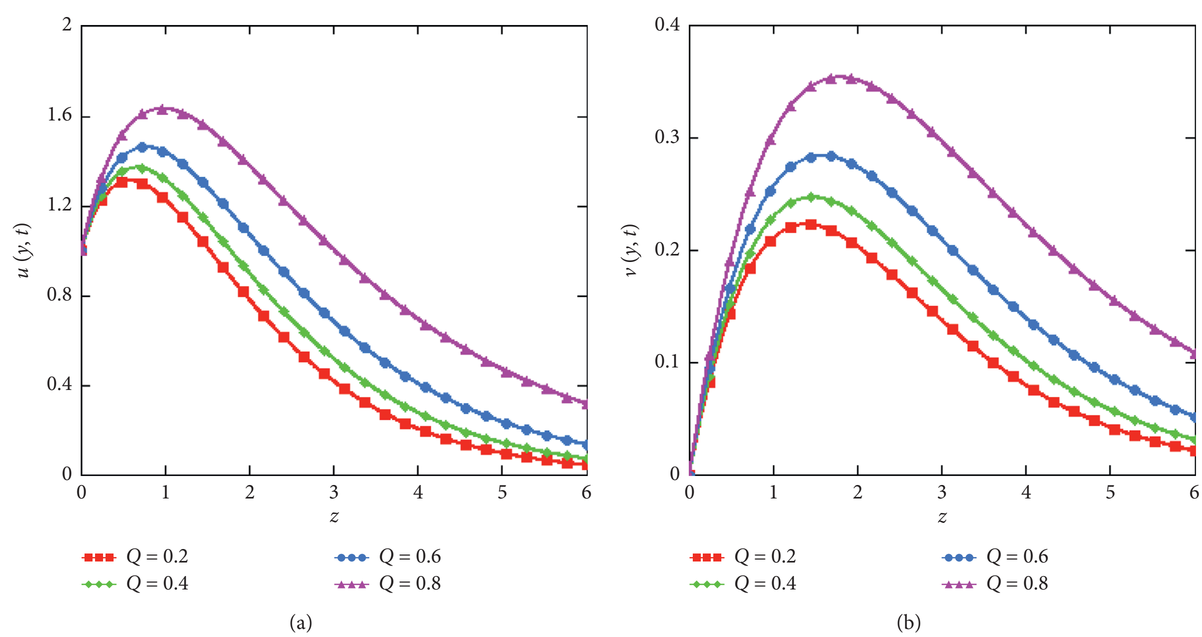


FIGURE 9: Velocity profiles versus z subject to variation of Q.

$$l = \pm\sqrt{\frac{(q+m) \pm \sqrt{(q+m)^2 + 4\mathrm{Ek}^2}}{2}}, m = \pm\frac{\sqrt{2}\mathrm{Ek}}{\sqrt{(q+m) \pm \sqrt{(q+m)^2 + 4\mathrm{Ek}^2}}}, z_1 = e^{-zl}\cos zm - e^{-z\sqrt{\mathrm{Pr}(q-Q)}}, \quad (24)$$

$$z_2 = -\mathrm{hsGr}(\sin zm)e^{-zl}, z_3 = (\mathrm{Pr}(q-Q) - q - M)\left(\sqrt{\mathrm{Pr}(q-Q)} - \mathrm{hs}\right)(q), z_4 = 2\mathrm{Ek}\left(\sqrt{\mathrm{Pr}(q-Q)} - \mathrm{hs}\right)(q).$$

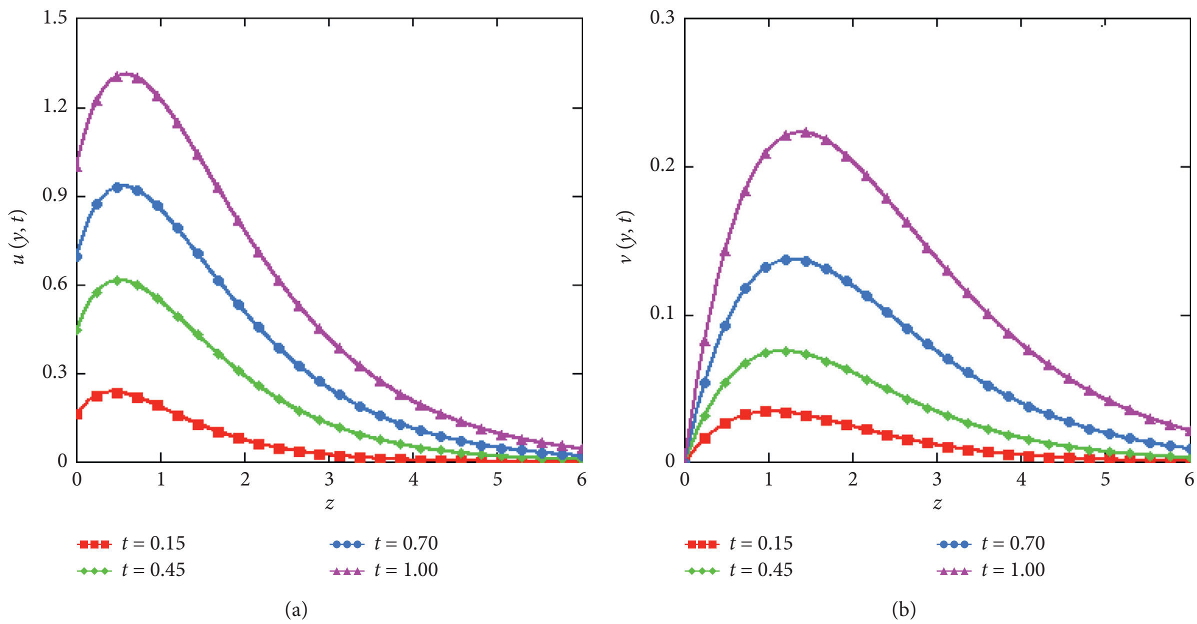


FIGURE 10: Velocity profiles versus z subject to variation of t.

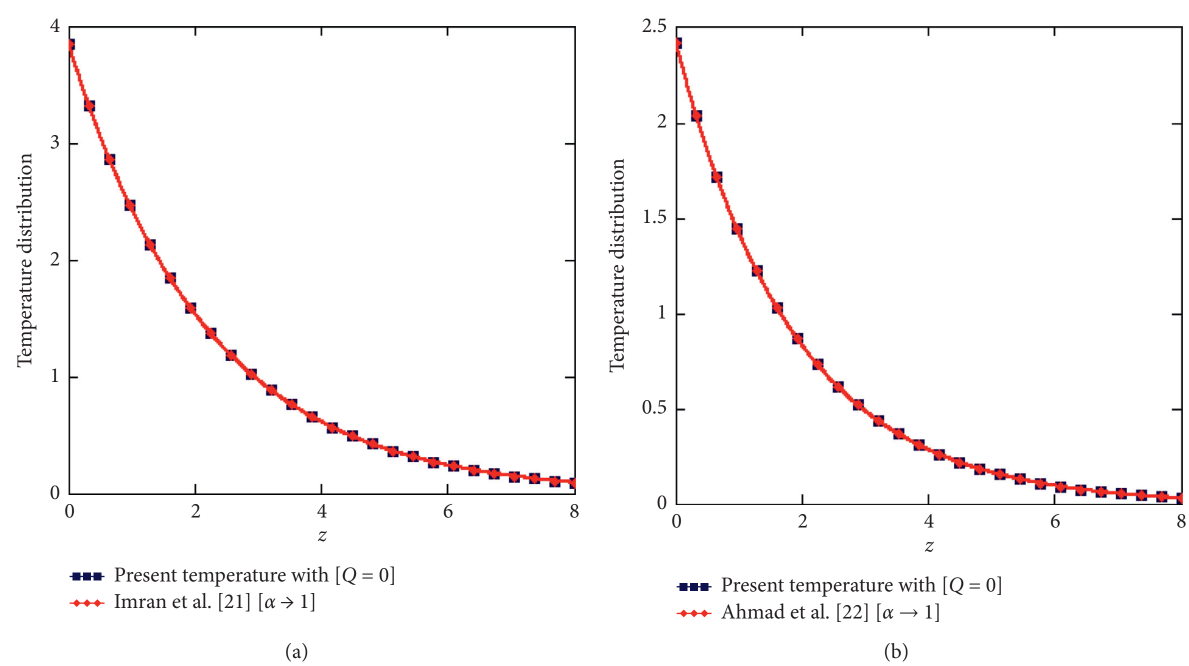
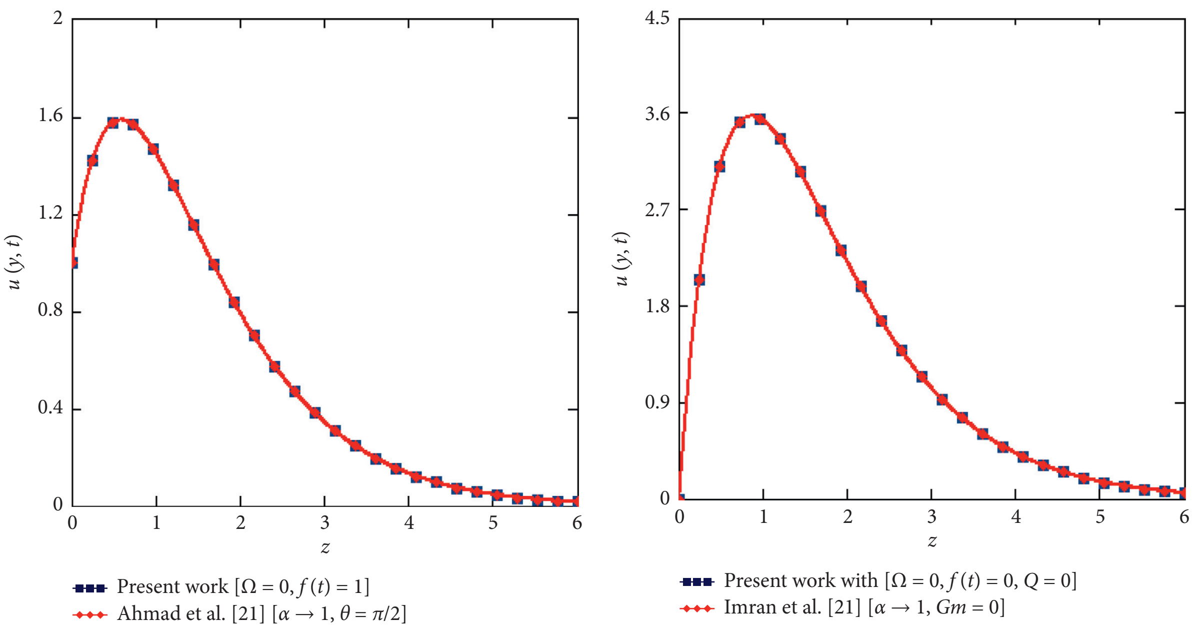


FIGURE 11: Comparison of temperature.

Equations (22) and (23) are complex relations and cannot be inverted by ordinary inverse relation of Laplace transform. Stehfest's and Tzou's algorithms are utilized for detransformation of velocity components and presented in Figure 2.

4. Results and Discussion

In this paper, the rotational flow of viscous fluid over a flat plate with the Newtonian heating is discussed. Analytical results for temperature and components of velocity fields are established with the help of Laplace transform. Some graphs of velocity against special variable z are sketched to see the physical effect of involved parameters. Figure 3 is plotted to see the effect of Pr and Q over the thermal profile, and it is noted that with the increasing values of Pr, fluid cools down and consequently thermal profile lowers down while it is raised with increasing value of Q. The effect of Newtonian heating and time over the temperature profile is presented in Figure 4. From the figure, it is clear that temperature profiles rise with increasing value of Newtonian heating parameter hs and time t. The effect of Pr over the velocity components is discussed in Figure 5, and it is observed that with the



(a) (b)

Figure 12: Comparison of velocity.

Table 1: Subjectivity of Nusselt number due to α for different values of Pr and S.

t	Pr = 1.5	Pr = 2	Pr = 2.5	Q = 0.3	Q = 0.5	Q = 0.7
0.1	1.45893971	1.36332825	1.29323441	1.28798185	1.21272314	1.17518651
0.2	1.46973354	1.37659053	1.30680985	1.28874896	1.21304572	1.17537098
0.3	1.48081222	1.38991945	1.32027242	1.28957462	1.21339402	1.17557059
0.4	1.49221241	1.40339890	1.33369919	1.29044904	1.21376360	1.17578257
0.5	1.50398704	1.41712090	1.34716076	1.29136149	1.21414937	1.17600370
0.6	1.51620697	1.43118859	1.36072051	1.29229999	1.21454580	1.17623089
0.7	1.52897061	1.44571909	1.37443112	1.29325166	1.21494653	1.17646033
0.8	1.54241361	1.46084228	1.38832548	1.29420241	1.21534522	1.17668814
0.9	1.55673282	1.47669347	1.40240685	1.29513598	1.21573466	1.17691038
1.0	1.57222017	1.49339487	1.41663477	1.29603494	1.21610801	1.17712268

increasing value of Pr, the fluid's velocity components decreased. The influence of Gr over the fluid's motion is highlighted in Figure 6, and profiles of velocity increased with the increasing value of Gr. Larger value of Gr is referred to the more bouncy effect that is why more fluid currents are generated for increasing values of Gr. The effect of Ekman number Ek over the velocity components is explained in Figure 7, and it is observed that both real and imaginary velocity components speed up with the increasing value of Ek. The subjectivity of magnetic parameter M can be seen in Figure 8, and it is noted that fluid slows down with the enhancing value of M. In the presence of magnetic field, there is some retarding force which creates some hindrance to fluid motion and consequently fluid slows down. The effect of heat generation parameter Q is studied in Figure 9, and it is concluded that fluid speeds up with the increasing value of Q, due to heat generation, there is more heat transfer; therefore, fluid velocity components are increased with the increasing value of Q of Q. The effect of the time over the velocity components is discussed in Figure 10, and it is clear that with the elapsed time, fluid increases, and it is a natural aspect of velocity with the elapsed time. Figure 11 presents a comparison of present temperature for $Q = 0$ with the temperature obtained by Imran et al. [21] and Ahmad et al. [22], and overlapping profile shows the validity of our result for temperature. The real and imaginary components of present velocity are also compared with the velocities obtained in [22, 23], and its overlapping profiles are presented in Figure 12. The heat transfer at boundary is discussed in terms of Nusselt number; moreover the effect of Pr and Q over the Nusselt number is presented in Table 1. Q, heat transfer is presented in Table 1, and from the tabular data, it is clear that Nusselt number increases with the increasing time, but it is reduced with the increasing value of Pr and Q.

5. Conclusion

In this article, rotational flow of viscous fluid over a flat plate with Newtonian heating is discussed for analytical result of temperature field and transformed result for velocity field is established with the help of Laplace transform. Some key findings of this study are listed below.

(i) Temperature lowers down with the increasing values of Pr while it is raised with increasing values of hs, Q, and time t. Heat transfer coefficient is enhanced with increasing time while it is reduced with increasing values of Pr and Q.

(ii) Velocity components decrease with increasing Pr and M, while they increase with the increasing value of Gr, Ek, Q, and time t.

(iii) Thermal boundary layer declines with greater values of Pr and enhances with increasing values Q, hs, and t, respectively.

(iv) Momentum boundary layer is reduced with increasing values of Pr, Ek, and M while it is enhanced with the increasing values of Gr, Q, and t.

(v) Our obtained results for temperature and velocity have a good agreement with the corresponding results of existing literature.

Data Availability

No datasets were generated or analyzed during the current study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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