https://dx.doi.org/10.4314/dujopas.v10i2c.24
ISSN (Print): 2476-8316
ISSN (Online): 2635-3490
Dutse Journal of Pure and Applied Sciences (DUJOPAS), *Vol. 10 No. 2c June 2024*

Magnetized Oscillatory Jeffrey Fluid Flow in A Porous Channel with Unequal Wall Temperature

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Abstract

The performance assessment of Jeffrey fluid impact on hydromagnetic oscillatory flow along a permeable plate immersed in porous medium is analysed in the optically thin thermal radiation regime. The exact solutions of the dimensionless equations have been determined. In view of the assumed oscillatory pressure gradient, the resultant linear partial differential equations were reduced to a boundary-valued-problem where the unsteady flow is superimposed on the mean steady flow. The influence of controlling parameters dictating the flow behaviour have been demonstrated graphically and explained thoroughly. It is established from the computational analysis that the function of Jeffrey fluid parameter is to increase the fluid velocity. Also, the shear stress is enhanced at both walls as the suction/injection parameter is increased. Interestingly, the results obtained for limiting case in this research is consistent with previous literature, thereby establishing the accuracy and correctness of the present analysis.

Keywords: Jeffrey fluid, Oscillatory flow, Magnetic field, Darcy porous medium, Slip parameter

INTRODUCTION

Basically, fluids are grouped as Newtonian and non-Newtonian fluids. Non-Newtonian fluids have many interesting and industrial advantages, and such fluids involving honey, blood, greases and oils. Since non-Newtonian fluids are difficult to be explained by a single constitutive equation like the Navier–Stokes equations, they appear to be more complex than Newtonian fluids. Despite their complexity, non-Newtonian fluids have portrayed more

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possible applications than Newtonian fluids. Some of the non-Newtonian models which have been investigated include the Jeffrey model (Nazeer *et al.* 2020, Nadeem *et al.* 2021), the Maxwell model (Fetecau *et al.* 2021, Sajid *et al.* 2021), the Oldroyd-B model (Elhanafy *et al.* 2019, Wang *et al.* 2019), and the Herschel–Bulkley model (Priyadharshini and Ponalagusamy 2015, Magnon and Cayeux 2021). One non-Newtonian fluid model of growing concern is the study of Jeffrey model, which is of the rate type. It demonstrates the linear viscoelastic effect of fluid which has several practical relevance in polymer productions (Yale *et al.,* 2019). The Jeffrey fluid showcases the impact of the quotient of relaxation to deceleration times and its constitutive equation can be minimized to that of a Newtonian fluid as a unique case. Unlike viscous fluid models, the Jeffrey model can be used in non-Newtonian fluids to explain the stress relaxation property and it produces better approximations to most physiological fluids (Kahshan *et al.* 2019). The Jeffrey fluid model was successfully used to model the peristaltic flow of chyme in the small intestines as reported by Akbar *et al.* (2013). Additionally, Sharma *et al.* (2017) used the Jeffrey fluid to model the flow of blood in narrow arteries. Nallapu and Radhakrishnamacharya (2014) provided an investigation of the effects of a magnetic field in the flow of the Jeffrey fluid in narrow tubes in a porous medium. Some other researches which have been completed on the Jeffrey model include the works by: Ellahi *et al.* (2014), Khan *et al.* (2018), Vaidya *et al.* (2020). Jeffery fluid flow problems are useful in nuclear engineering in connection with the cooling of reactors, in the case of flow past a semi-finite vertical plate under the action of transverses magnetic field and in the presence of suction as reported by Raju *et al.* (2019).

Magneto-hydrodynamics (MHD) is the analysis of electrically conducting liquids, namely, salty water, electrolytes, plasma, and liquid metals. This kind of fluid has a variety of scientific and technological significance, namely, in production of crystals, reactor cooling, magnetic drug targeting and MHD sensors. The empirical analysis of contemporary MHD flow in a laboratory was first done by Hartmann and Lazarus (1937). This investigation established the basic ideas for the creation of several MHD equipment, such as MHD pumps, MHD generators, brakes, flow meters and so on. Buoyancy-induced flow along a magnetized oscillating system with heat transfer across different geometrical settings, has been a topic of growing interest among many researchers today owing to its vast applications in geophysics, solid mechanics, hydrology, oil recovery and in the field of engineering, to cite a few (Chitra and Suhasini, 2018). With these concerns in mind, Usman *et al.* (2024) recently investigated the impact of thermophoresis on a thermally and chemically controlled Nanofluid flow affected by a magnetized oscillating system along a permeable sheet. Usman and Sanusi (2023) investigated the impacts of non-Newtonian nanofluid flows across a semi-infinite flat plate entrenched in a porous media affected by heat radiation, Soret, and pressure terms. Narayana and Venkateswarlu (2016) explained the implications of chemical reaction and heat generation impacts on transient MHD convection of a nanofluid flow within a semi-infinite flat plate in an oscillating system. Ramaiah *et al.* (2016) deliberated on the impacts of chemical reaction and radiation absorption on MHD convective of a chemically and thermally controlled flow of visco-elastic fluid through a porous medium restricted to an oscillating porous wall in the presence of heat absorption/generation. Sharma *et al.* (2022) presented the numerical study of MHD oscillatory flow of viscous dissipative fluid along an upstanding channel entrenched with porous medium due to heat source and thermal radiation impacts. Falade *et al.* (2017) deliberated on suction/injection effects in a magnetized oscillatory slip flow along a vertical plate with unequal wall temperature confined to an applied magnetic field. Hamza *et al.* (2011) outlined the influence of chemical reaction and slip condition on a transient MHD heat and mass transfer flow via a vertical plate filled with porous medium in an oscillating system.

The study of thermal radiation effect, which is the electromagnetic wave radiation that a surface generates because of its heat, is gaining growing attention, especially when a magnetic field is applied, due to its relevance in constructing different advanced energy conversion systems capable of operating at high temperatures (Jamaludin *et al.* 2020). Other areas of possible advantages include nuclear plants, solar technology, spacecraft aerodynamics, to state a few. In view of this, several scholars have carried out investigations on the impact of heat radiation in a number of physical configurations. With the numerous advantages of thermal radiation in mind, Hamza *et al.* (2023) recently scrutinized the consequences of thermal radiation and super-hydrophobicity on a magnetized natural convection fluid through a heated porous superhydrophobic microchannel. Shah *et al*. (2023) investigated the impact of heat transfer in MHD Casson flow in the presence of thermal and chemical reactions influenced by thermal fluid properties. Ojemeri *et al*. (2023) put forth MHD flow of an electrically conductive Casson fluid with thermal radiation effect in a vertical porous plate, Using Darcy's model, Gireesha *et al.* (2020) outlined how thermal radiation and free convection affected the flow of a water-based hybrid nanofluid containing nanoparticles through a porous vertical channel, and Goud *et al.* (2023) examined the analysis of transient MHD flow through a permeable medium across an upright plate in the context of the coexistence of viscous dissipation and thermal radiation effects. The impacts of thermal radiation, heat generation, and an induced magnetic field on the free convection of a couple stress fluid in a flux-isothermal upstanding plate have been analysed by Hasan *et al*. (2020) employing the method of indeterminate coefficient. Using the quasi-linearization technique, Kaladhar *et al.* (2016) highlighted couple stress fluid mixed convection in an upright channel in the coexistence of thermal radiation and Soret components. In the presence of thermal radiation, Bejawada and Nandeppanavar (2022) studied the effects of the MHD heat transfer problem on the micropolar fluid through a vertically permeable moving plate. Parthiban and Pasad (2023) outlined a theoretical investigation of radiative-convection effects on MHD fluid flow in a heated square enclosure having a non-Darcy square cavity in the coexistence of the Hall effect and the heat source or sink. Using a spectral relaxation method, Haroun et al. (2017) highlighted the impact of heat radiation on magnetized mixed convection nanofluid flow along a moving plate. The effects of combined convective radiation on the stagnation point flow of nanofluid across a stretching or contracting sheet with porosity implications have been highlighted by Pal and Mondal (2015) in the context of viscous dissipation and heat source coexistence.

A close examination of the above reviewed literature indicates that, little or no work has been done on the impact of Jeffrey fluid on magnetized oscillatory fluid flow across a porous medium through porous channel affected by suction/injection effect. Therefore, the main purpose of this paper is to build on the work done by Falade *et al*. (2017) by investigating the influence of Jeffrey fluid on hydromagnetic oscillatory flow coated with suction/injection effects filled with porous medium. The results of this kind of research would be useful in engineering and industry applications, particularly for exploration of crude oil from petroleum products. Further, Jeffrey fluid is one of the rate type materials that demonstrates the linear viscoelastic effect of fluid which also has several advantages in polymer factories. Hence, the motivation for this study.

DESCRIPTION OF THE FLOW PROBLEM

Imagine the steady natural convection flow of a Jeffrey fluid within an upstanding permeable channel in an oscillating system affected by an applied transverse magnetic field. It is thought of that there is no applied voltage which signifies the non-involvement of an electric field. The flow is assumed to be in the x -direction which is taken along the plate in the upward direction, the y –axis is perpendicular to it and the z axis along the wideness of the channel as sketched in Figure 1. Also, it is assumed that the whole system is rotating with a constant vector Ω about y –axis. Since it is presumed that the plate surface is semi-infinite, the flow variables are functions of y only. Following Falade *et al*. (2017) and taking into account the Jeffrey fluid parameter, while obeying the Bousinesq approximation, the resultant equations of this problem can be modelled as:

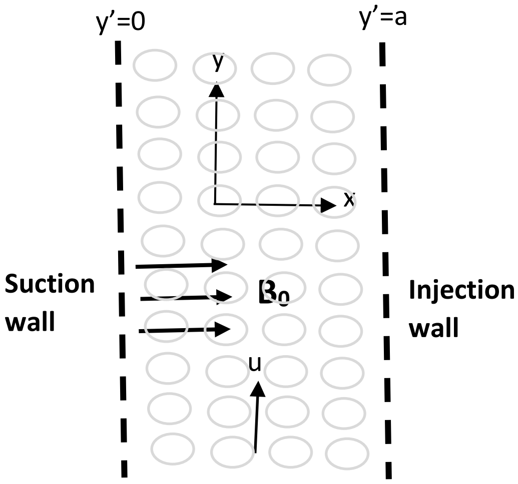

Figure 1. Sketch of the flow system

$$\frac{\partial u'}{\partial t'} - v_0\frac{\partial u'}{\partial y'} = -\frac{1}{\rho}\frac{dP}{dx'} + \frac{v}{(1+B)}\frac{\partial^2 u'}{\partial y'^2} - \frac{v}{K}u' - \frac{\sigma_e B_0^2 u'}{\rho} + g\beta(T' - T_O) \quad (1)$$

$$\frac{\partial T'}{\partial t'} - v_0\frac{\partial T'}{\partial y'} = \frac{k_f}{\rho c_\rho}\frac{\partial^2 T'}{\partial y'^2} + \frac{4\alpha^2}{\rho c_\rho}(T - T_O) \quad (2)$$

With the boundary condition $T = T_1$

$$u' = \frac{\sqrt{K}}{\alpha_s}\frac{\partial u'}{\partial y'}, T = T_0 \;\; on\; y' = 0 \quad (3)$$

$$u' = 0, T' = T_1 \;\; on\; y' = a \quad (4)$$

While the dimensionless quantities used are provided below:

$$(x\;\; y) = \frac{(x',y\prime)}{h}, u = \frac{hu\prime}{v}, t = \frac{vt\prime}{h^2}, p = \frac{h^2 p\prime}{\rho v^2}, Gr = \frac{g\beta(T_1 - T_0)h^3}{v^2}, Pr = \frac{h^2 p\prime}{\rho v^2}, \theta = \frac{T - T_0}{T_1 - T_0}$$

$$\delta = \frac{4x^2h^2}{\rho C_p v}, \gamma = \frac{\sqrt{K}}{\alpha_s h}, Ha^2 = \frac{\sigma_e B_0^2 h^2}{\rho v}, Da = \frac{K}{h^2}, s = \frac{v_0 h}{v}$$

(5)

Inserting equation (5) into equations (1 – 4), we have the dimensionless governing equations as follows:

$$\frac{\partial u}{\partial t} - s\frac{\partial u}{\partial y} = -\frac{dP}{dx} + \left(\frac{1}{1+B}\right)\frac{\partial^2 u}{\partial y^2} - \left(Ha^2 + \frac{1}{Da}\right)u + Gr\theta \quad (6)$$

$$\frac{\partial \theta}{\partial t} - s\frac{\partial \theta}{\partial y} = \frac{1}{Pr}\frac{\partial^2 u}{\partial y^2} + D\theta \quad (7)$$

With the appropriate boundary conditions

$$\left.\begin{aligned} u = \gamma\frac{du}{dy},\;\; \theta = 0 \;\; on \;\;\; y = 0 \\ u = 0,\;\; \theta = e^{iwt} \;\;\; on \;\;\; y = 1 \end{aligned}\right\} \quad (8)$$

3.0 Solution Procedure

We employed the theory of simultaneous differential equations to solve the resultant linear partial differential equations restricted to relevant boundary condition, after the unsteady flow is superimposed on the mean steady flow, so that in the neighbourhood of the plate, and assuming that an oscillatory pressure gradient as shown eqn (9), the solutions of velocity and temperature is in the form:

$$-\frac{dP}{dx} = \lambda e^{iwt},\ \mathrm{u(t,y)} = u_0(y)e^{iwt},\ \theta(t,y) = \theta_0(y)e^{iwt} \tag{9}$$

Where λ is any constant, and ω is the frequency of oscillation (See Falade *et al.* (2017)). In view of (9), eqns (6 – 8) reduced to a boundary-valued-problem as follows:

$$u_0'' + \frac{s}{a_1}u_0' - \frac{1}{a_1}\left(Ha^2 + \frac{1}{Da} + i\omega\right)u_0 = -\frac{\lambda}{a_1} - \frac{Gr}{a_1}\theta \tag{10}$$

$$\theta_0'' + sPr\theta_0' - (D - i\omega)\theta_0 = 0 \tag{11}$$

Subject to relevant boundary conditions:

$$\left.\begin{array}{l} u_0 = \gamma u_0',\ \theta_0 = 0 \quad on \quad y = 0 \\ u_0 = 0, \quad \theta_0 = e^{iwt} \quad on \quad y = 1 \end{array}\right\} \tag{12}$$

The exact solutions of temperature and velocity is obtained as:

$$\theta(t,y) = (A_0e^{m1y} + B_0e^{m2y})e^{iwt} \tag{13}$$

$$u(t,y) = (A_1e^{m3y} + B_1e^{m4y} + C_1 + D_1e^{m1y} + E_1e^{m2y})e^{iwt} \tag{14}$$

The heat transfer rate and frictional force is also computed as follows:

$$Nu = \frac{\partial\theta}{\partial y} = (A_0m1e^{m1y} + B_0m2e^{m2y})e^{iwt} \tag{15}$$

$$S_f = \frac{\partial u}{\partial y} = (A_1m3e^{m3y} + B_1m4e^{m4y} + m1D_1e^{m1y} + m2E_1e^{m2y})e^{iwt} \tag{16}$$

where

$$m1 = \frac{sPr+\sqrt{(sPr)^2-4\mathrm{Pr}\,(D-i\omega)}}{2}\ m2 = \frac{-sPr-\sqrt{(sPr)^2-4\mathrm{Pr}\,(D-i\omega)}}{2}, m3 = \frac{\frac{s}{a_1}+\sqrt{\left(\frac{s}{a_1}\right)^2-\frac{4}{a_1}\left(Ha^2+\frac{1}{Da}+i\omega\right)}}{2}$$

$$m4 = \frac{-\frac{s}{a_1} - \sqrt{\left(\frac{s}{a_1}\right)^2 - \frac{4}{a_1}\left(Ha^2 + \frac{1}{Da} + i\omega\right)}}{2}, A_0 = -\frac{1}{e^{m2} - e^{m1}}, B_0 = \frac{1}{e^{m2} - e^{m1}},$$

$$C_1 = \frac{\lambda}{\left(Ha^2+\frac{1}{Da}+i\omega\right)},\ D_1 = -\frac{GrA_0}{m_1^2+sm1-\left(Ha^2+\frac{1}{Da}+i\omega\right)},$$

$$E_1 = -\frac{GrB_0}{m_2^2+sm2-\left(Ha^2+\frac{1}{Da}+i\omega\right)}, a_1 = \frac{1}{1+B}, a_2 = C_1 + D_1 + E_1, a_3 = m1\gamma D_1 + m2\gamma E_1,$$

$$a_4 = C_1 + D_1e^{m1} + E_1e^{m2},\ B_1 = -\frac{\left(a_4+\frac{(m4\gamma-1)e^{m3}}{1-m3\gamma}\right)}{\left(e^{m4}+\frac{(m4\gamma-1)e^{m3}}{1-m3\gamma}\right)},\quad A_1 = \frac{B_1(m4\gamma-1)+a_3-a_2}{1-m3\gamma}$$

RESULTS AND DISCUSSION

The study of Jeffrey fluid on MHD oscillating system equipped with radiation and porous medium impacts on natural convection flowing through an immeasurable upstanding permeable plate has been performed. The flow is instigated by buoyancy-induced growing pressure gradient along an upward facing plate. In order to point out the effects of physical parameters such as; Jeffrey fluid parameter B, suction parameter s, magnetic parameter Ha and thermal Grashof number Gr, on the flow behaviours, computation of the flow fields is carried out. The influences of the major controlling parameters on the temperature and velocity distributions have been presented and discussed in Figures 4.2 to 4.12. The main default values selected for this analysis as they relate to real life applications are $B = 0.1$, s=1, Ha=1, $\delta = 1$, Da=1, $\omega = \pi$ and Gr=1. The graphical comparison of the work of Falade *et al.* (2017) and the present investigation is portrayed in Figure 4.1. The comparison displays an excellent agreement for the limiting case when Jeffrey parameter, B is zero.

The action of Jeffrey fluid parameter on the fluid velocity is depicted in Figure 4.2. It can clearly be seen that with the enhancement of the Jeffrey fluid parameter, the fluid flow increases its flow pattern hence the velocity profile experience a growth. The velocity gradient for the application of various values of magnetic effect and is illustrated in Figure 4.3. The action of magnetic field perpendicular to the flow in an electrically conducting fluid produces a Lorentz force, which opposes the flow. With the aid of Figure 4.4, we comprehend the behaviour of fluid velocity as the Darcy porous medium is varied. It is apparent from this diagram that the fluid motion grows as Darcy number is raised. This is true since, with stronger permeability of the porous material, the barriers placed on the flow path reduces, thereby encouraging free flow leading to stronger fluid speed. This action makes the fluid boundary wall and thickness to rise, which in turn escalates the fluid velocity. Thermal radiation's impact on the fluid temperature and velocity are seen in Figure 4.5 and Figure 4.6 respectively. It is noteworthy to report that when the thermal radiation is increased, the temperature of the fluid is notice to improve. This is attributable to the heat transport from the upper surface to the fluid because the fluid takes in its own radiations. Further, as displayed in Figure 4.6, the fluid motion is accelerating as a function of growing thermal radiation effect owing to heat production that elevates the flow movement. This is so because the heat emitted from the heated wall strengthens the fluid particles. The consequences of varying suction/injection parameter are demonstrated in Figure 4.7 and Figure 4.8 respectively. From the sketch in Figure 4.7, it is viewed that mounting level of suction/injection parameter encourages the fluid temperature. The concavity with the rise in the suction/injection parameter is due to the direction of temperature flow from the hot plate towards the cold wall. Similarly, it is evident that increasing the suction/injection raises the fluid velocity towards the cold wall as shown in Figure 4.8. Figure 4.9 explains that increasing the frequency of oscillation retards the fluid temperature inside the channel which is due to the weakening in the heat transfer amount as the heating frequency. The effect of Jeffrey fluid parameter is demonstrated in Figure 4.10. It is seen that a rise in the skin friction is established in the cold plate while a reverse attribute happens in the heated wall. However, a point of intersection is viewed near the middle of the vertical channel. Figure 4.11 illustrates the function of suction/injection effect on the heat transfer amount across the channel. It is evident that the heat transfer rate is lowered in the fluid layer near the heated wall whereas a contrast behaviour is established close to the cold wall. The skin friction is enhanced at both plates as the suction/injection parameter increases as plotted in Figure 4.12.

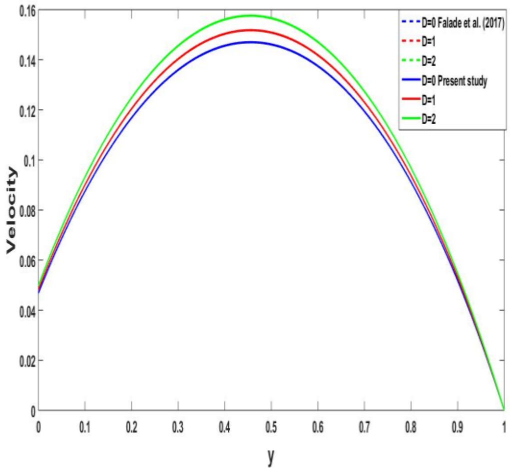

Figure 4.1: Comparison with the work of Falade *et al.* (2017) and the present work

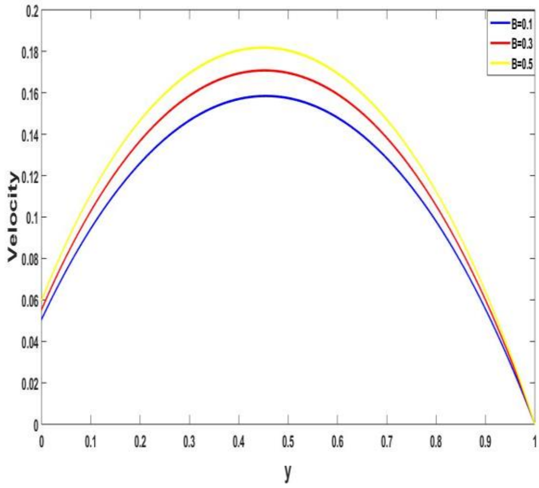

Figure 4.2: Application of Jeffrey parameter on Velocity distribution

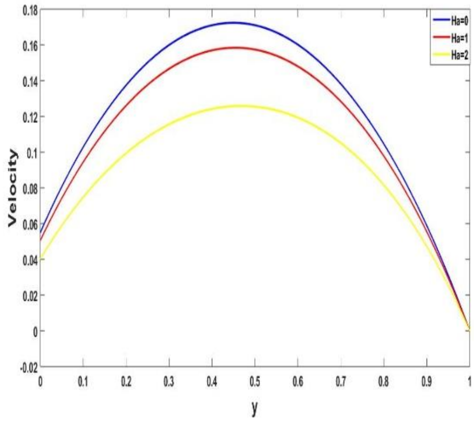

Figure 4.3: Application of Hartmann number on Velocity distribution

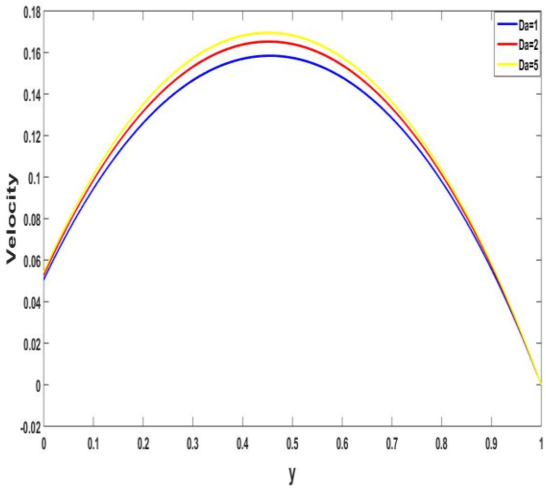

Figure 4.4: Application of Darcy number on Velocity distribution

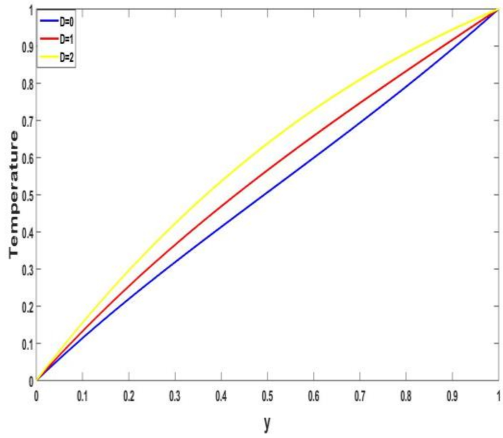

Figure 4.5: Application of thermal radiation on Temperature distribution

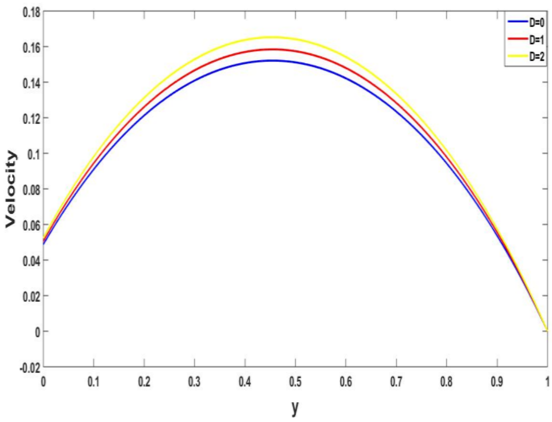

Figure 4.6: Application of thermal radiation on Velocity distribution

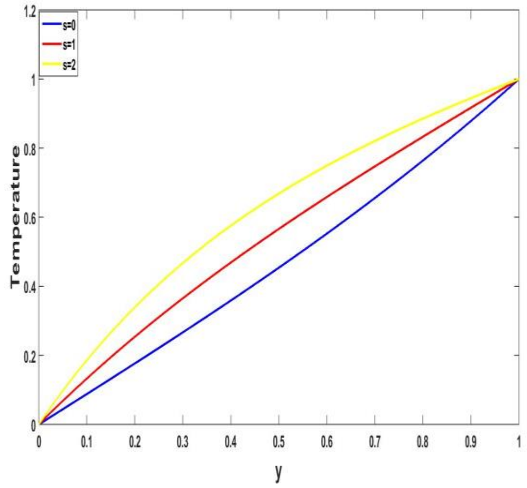

Figure 4.7: Application of suction/injection on Temperature distribution

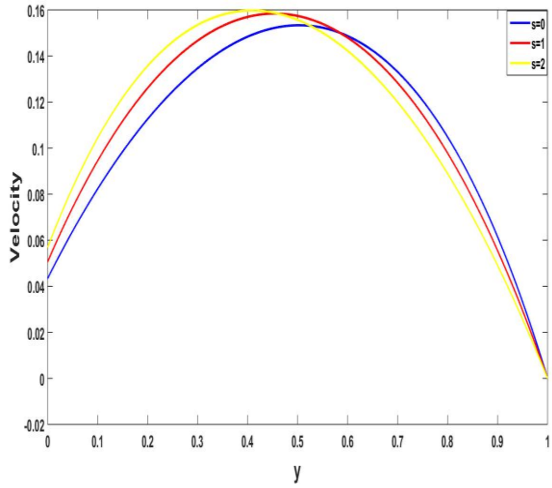

Figure 4.8: Application of suction/injection on Velocity distribution

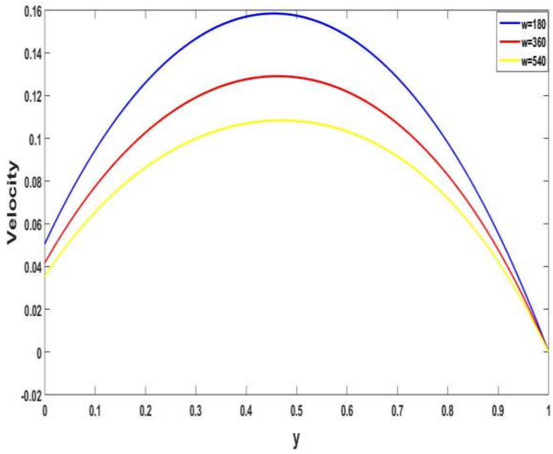

Figure 4.9: Application of oscillation parameter on Velocity distribution

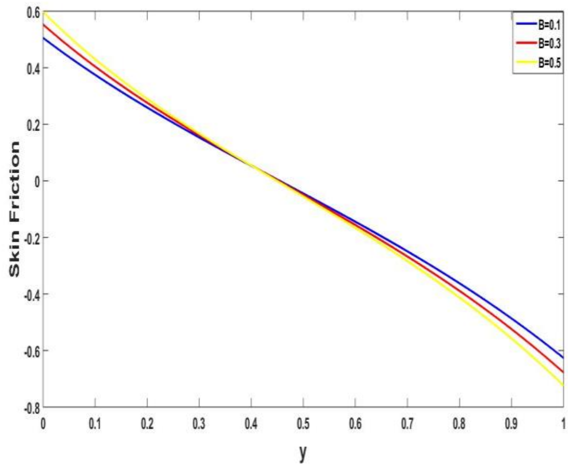

Figure 4.10: Application of Jeffrey parameter on Skin friction

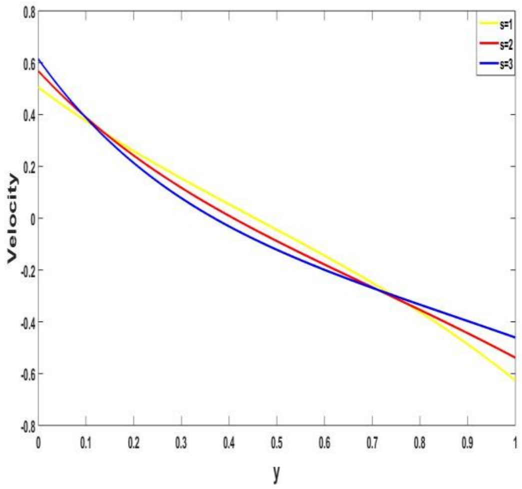

Figure 4.11: Application of suction/injection on Skin friction

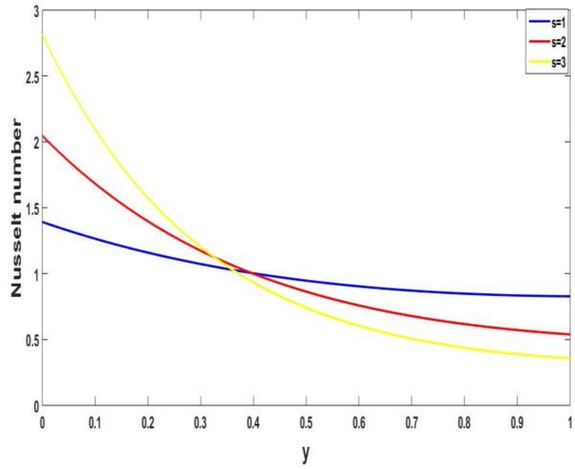

Figure 4.12: Application of suction/injection on Nusselt number

CONCLUSION

The analysis of Jeffrey fluid effect on hydromagnetic oscillatory flow along a permeable channel saturated with porous material is investigated in the optically thin thermal radiation regime. The exact solutions of the non-dimensional equations have been derived and the impacts of pertinent embedded parameters dictating the flow pattern have been illustrated graphically and discussed. The Jeffrey fluid model is an easier model that adequately explains the physiological and peristaltic flows of non-Newtonian form. Additionally, the Jeffrey fluid's viscoelastic characteristics have led to various practical uses in the synthesis of polymers. The summary of the major outcome from this work is stated as:

i. The application of Jeffrey fluid parameter is observe to drastically enhance the fluid velocity
ii. Suction/injection increases the fluid temperature and velocity respectively
iii. The amount of heat transfer is decreased at the heated wall for growing values of suction/injection while a counter attribute happens at the cold plate
iv. The effect of Jeffrey fluid parameter is observed to raise the shear stress at the cold plate while a reverse attribute happens in the heated wall
v. In the future, the impacts of viscous dissipation, heat source/sink and variable thermal conductivity will be studied on this model.

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