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UNSTEADY HYDROMAGNETIC FLOW OF A NANOFLUID IN THE PRESENCE OF INCLINED MAGNETIC FIELD IN A POROUS MEDIA

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ABSTRACT

The unsteady hydromagnetic flow of a nanofluid in the presence of an angled magnetic field in porous media is investigated, with consideration given to the effect of the nanofluid's viscosity variation parameter. The governing partial differential equations are obtained and transformed into dimensionless form by employing dimensionless quantities. Because of its stability, consistency, and high convergence rate, the finite difference approach is used to derive the numerical schemes of transformed partial differential equations, in line with the Crank-Nicolson method. The study subsequently examined at how dimensionless numbers, a viscosity variation parameter, and the magnetic field's inclination angle affected velocity and temperature profiles. The results show that raising the Reynolds number and magnetic parameter increases the velocity profiles of the nanofluid, whereas increasing the permeability parameter reduces the velocity of the nanofluid.

Higher Reynolds, Eckert, and Prandtl numbers lead to larger temperature profiles of the fluid flow. Moreover, study found that increasing the viscosity parameter and magnetic field inclination angle can accelerate fluid flow velocity profiles. In addition, the temperature profiles of the fluid flow grow with the viscosity parameter and the angle of inclination of the magnetic field. The current findings are consistent with previous research, indicating their correctness and validity.

KEYWORDS: Nanofluid, Unsteady, Hydromagnetic, Magnetic Field, Porous Medium, Dimensionless Numbers, Inclination Angle.

INTRODUCTION

The importance of nanofluid flow in porous media has increased recently. More uses of flow in porous media can be found in science and engineering, including groundwater hydrology, petroleum engineering, reservoir engineering, irrigation and drainage systems for agriculture, chemical reactors, and the extraction of crude oil from reservoir rocks' pores. The discussion of multiple research investigations on hydromagnetic flow, nanofluid in a porous media, and inclined magnetic field, carried out by various mathematicians and scientists, is provided below.

Using an angled magnetic field and a stretched surface, Hussain and Sheremet (2023) investigated convection analysis of radiative nanofluid flow through porous media. It was found that as estimations of nanoparticle concentrations and radiation parameters increase, the thermal profile of the nanofluid improves as well. Additionally, fluid velocity decreased with increasing Hartmann's number and magnetic field inclination angle. Moreover, the temperature distributions of the nanofluids decreased as the Darcy number increased.

Izadi, Sheremet, and Mehryan (2020) investigated how an inclined periodic magnetic field inside a porous media influenced the natural convection of a hybrid nanofluid. This work has investigated the effects on flow and thermal patterns of the Darcy, Hartmann, Rayleigh, magnetic field periodicity, magnetic field inclination angle, thermal conductivity ratio, and medium porosity. It has been discovered that the periodic magnetic field's parameters affect heat transfer performance in a non-monotonic way.

Kumar (2014) presented exact solutions for non-Newtonian fluids in porous mediums with Hall effect and defined vorticity distribution functions.

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This study found exact solutions to the governing equations of incompressible second grade fluid in a porous medium with Hall currents, assuming that vorticity distribution is proportional to the stream function and perturbed by a quadratic factor.

Sobamowo, Yinusa, and Makinde (2019) investigated how a vertical plate's free convection of Casson nanofluid was affected by an angled magnetic field, porosity in the flow medium, and thermal radiation. It was observed that within the boundary layer, an increase in the magnetic field inclination parameter typically resulted in a decrease in fluid velocity and an increase in fluid temperature. In addition, as the magnetic field increased, the fluid's velocity and the flow's temperature gradient both diminished. Furthermore, the temperature profiles increased as the magnetic field parameter values increased. Moreover, as the permeability parameter increased, the fluid's flow velocity decreased. Also, the temperature of the nanofluid decreased as the Prandtl number increased, but the velocity of the fluid decreased.

Sandeep and Sugunamma (2014) investigated how radiation and slanted magnetic fields affect unsteady hydromagnetic free convection flow across a moving vertical plate in a porous media. Increasing the magnetic, rotation, and radiation parameters lowered fluid flow in the isothermal case but increased fluid flow in the ramping temperature. Increasing rotation parameter, time, and angle of inclination resulted in decreased fluid flow in both ramping and isothermal cases. Increasing the Prandtl number led to higher fluid flow temperatures, while decreasing the radiation parameter led to lower temperatures.

Mahato, Das, Sen, and Shaw (2022) investigated the formation of entropy on unsteady stagnation-points. Casson nanofluid flow exhibiting both homogeneous and heterogeneous responses across a stretching sheet in a porous media when subjected to an angled magnetic field. The enhanced volume percentage of nanoparticles accelerated temperature, but it slowed down concentration and velocity distributions, according to the results. Higher Eckert numbers increased temperature and velocity while decreasing the Nusselt number and skin friction coefficient. An increase in the Brinkman number increased the formation of entropy, but it decreased Bejan's number.

Using the Darcy-Forchheimer law, Abbas, Jeelani, and Alharthi (2022) examined the impact of magnetohydrodynamics on third-grade fluid flow and heat transfer over an inclined exponentially stretching sheet embedded in a porous medium. It was observed that the velocity profile rose as the third-grade fluid parameter was raised, while the mass concentration and temperature field declined. Additionally, it was noted that the mass concentration rose and the velocity distribution reduced as the permeability parameter increased. The findings indicated that the velocity profile decreased but the mass concentration increased in response to an increase in the local inertial coefficient. Furthermore, it was determined that, in accordance with the physics of magnetic field parameters, the velocity field was decreased and the temperature field was raised as the magnetic field parameter values increased.

The importance of an inclined magnetic field in a Darcy-Forchheimer flow with varying porosity and thermal conductivity was examined by Saif, Muhammad, and Sadia (2020). Higher values of the Reynolds number, local permeability parameter, and variable permeability were found to increase velocity, whereas higher values of the unsteady parameter, local permeability parameter, Reynolds number, and Prandtl number were found to decrease temperature.

Maswai, Kinyanjui, and Kwanza (2015) studied MHD turbulent flow through an angled magnetic field past a rotating semi-infinite plate. Increasing the degree of inclination led to higher velocity profiles. Increasing the Eckert number and rotation parameter resulted in lower fluid velocity profiles. Increasing the Eckert number, Hall effect, and rotation parameters resulted in higher temperature profiles.

In a porous medium with varying temperature, Endalew and Nayak (2019) examined the effects of thermal radiation and inclined magnetic fields on MHD flow across a linearly accelerated inclined plate. It was found that the flow velocity and local skin friction were reduced when the inclination angle of an applied magnetic field increased. Additionally, when the mass Grashof number increased, so did the boundary layer's thickness and velocity. Additionally, because of the Lorentz force operating on the flow field, the Hartmann number contributed to the decrease in flow velocity. Additionally, as radiation increased throughout the fluid region, temperature decreased; however, the velocity profile showed the opposite impact. Moreover, there was a delay in the thermal boundary layer with a rising Prandtl number.

In the presence of fluctuating transverse magnetic fields, Mburu, Kinyanjui, and Giterere (2016) investigated hydromagnetic fluid flow between parallel plates where the upper plate is porous. It was determined that the magnetic number, hydrodynamic Reynolds number, Prandtl number, Eckert number, pressure number, and suction parameter all had an impact on the rates of heat and mass transfer on the parallel plates.

In the presence of an inclined magnetic field, Enock, Kinyanjui, and Giterere (2019) investigated the hydromagnetic flow of a non-Newtonian fluid induced by a moving plate in a porous medium. The results of this investigation showed that raising the inclination angle causes the fluid flow's primary and secondary velocity profiles to enlarge. This suggests that there was a direct proportionality between the velocity and the inclination angle. Moreover, rising Reynolds numbers and magnetic parameters cause the fluid flow's primary and secondary velocity profiles to rise.

Thus, in this study, the velocity varied in a direct relation to the magnetic parameter and Reynolds number. A rise in the permeability parameter caused the fluid flow's primary and secondary velocity profiles to decrease. Furthermore, increasing the Reynolds, Eckert, and Prandtl numbers resulted in an increase in the magnitude of the temperature profiles of the fluid flow, implying that the velocity varies inversely proportional to the permeability parameter. This implies that the temperature of the fluid flow varies directly proportional to the Reynolds, Eckert, and Prandtl numbers.

Ali, Gohar, and Khan (2016) studied the MHD flow of a water-based Brinkman type nanofluid over a vertical plate embedded in a porous medium with variable surface velocity, temperature, and concentration. The study found that increasing the permeability parameter of the porous plate decreased the velocity field.

By applying partial magnetic fields, Mondal, Biswas, Mandal, Manna, and Chamkha (2022) evaluated the thermal performance of hybrid nanofluid flow in a tilted porous enclosure. The study revealed that the heat transport mechanism is significantly impacted by partial magnetic fields with cavity tilt. The research findings demonstrate that the local and global transport phenomena under the multiphysical scenario can be substantially modulated by varying the cavity angle, the position and width of the applied magnetic fields, and other relevant factors. Compared to a no-magnetic field, this method permits a reduction in heat transfer of about 15% in a partial magnetic field and 30% in a whole domain magnetic field.

The effects of heat and mass transfer on the unsteady MHD natural convection flow of a chemically reactive and radiating fluid past a moving vertical plate with an arbitrarily ramping temperature were examined by Seth, Mandal, and Chamkha (2016) in the context of a porous medium. This study found that in the boundary layer region, the crucial period for rampedness tends to decrease both fluid flow and fluid temperature. Additionally, it was noted that while radiation and chemical reactions have the opposite effect on fluid flow in the boundary layer region, the Surface Acceleration Parameter, Mass Diffusion, Solutal Buoyancy Force, Permeability of Porous Medium, and Time tend to accelerate fluid flow for both ramped temperature and isothermal plates.

Unsteady MHD fluid flow over an inclined vertical porous plate in the presence of radiation, Soret effects, and an aligned magnetic field was studied by Raghunath, Gulle, Vaddemani, and Mopuri (2022). In this investigation, it was found that the presence of permeability and an increase in Soret number caused the velocity distribution to increase; however, the opposite effects were seen when the magnetic field was aligned, the inclined parameter, the heat absorption coefficient, the magnetic parameter, the radiation parameter, and the chemical reaction parameter were considered.

Using a porous stretching sheet, Hymavathi, Mathews, and Kumar (2022) investigated the effects of an inclined magnetic field and heat transfer on the unsteady free convection flow of water-based nanofluids containing magnesium oxide and molybdenum disulphide. A presentation and analysis of the effects of various flow amounts on the temperature and velocity fields was done. The outcomes demonstrated that in both nanofluids, flow reversal was inhibited by the porous media and magnetic field.

Mishra and Sharma (2017) investigated MHD Mixed Convection Flow in a Rotating Channel in the Presence of Inclined Magnetic Field with the Hall Effect. They found that increasing the injection or suction parameter increased both the velocity profiles and the skin friction coefficient. They also found that the fluid flow was significantly affected by the magnetic field’s angle of inclination. Lastly, they discovered that increasing the Grashof number increased the magnitude of both velocities and the skin friction coefficient.

Ahmed, Aly, and Raizah (2019) investigated the enhancement of heat transmission from an inclined plate through a porous medium with varying porosity and heat-generating nanofluids as a result of solar radiation. While the local Nusselt number rises, the velocity profiles fall as the loss coefficient increases. The velocity and temperature profiles decrease as the volume percentage of nanoparticles increases, but the local Nusselt number increases. The local temperature rises but the velocity profiles fall as the magnetic parameter rises.

Heat transfer on MHD rotating non-Newtonian fluid flow through a parallel plate porous channel was covered by Lakshmanna and Venkateswarlu (2018). According to this study, the viscoelastic fluid parameter or Ekman number increases with the resulting velocity. It was found that as the magnetic field parameter, Darcy parameter, viscoelastic fluid parameter, and Prandtl number increase, so does the fluid temperature. Additionally, it was discovered that a rise in the Grashof number causes the fluid flow’s primary and secondary velocities to increase. It was discovered that the Ekman number, Darcy parameter, Grashof number, and Prandtl number increased the magnitudes of the rate of heat transfer.

In the presence of uniform heat generation/absorption, Massoudi, Ben Hamida, and Almeshaal (2021) investigated the free convection and thermal radiation of nanofluid inside a nonagon inclined cavity containing a porous medium influenced by a magnetic field with changing direction. The collected results demonstrate that increasing the hot source length improved convection heat transfer. Increasing Hartmann numbers decreased convection heat transmission, but increasing Rayleigh and Darcy numbers increased it. The heated source length also increased convection heat transfer. When there is uniform heat generation and absorption, the radiation parameter leads to an improvement in convection heat transfer.

In order to better understand heat and mass transmission in MHD stagnation-point flow approaching an inclined stretched sheet immersed in a porous medium, Biswal, Swain, Das, and Dash (2022) conducted research.

The results showed that the oblique surface lessened the effect of body forces, the low permeability of the medium caused flow instability due to a sudden drop in velocity, and the surface's Newtonian cooling was aided by the Biot number. These findings may be useful in meeting heat exchange design requirements.

The impact of magnetic field on heat and mass transfer of fluid flow through a porous medium onto a moving vertical plate was examined by Goud and Nandeppanavar (2022) in relation to chemical reaction and MHD flow. It has been noted that velocity decreased with increasing local magnetic parameter. The temperature distribution became linear in the absence of a porous material and a source parameter. In all situations, porosity increased the temperature field whereas an increase in the source parameter decreased the temperature profile. Temperature profiles increased as the magnetic field's strength increased.

MHD convection of nanofluid in porous media affected by slanted Lorentz force was examined in Sureshkumar et al. (2020). The overall rate of heat transfer is increased in the forced convection regime compared to the mixed convection regime, according to the results, which also showed that the slope of the applied magnetic field altered the magnetic field intensity. In the mixed convection regime, a rise in the Hartmann and Darcy numbers had no effect on the mean rate of heat transfer.

Luo, Rothan, Alazwari, Abu-Hamdeh, and Selim (2021) investigated the effects of a magnetic field on nanofluid in a multiphysics experiment within a porous media.

It was found that when more magnetic force was applied, the speed of the nanoparticles decreased and the isothermal distortion decreased. Reduced hot wall temperature was achieved through increasing the permeability parameter. A zone with greater permeability had higher nanofluid velocity. A numerical study on the effects of magnetic fields on forced convection flow of a hybrid nanofluid in a cylinder packed with porous media was presented by Aminian, Moghadasi, and Saffari (2020). The findings showed that the enhancement of the Hartmann and Darcy numbers had a considerable effect on the increase in the heat transfer coefficient. Furthermore, adding nanoparticles to the base fluid raised the performance evaluation standards across the board. Furthermore, configurations with permeable porous media saw the Performance evaluation criterion reach its maximum value.

The Peristaltic transport of biological graphene-blood nanofluid in a porous medium was examined by Khazayinejad, Hafezi, and Dabir (2021), taking into account an inclined magnetic field and thermal radiation. The temperature profile rapidly falls as the inclination angle increases, according to the results. An increase in the Hartman number caused the temperature to rise.

Inspired and driven by nanofluids and fluid flow in porous media, this research studies the unsteady hydromagnetic flow of a nanofluid in the presence of an inclined magnetic field in porous media. The study simulates the flow of a nanofluid passing through porous media in the presence of an inclined magnetic field. The governing equations of the flow problem are formed, transformed into dimensionless form, and then numerically solved using the Crank-Nicolson method. The effects of dimensionless numbers, the viscosity variation parameter, and the inclination angle on the velocity and temperature profiles are finally investigated.

MATHEMATICAL FORMULATION

This study investigates the unsteady two-dimensional hydromagnetic flow of an incompressible nanofluid in a porous medium in the presence of an inclined magnetic field with an angle θ. In porous media, the fluid flows with a constant velocity (u_0) along the x-axis. A homogenous magnetic flux density (B_0) is provided in a flow direction that is at an angle θ to the porous media saturated with nanofluid. In addition, in this instance, the viscosity μ of the nanofluid is represented as a function of the viscosity of the ambient fluid μ_0, and the viscosity variation parameter, γ which is expressed as a function of the fluid's film temperature. Furthermore, this study makes the assumptions that the porous media is isotropic and non-magnetic, and that the force resulting from the electric field is negligible in comparison to the Lorentz force. The regime is represented in Figure 1.

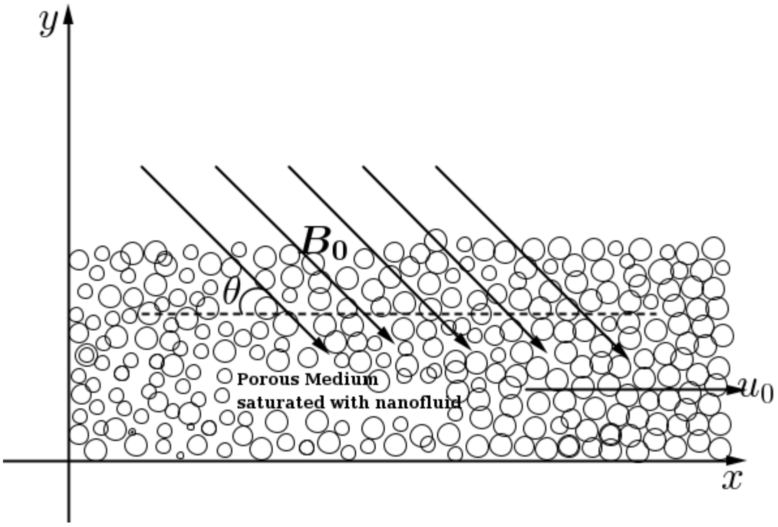

Figure 1: Flow Configuration

GOVERNING EQUATIONS

The fluid flow equations governing the above setup are as follows, based on the flow descriptions and assumptions:

1.1 Continuity Equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

1.2 Momentum Equation along x-axis

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\mu\frac{u}{K_p}+F_x \tag{2}$$

1.3 Momentum Equation along y-axis

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\mu\frac{v}{K_p}+F_y \tag{3}$$

1.4 The Energy Equation

$${}_{\rho}C_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\mu\phi \tag{4}$$

Where $F_x=\sigma B_0^2(u\cos^2\theta-v\cos\theta\sin\theta)$ and $F_y=\sigma B_0^2(v\sin^2\theta-u\cos\theta\sin\theta)$ which are the electromagnetic force vector components along x-axis direction and along y-axis direction respectively. Also, $\phi=\left(2\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2$ is the viscous dissipation function.

The viscosity μ of the nanofluid in this case takes the form of the one used by Molla, Saha, and Hossain (2012) which is expressed as a function of temperature i.e.

$$\mu=\mu_0(1+\gamma) \tag{5}$$

Where $\mu_0$is the ambient fluid's viscosity and γ is the viscosity variation parameter expressed as $\gamma=\frac{1}{\mu}\left(\frac{\partial\mu}{\partial T}\right)T_f\left(\frac{T-T_\infty}{T_w-T_\infty}\right)$ with T_f being the fluid's film temperature.

The following are the suitable boundary conditions that were applied:

At $t=0: u(x,0)=u_0, v(x,0)=0, T(x,0)=T_w$

At $t\geq 0: u(x,\infty)=0, v(x,\infty)=0, T(x,\infty)=T_\infty$

Here, T_w and T_∞ are temperatures of porous medium's wall and temperature of the free stream respectively, while u_0 is the initial velocity of the nanofluid in the porous medium.

DIMENSIONLESS FORM OF THE GOVERNING EQUATIONS

In this work, the following non-dimensional quantities were employed to convert Equation (2) to (4) into non-dimensional form.

$t^* = \frac{u_0 t}{L}$, $x^* = \frac{x}{L}$, $y^* = \frac{y}{L}$, $u^* = \frac{u}{u_0}$, $v^* = \frac{v}{u_0}$, $T^* = \frac{T - T_\infty}{T_W - T_\infty}$

Therefore, the following is the non-dimension form of Equation (2) to (4):

$$\frac{\partial u^*}{\partial t^*} + u^* \frac{\partial u^*}{\partial x^*} + v^* \frac{\partial u^*}{\partial y^*} = \frac{(1+\gamma)}{Re}\left(\frac{\partial^2 u^*}{\partial x^{*2}} + \frac{\partial^2 u^*}{\partial y^{*2}}\right) + \frac{Re}{X}(1+\gamma)u^* + MRe(u^* \cos^2\theta - v^* \cos\theta \sin\theta) \quad (6)$$

$$\frac{\partial v^*}{\partial t^*} + u^* \frac{\partial v^*}{\partial x^*} + v^* \frac{\partial v^*}{\partial y^*} = \frac{(1+\gamma)}{Re}\left(\frac{\partial^2 v^*}{\partial x^{*2}} + \frac{\partial^2 v^*}{\partial y^{*2}}\right) + \frac{Re}{X}(1+\gamma)v^* + MRe(v^* \sin^2\theta - u^* \cos\theta \sin\theta) \quad (7)$$

$$\frac{\partial T^*}{\partial t^*} + u^* \frac{\partial T^*}{\partial x^*} + v^* \frac{\partial T^*}{\partial y^*} = \frac{1}{RePr}\left[\frac{\partial^2 T^*}{\partial x^{*2}} + \frac{\partial^2 T^*}{\partial x^{*2}}\right] + (1+\gamma)\frac{Ec}{Re}\left[\left(2\frac{\partial v^*}{\partial y^*}\right)^2 + \left(\frac{\partial u^*}{\partial y^*} + \frac{\partial v^*}{\partial x^*}\right)^2\right] \quad (8)$$

Here, $Re = \frac{u_0 L}{V}$ is the Reynolds number, $X = \frac{U_0^2 K_p}{V^2}$ is the Permeability parameter, $M = \frac{\sigma B_0^2 V}{\rho u_0^2}$ is the Magnetic parameter, $Pr = \frac{\rho C_p V}{k} = \frac{V}{k}$ is the Prandtl number, and $Ec = \frac{u_0^2}{C_p(T_W - T_\infty)}$ is the Eckert number referred to as non-dimensional numbers or quantities.

METHOD OF SOLUTION

The derived governing equations are coupled and nonlinear partial differential equations (PDEs), requiring numerical solutions. The finite difference method is used for its stability, consistency, and high convergence rate. This method involves using finite difference grids to cover the solution domain. Grid points, also known as mesh points, are the intersections of grid lines where the differential equation's finite difference solution can be achieved. Thus, in this study, the numerical schemes for solving Equation (6) to (8) were obtained using the Crank-Nicolson method. The appropriate Finite Difference Equations (FDEs) of each governing equation were found using the knowledge of central difference for solving Partial Differential Equations (PDEs). The FDEs that were acquired were implemented in MATLAB and run at various non-dimensional number values along with the magnetic field's inclination angle, θ, and viscosity variation parameter, λ, to ascertain the fluid flow's temperature and velocity profiles. Section 5 further discusses the effect of the magnetic field's inclination angle, θ, viscosity variation parameter, λ, and dimensionless numbers such as Reynolds number (Re), Magnetic parameter (M), Permeability parameter (X), Eckert number (Ec), and Prandtl number (Pr) on the obtained temperature profiles and velocities.

RESULTS AND DISCUSSION

Figures 2 and 3 show that increasing the Reynolds number (Re) increases both the primary and secondary velocity profiles of a fluid flow. This is because, the Reynolds number represents the ratio of inertia force to viscous force.

Thus, increasing the Reynolds number decreases the viscous force, which resists fluid flow. Hence, as the Reynolds number increases, the force opposing fluid flow diminishes, as a result, primary and secondary velocity profiles increase. Furthermore, from Figure 4 it has been noticed that as the Reynolds number increases, so do the temperature profiles. This is due to the fact that increasing the

Reynolds number reduces the viscous force. Hence, as the viscous force decreases, the fluid's velocity increases, leading to more collisions among the fluid particles. This increases heat dissipation in the porous medium's boundary layers, resulting in higher temperature profiles for the fluid flow. These findings are comparable to those reported by Saif et al. (2020) and Enock et al. (2019).

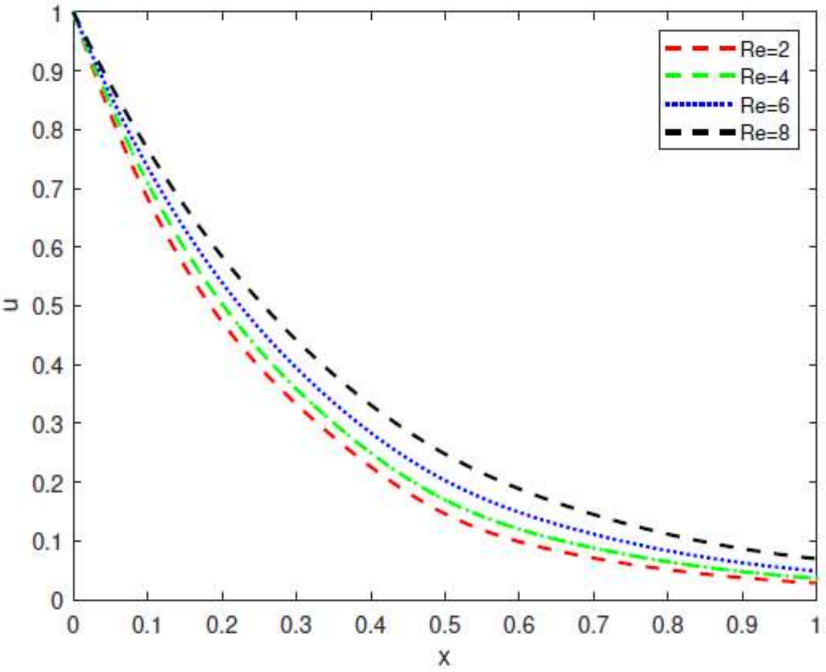

Figure 2: The impact of Reynolds number on primary velocity profiles.

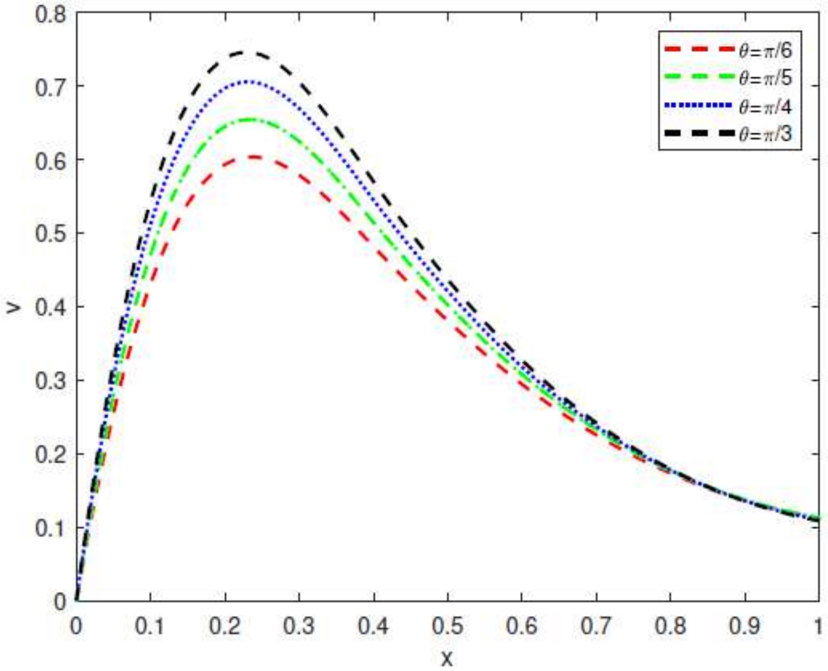

Figure 3: The impact of Reynolds number on secondary velocity profiles.

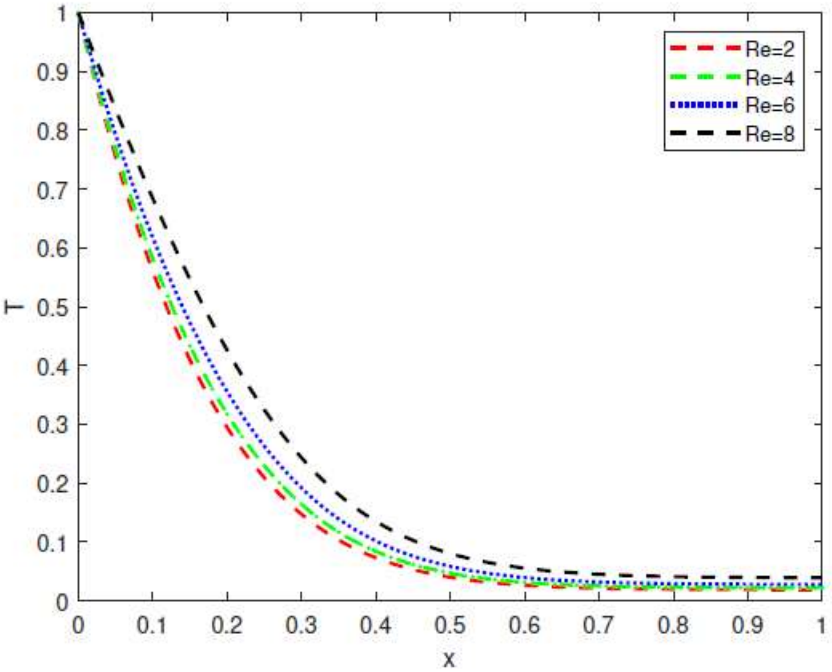

Figure 4: The impact of Reynolds number on temperature

Figures 5 and 6 demonstrate that increasing the angle of inclination of the magnetic field (θ) results in larger primary and secondary velocity profiles. The magnetic field is tilted clockwise at an angle θ from the porous media towards the flow direction. A clockwise angle from the porous media, along with a uniform magnetic field flux density (B_0) in the flow direction, promotes fluid mobility. Hence, both primary and secondary velocity profiles grow with the magnetic field's angle of inclination (θ). Therefore, raising the inclination angle accelerates the fluid flow. Furthermore, when the fluid flow velocity increases, so does the collision between fluid particles, increasing heat dissipation in the porous medium's boundary layers. That is why as the angle of inclination of the magnetic field (θ) increases, so do the temperature profiles of the fluid flow, as shown in Figure 7. These results are consistent with those found by Sobamowo et al. (2019).

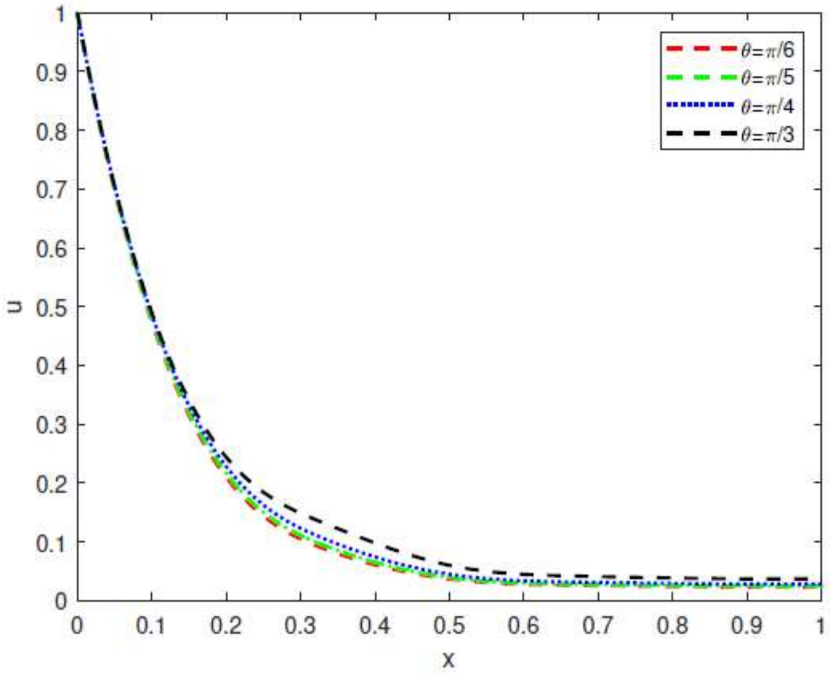

Figure 5: The impact of inclination angle on primary velocity profiles.

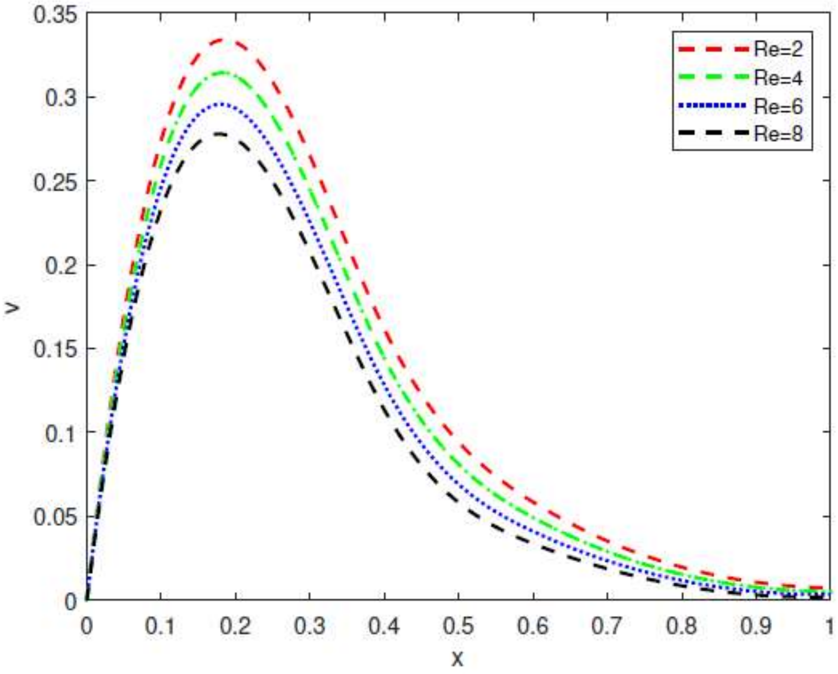

Figure 6 The impact of inclination angle on secondary velocity profiles.

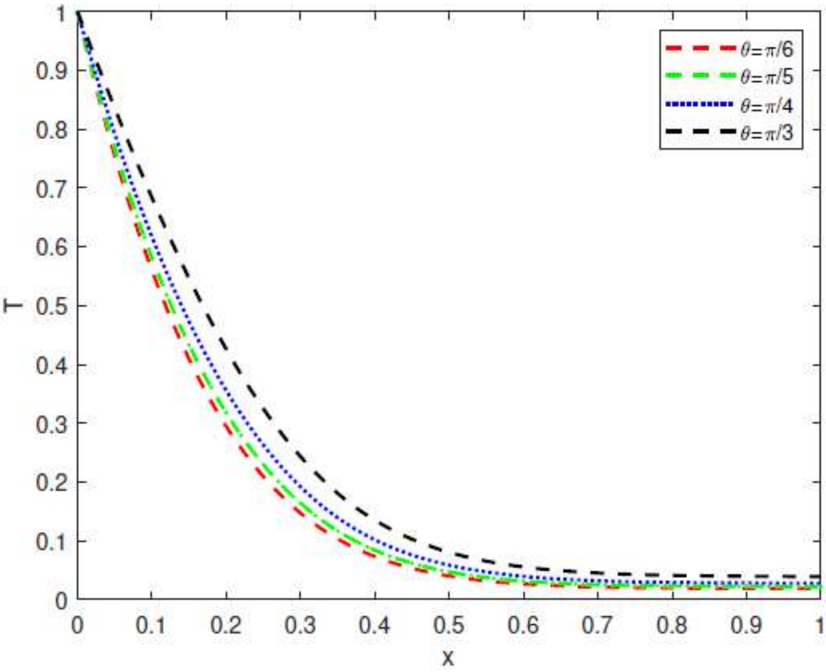

Figure 7: The impact of inclination angle on temperature profiles.

The impact of the viscosity variation parameter, (Φ), on fluid velocity is depicted in Figures 8 and 9. The findings show that raising the viscosity parameter, which implies lowering viscosity, raises the fluid flow's primary and secondary velocity profiles. This is due to the fact that viscosity determines the viscous force that prevents the fluid flow from moving, which in turn defines the fluid's resistance to motion. The fluid flow particles' mobility through the porous media increases as a result of the viscosity variation parameter being increased, which reduces the fluid's viscosity and hence decreases the viscous force. As a result, there is an increase in the primary and secondary velocity profiles. Again, when the fluid flow velocity increases, so does the collision between fluid particles, resulting in increased heat dissipation in the porous media boundary layers. Figure 10 illustrates that when the viscosity variation parameter (Φ) increases, so do the temperature profiles of the fluid flow. These outcomes align with the findings of Sobamowo et al. (2019).

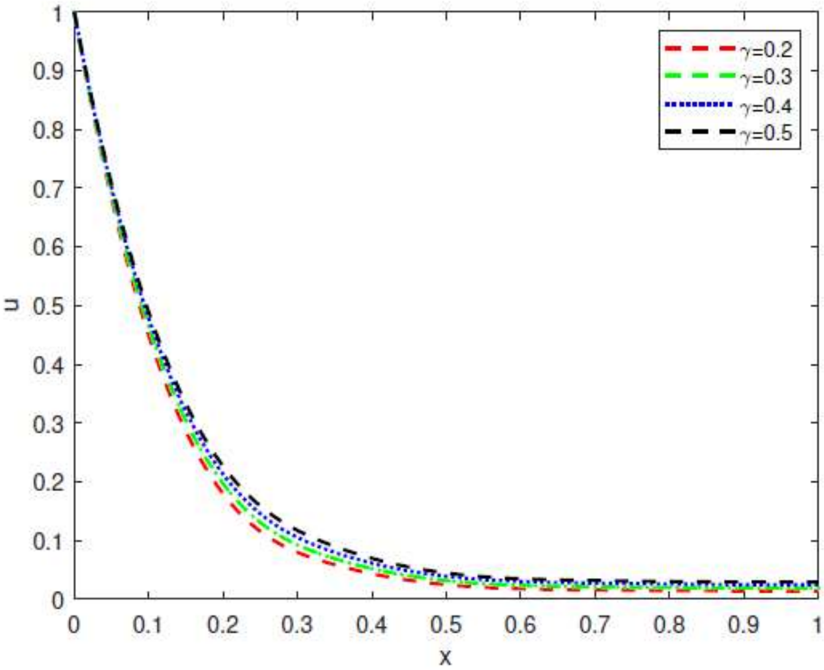

Figure 8 The impact of viscosity variation parameter on primary velocity profiles.

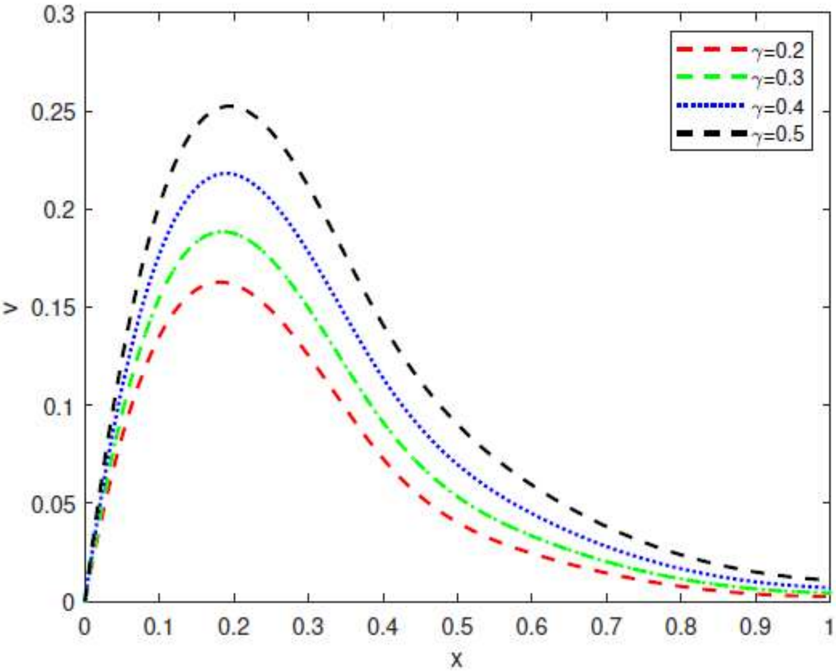

Figure 9 The impact of viscosity variation parameter on secondary velocity profiles.

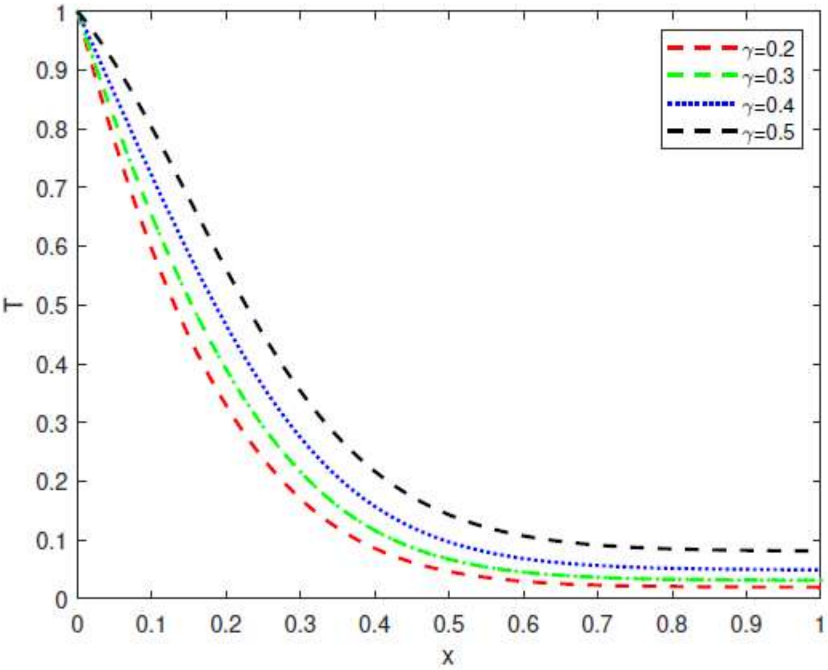

Figure 10 The impact of viscosity variation parameter on temperature profiles.

It can be seen from Figures 11 and 12 that both the primary and secondary velocity profiles rise when the magnetic field parameter (M) increases. A fluid that conducts electricity will exhibit the Lorentz force if magnetic fields are added to the fluid. In this investigation, a homogeneous magnetic field, B_0 is provided at an angle, α and in the same direction as the fluid flow. Hence, the magnetic field introduces the Lorentz force into the flow. Consequently, raising the magnetic field parameter increases the Lorentz force, which is caused by electromagnets. Therefore, increasing the magnetic field parameter increases the magnitude of both primary and secondary velocity profiles, as the Lorentz force acts in the same direction as the fluid flow. These results agree with those obtained by Raghunath et al. (2022).

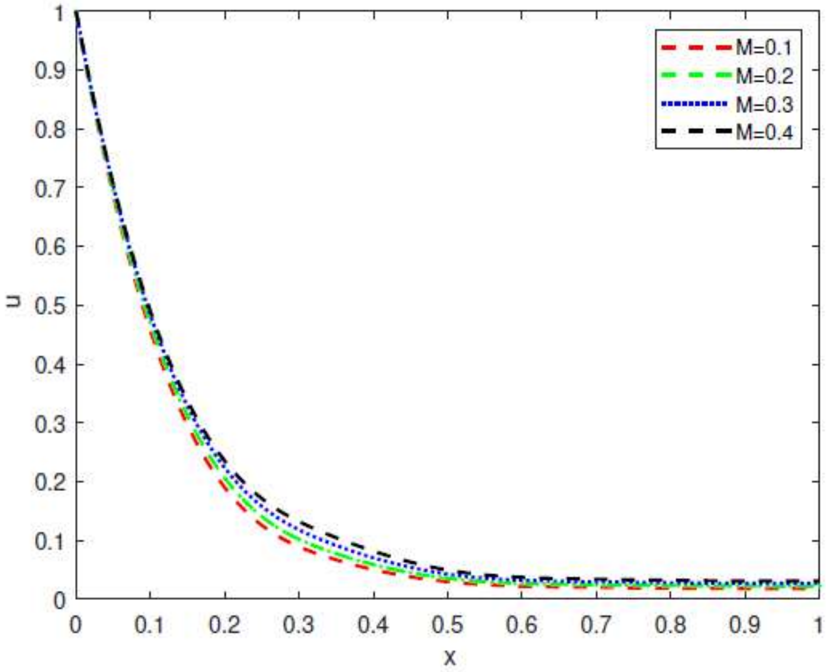

Figure 11 The impact of magnetic parameter on primary velocity profiles

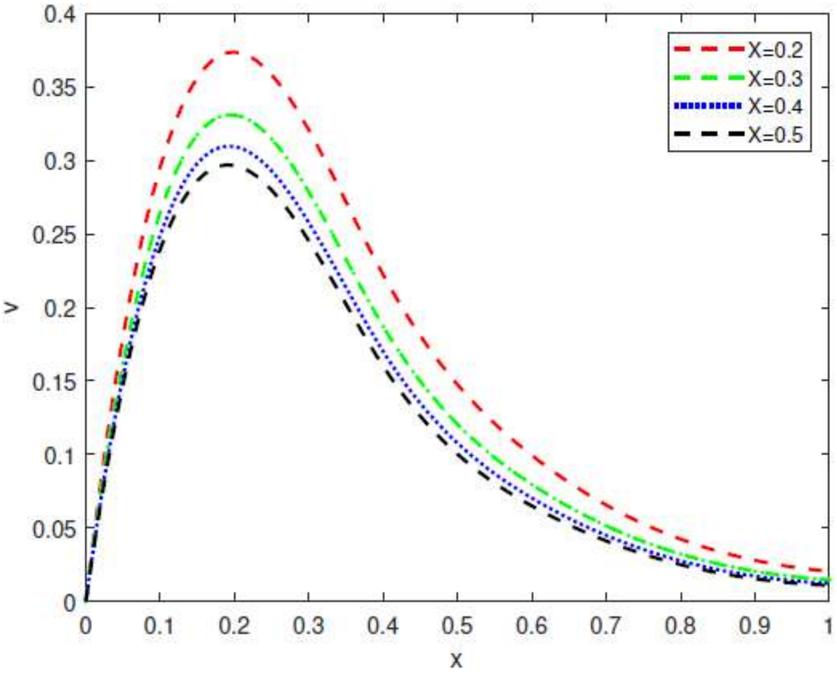

Figure 12: The impact of magnetic parameter on secondary velocity profiles.

It is evident from Figures 13 and 14 that a drop in the fluid flow's primary and secondary velocity profiles is caused by an increase in the permeability parameter (X). A higher permeability parameter causes the porous medium to become more porous, which in turn slows down the rate at which fluid moves through it. The magnitude of the fluid flow's primary and secondary velocity profiles both drop as the fluid flow's acceleration is decreased because it lessens the movement of the particles. The results obtained concur with those of Sobamowo et al. (2019).

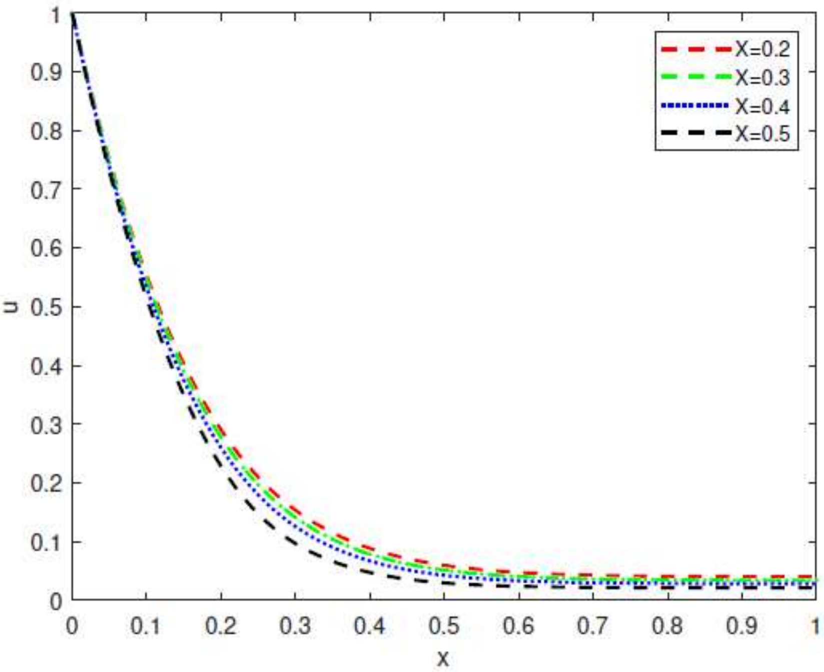

Figure 13 The impact of permeability parameter on primary velocity profiles.

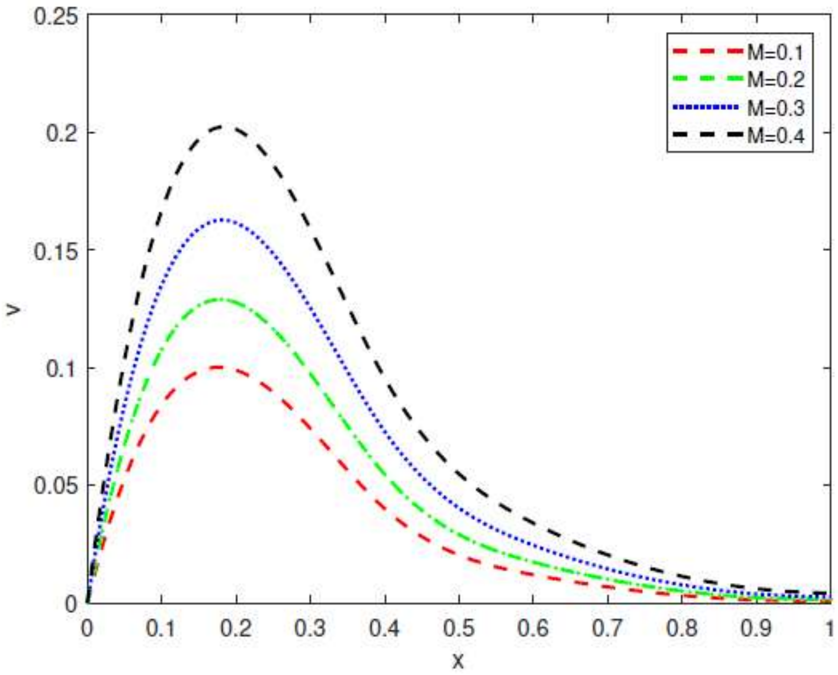

Figure 14 The impact of permeability parameter on secondary velocity profiles.

It can be seen from Figure 15 that temperature profiles rise as the Eckert number (Ec) rises. Since the Eckert number represents the relationship between kinetic energy and fluid enthalpy, increasing the Eckert number indicates high amounts of kinetic energy. When the fluid flow velocity is high, the kinetic energy is always high. Due to heat dissipation in the fluid's boundary layers within the porous media, caused by high fluid velocity that causes more fluid particle collisions, which in turn enhances the effects of self-heating, a temperature increase is implied. Consequently, raising the Eckert number causes the fluid flow's temperature profiles to rise. The results found are consistent with those of Mahato et al. (2022).

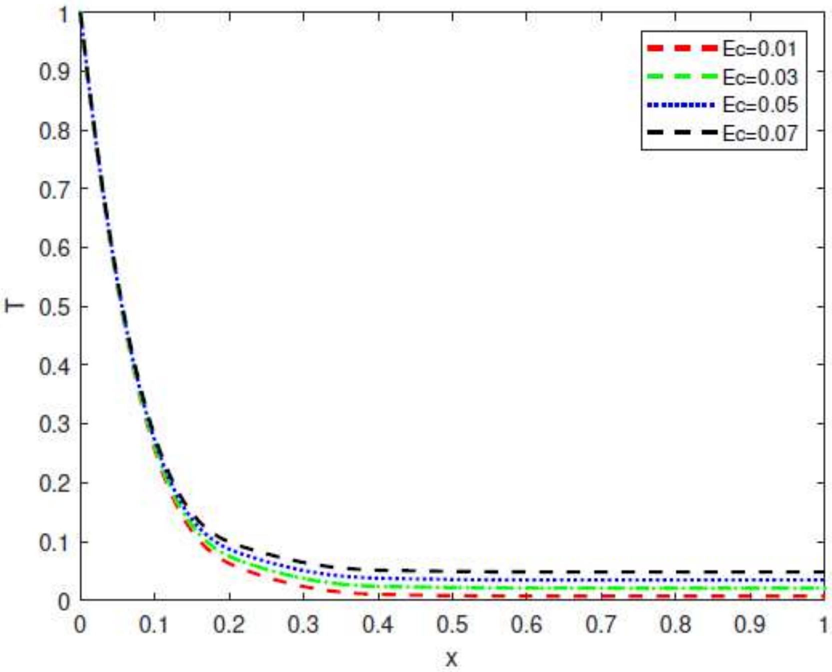

Figure 15 The impact of Eckert number on temperature profiles.

Figure 16 shows that temperature profiles rise in proportion to an increase in Prandtl number (Pr). The Prandtl number can be defined as the ratio of kinematic viscosity to thermal diffusivity, which represents the ratio of the viscous diffusion rate to the thermal diffusion rate. A higher Prandtl number indicates that the fluid has low thermal diffusivity, which causes the fluid to expand and its molecules to separate, raising the fluid's temperature. Consequently, a rise in the Prandtl number causes the fluid flow's temperature profiles to rise. The outcomes are in agreement with the research conducted by Sandeep and Sugunamma (2014), Lakshmanna and Venkateswarlu (2018), and Enock et al. (2019).

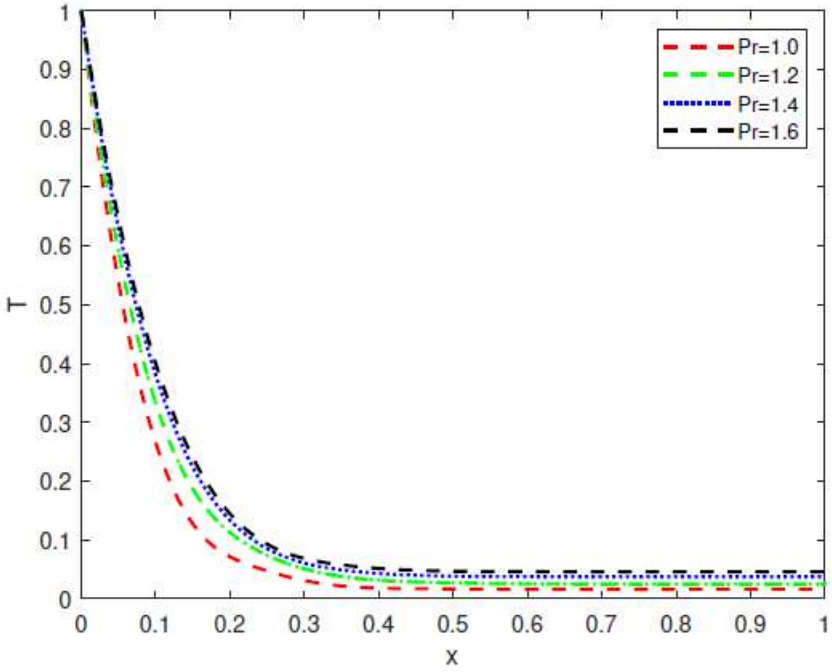

Figure 16 The impact of Prandtl number on temperature profiles.

CONCLUSION

This study examined the impacts on the temperature and velocity profiles of several dimensionless numbers, including the Reynolds number (Re), magnetic parameter (M), permeability parameter (X), Eckert number (Ec), and Prandtl number (Pr). In addition, the effects of the inclination angle (θ) and the viscosity variation parameter (γ) on the temperature and velocity profiles have been explored. The results reveal that increasing the permeability parameter (X) causes the primary and secondary velocity profiles of the fluid flow to decrease, while increasing the Reynolds number (Re) and the magnetic parameter (M) increases the primary and secondary velocity profiles of the fluid flow.

The aforementioned indicates that the velocity increases concomitantly with the Reynolds number (Re) and the magnetic parameter (M), and is inversely proportional to the permeability parameter (X). Additionally, it has been noted that higher Reynolds (Re), Eckert (Ec), and Prandtl (Pr) numbers all result in larger fluid flow temperature profiles. Therefore, in this study, the temperature of the fluid flow varies directly proportional to the Reynolds number (Re), Eckert number (Ec), and Prandtl number (Pr).

Furthermore, it is discovered that larger viscosity variation parameter (γ) and magnetic field inclination angle (γ) lead to an increase in both velocity and temperature profiles of the fluid flow.

Nomenclature

Symbol	**Meaning**
B	Magnetic flux density, $[T]$
x, y	Dimensionless Cartesian coordinates
u, v	Components of velocity
L	Length of porous media $[m]$
Φ	Viscous dissipation function $[s^{-1}]$
k	Thermal conductivity of a fluid, $[WK^{-1}m^{-1}]$
M	Magnetic parameter
K_p	Darcy permeability, $[m^2]$
u_0	Initial Velocity of the fluid, $[ms^{-1}]$
Pr	Prandtl number
Re	Reynolds number
Ec	Eckert number
X	Permeability parameter
T	Absolute free temperature of the fluid, $[K]$
T_w	Temperature of the wall, $[K]$
T_∞	Temperature of the free-stream, $[K]$
T_f	Fluid’s film temperature
C_p	Specific heat at a constant temperature, $[\mathrm{JKg^{-1}K^{-1}}]$
μ	Coefficient of viscosity, $[Kgm^{-1}s^{-1}]$
v	Coefficient of kinematic viscosity, $[m^2s^{-1}]$
μ_0	Ambient fluid’s viscosity, $[Kgm^{-1}s^{-1}]$
ρ	Fluid’s density, $[Kgm^{-3}]$
σ	Electrical conductivity, $[\Omega^{-1}m^{-1}]$
k	Thermal diffusivity, $[m^2s^{-1}]$
θ	Angle of inclination
γ	Viscosity variation parameter

DATA AVAILABILITY

Only the parameter values were used as data in the present study.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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