

Numerical Study of Magnetohydrodynamic (MHD) Mixed Convection with Slip Effects Near a Stagnation Point Over a Nonlinear Stretching Vertical Sheet of Jeffrey Fluid in a Porous Medium with Suction and Injection: A Biofluid Heat Transfer Modeling Approach

Dr. Arjun Mehta^{1*}
Prof. Rakesh Sharma²
Dr. Neha Verma³

¹ University of São Paulo, Department of Applied Mathematics and Biomedical Fluid Dynamics, São Paulo, Brazil

² University of Cape Town, Centre for Computational Transport Phenomena in Bioengineering, Cape Town, South Africa

³ University of Tokyo, Institute of Theoretical and Applied Fluid Mechanics, Tokyo, Japan

ABSTRACT

We investigate numerically the effects of linear or non-linearly stretching and suction or injection of MHD mixed convection stagnation-point of Jeffrey fluid flow with slip and radiation on a near stagnation-point towards a vertical plate embedded in a porous medium. The partial momentum and energy equations are transformed into a set of ordinary differential equations by employing suitable similarity transformations and are solved numerically using Runge-Kutta fourth order in association with shooting technique in MATLAB. The effects of non-dimensional parameters such as Jeffrey parameter, suction/injection parameter, slip velocity parameter, linear or non-linearity parameter, magnetic parameter, permeability parameter, velocity ratio parameter, Prandtl number, thermal radiation parameter and Eckert number on velocity and temperature profiles are presented graphically while the skin friction and the rate of heat transfer are represented numerically.

Keyword: Jeffrey parameter, MHD mixed convection, non-linearly stretching sheet, Porous medium, slip flow, thermal radiation, viscous dissipation.

I. INTRODUCTION

The problem of stagnation-point flow and heat transfer on stretching sheet arises in abundance of practical applications in industry and engineering, such as cooling of electronic devices and nuclear reactors, polymer extrusion, drawing of plastic sheets and more over the magneto hydrodynamic (MHD) flow which has both liquid and magnetic properties and can exhibit particular characteristics in thermal conductivity. The flow regime is called the slip flow regime and its effect cannot be neglected. The problem of the slip flow regime is much important in this area of modern science, technology and vast ranging industrialization. Copious devotion has been given to the stretching sheet with stagnation-point flow is of its decisive practical applications. These applications consist of, glass fiber, cooling of metallic plates, extrusion of polymers and aerodynamics. Stagnation flow is the name given to fluid flow near a stagnation-point. In the stagnation area fluid pressure and the rate of heat and mass transfer are highest. The study of convective heat transfer through porous medium for an incompressible fluid on the heated surface has received major attention because of its diverse uses in the insulation of nuclear reactors, petroleum industry, geothermal problems, storage of nuclear waste, and several other areas.

The study of MHD mixed convection flow near the stagnation-point flow on stretching sheet has attracted many researchers in recent times, and many problems are discussed as regards different aspects (suction/injection and linear or non-linear) including the effect of slip [1-6]. Aman et al. [7] investigated the steady 2-D stagnation-point flow of MHD incompressible viscous fluid towards stretching/ shrinking sheet. MHD stagnation-point flow of a viscous, incompressible and electrically conducting fluid over a stretching/shrinking permeable semi-infinite flat plate is studied numerically by Sharma et al. [8]. Sin Wei Wong et al. [9] an analysis is carried out to study the steady two-dimensional stagnation-point flow of an incompressible viscous fluid towards a stretching vertical sheet. It is assumed that the sheet is stretched non-linearly, with prescribed surface heat flux. Falade et al. [10] investigated the effect of suction/injection on the unsteady oscillatory flow through a vertical channel subjected to a transverse magnetic field. Exact solution of the governing equation has been obtained under the usual Boussinesq

approximation and the effects of the flow parameters on temperature, velocity profiles, skin friction and rate of heat transfer are discussed. Shenet al. [11] described MHD mixed convection near a stagnation-point flow over a non-linear stretching sheet with heat flux in the presence of slip velocity. Layek et al. [12] studied the boundary layer flow near stagnation point in a porous medium over a stretching sheet with heat generation and injection/suction. Mukhopadhyay [13] studied the impact of velocity slip on boundary-layer over a non-linearly stretching surface with suction/injection.

The study of non-Newtonian fluids has been focusing on several investigations during the past few decades because of its extensive engineering and industrial applications. Especially, industries and engineering, polymer solutions and in polymer melt in the plastic processing, non-Newtonian fluids and heat transfer play central role in food engineering, petroleum production also. Wang [14], Labropulu and Li [15] examined the effect of slip flow of a non-Newtonian fluid behavior at a stagnation-point over a plate. Abel and Mahesha [16] analyzed the effects of MHD flow of a non-Newtonian visco-elastic fluid over a stretching sheet in the presence of non-uniform radiation and heat source. Mahanta and Shaw [17] investigated the MHD Casson fluid flow over a linearly stretching porous sheet with convective boundary. Ramachandran et al. [18] discuss the consequent flow and heat transfer characteristics that are also brought about by the stretching sheet with power-law velocity variation. Hsiao [19] described MHD mixed convection heat transfer of a second-grade viscoelastic fluid past a wedge in porosity with suction or injection.

Radiation is the process by which heat energy is transmitted from one place to another without the aid of any material medium. When a body is hot, the energy of vibration of the atoms and molecules is sent out from it in the form of radiant heat waves. These waves when falling on another body induce the molecules to vibrate there and hence the body is heated up. In many fluid-particle flows, thermal radiation effects play an important role in altering the heat transfer characteristics. Muthucumaraswamy and Visalakshi [20] studied radiative flow and heat transfer past an exponentially accelerated vertical plate with uniform mass diffusion. Effects of thermal radiation and porosity on MHD mixed convection flow in a vertical channel using homotopy analysis method were also carried out by Srinivas and Muthuraj [21]. Rosca and Pop [22] explored steady forced flow and convection heat transfer over a vertical shrinking/stretching sheet using slip condition. Andersson [23] studied the effect of slip on viscous fluid flow past a linearly stretching sheet, it is identified that the assumption of the convective no-slip condition at the boundary is not always true and therefore should be replaced by partial slip boundary conditions in certain situations. Chaudhary and Kumar [24] analyzed the steady 2-D boundary-layer flow of electrically conducting incompressible fluid near a stagnation-point past a shrinking sheet with slip conditions. Recently Ming Shen et al. [25] studied on mixed convection MHD viscous flow near a stagnation-point region over a non-linear stretching sheet with velocity slip and prescribed surface heat flux.

Inspired by the above applications and surveys explained, the purpose of this present study is to investigate numerically the effects of linear or non-linearly stretching and suction or injection of MHD mixed convection stagnation-point of Jeffrey fluid flow with slip and radiation on a near stagnation-point towards a vertical plate embedded in a porous medium. The results are presented graphically and in tabular form. The results for special cases are also compared to those by Stanford Shateyi and Fazole Mabood [26] and Wang [14]. Approximations of skin friction and the rate of heat transfer which are very dynamic role in engineering applications point of view are also presented in this study. It is predicted that the results obtained in this study will contribute as a corresponding to previous studies and also provide useful information for further investigation.

II. MATHEMATICAL FORMULATION OF THE PROBLEM

In this study we investigate numerically the effects of linear or non-linearly stretching and suction or injection of MHD mixed convection Jeffrey fluid flow with slip and radiation on a near stagnation-point towards a vertical plate embedded in a porous medium. Here the prescribed surface heat flux is also considered. The axis is taken along the continuous stretching surface in the direction of motion with the slot as the origin and y -axis is perpendicular to it and the flow is confined in half plane $y > 0$.

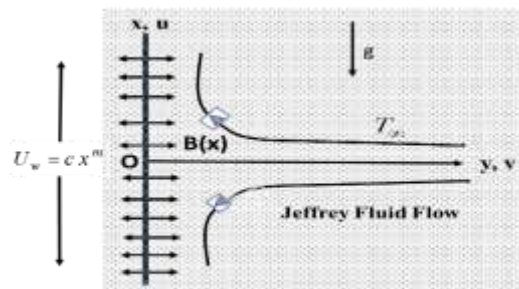


Figure 1. Physical model

A uniform magnetic field of strength $B(x)$ is applied normal to the direction of level surface, fig. 1. The stretching sheet velocity is supposed to be $u_w(x) = cx^m$ and $u_e(x) = ax^m$ as an external velocity, where c and a are positive constants. While m is the linearity parameter, with $m = 1$ for the linear case and $m \neq 1$ for the non-linear case. Under the above assumptions and the boundary-layer and Boussinesq approximation, the governing equations for the current study are given by:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = u_e \frac{du_e}{dy} + \frac{v}{1 + \lambda_1} \frac{\partial^2 u}{\partial y^2} - \frac{\sigma B^2(x)}{\rho} (u_e - u) - \frac{v}{K} u + g\beta(T - T_\infty) \quad (2)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho C_p} \frac{\partial q_r}{\partial y} + \frac{\mu}{\rho C_p} \left(\frac{\partial u}{\partial y} \right)^2 \quad (3)$$

The associated boundary conditions to the current model is given by:

$$u = u_w(x) + \frac{2 - \delta_v}{\delta_v} \lambda_0 \frac{\partial u}{\partial x}, \quad v = v_w(x), \quad \frac{\partial T}{\partial y} = -\frac{q_w(x)}{k} \quad \text{at } y=0 \quad (4)$$

$$u \rightarrow u_e(x), \quad T \rightarrow T_\infty \quad \text{as } y \rightarrow \infty \quad (5)$$

By using the Rosseland diffusion approximation, Hossain *et al.* [27] and Raptis [28] among other researcher the radiative heat flux q_r is given by:

$$q_r = -\frac{4\sigma^* T_\infty^3}{3K_s} \frac{\partial T^4}{\partial y} \quad (6)$$

We assume that the temperature differences within the flow are sufficiently small so that T^4 may be expressed as a linear function of temperature T .

$$T^4 \approx 4T_\infty^3 T - 3T_\infty^4 \quad (7)$$

Using eqs. (6) and (7) in the fourth term of eq. (3) we obtain:

$$\frac{\partial q_r}{\partial y} = -\frac{16\sigma^* T_\infty^3}{3K_s} \frac{\partial^2 T}{\partial y^2} \quad (8)$$

III. SIMILARITY ANALYSIS

We introduce the following similarity transformations followed by Shen *et al.* [14]:

$$\eta = \sqrt{\frac{a}{v}} y x^{\frac{m-1}{2}}, \quad \psi = \sqrt{av} x^{\frac{m+1}{2}} f(\eta), \quad \theta = \sqrt{\frac{a}{v}} \frac{k(T - T_\infty)}{q_0 x^{2m-1}} \quad (9)$$

Here ψ is the stream function such that $u = \frac{\partial \psi}{\partial y}$, $v = -\frac{\partial \psi}{\partial x}$ and continuity equation is automatically satisfied. By

using eq. (9), the velocity components for u and v are given:

$$u = ax^m f'(\eta), \quad v = -\sqrt{av} x^{\frac{m-1}{2}} \left[\frac{m+1}{2} f(\eta) + \frac{m-1}{2} \eta f'(\eta) \right] \quad (10)$$

where primes denote differentiation with respect to η . We remark that to obtain similarity solutions, $B(x)$, $v_w(x)$ and $q_w(x)$ are taken:

$$B(x) = B_0 x^{\frac{m-1}{2}}, \quad v_w = -\frac{\sqrt{av}(m+1)}{2} x^{\frac{m-1}{2}} f_w, \quad q_w(x) = q_0 x^{\frac{5m-1}{2}} \quad (11)$$

where B_0, f_w and q_0 are arbitrary constants. We also have $f_w > 0$ and $f_w < 0$ are the injection and suction cases respectively and substituting the similarity variables in eqs. (2) and (3) we obtain the following system of ODE:

$$\frac{1}{(1+\lambda_1)} f''' + \left(\frac{m+1}{2}\right) f f'' - m(1-f'^2) - \left(\frac{1}{K} + M\right)(1-f') + \lambda \theta = 0 \quad (12)$$

$$\left(1 + \frac{4}{3R}\right) \theta'' + \text{Pr} \left\{ \left(\frac{m+1}{2}\right) f \theta' - (2m-1) f' \theta + Ec(f'')^2 \right\} = 0 \quad (13)$$

the corresponding boundary conditions are:

$$f(0) = f_w, \quad f'(0) = \varepsilon + \delta f''(0), \quad \theta'(0) = -1 \quad (14)$$

$$f(\infty) = 1, \quad \theta(\infty) = 0 \quad (15)$$

We have $M = B_0^2 / \rho a$ is the magnetic parameter, $\lambda = g\beta q_0 (v)^{1/2} / k a$ is the mixed convection parameter, $\text{Pr} = \nu / \alpha$ is the Prandtl number, $Ec = a^{3/2} x^{3m} / \rho C_p$ is the Eckert number, $\varepsilon = c/a$ is the velocity ratio parameter, $R = 4\sigma^* T^3 / \rho C_p k_1$ is the thermal radiation parameter $\delta = (2 - \sigma_v) k x_n \text{Re}_x^{1/2} / \sigma_v$ is the velocity slip parameter.

IV. LOCAL SKIN FRICTION AND NUSSELT NUMBER

The physical parameters interest for the present problem are the local skin friction coefficient C_f and the local Nusselt number Nu_x , which are defined as:

$$C_f = \frac{\tau_w(x)}{\rho(1+\lambda_1)u_p^2}, \quad Nu_x = \frac{xq_w(x)}{k(T_w - T_\infty)} \quad (16)$$

with the surface shear stress $\tau_w(x) = \partial u / \partial y|_{y=0}$ and $q_w(x)$ is the wall heat flux. We then obtain the following expressions after applying the similarity variables:

$$\text{Re}_x^{1/2} C_f = \frac{f''(0)}{(1+\lambda_1)}, \quad \text{Re}_x^{1/2} Nu_x = \frac{1}{\theta'(0)} \quad (17)$$

with $\text{Re}_x = u_e x / \nu$ being the Reynolds number. Numerical values of the function $f''(0)$ and $\theta'(0)$ which represent the wall shear stress and the heat transfer rate at the surface respectively for various values of the parameter are presented in Table 1.

V. RESULTS AND DISCUSSION

In this paper, the effects of linear or non-linear stretching sheet of suction or injection of MHD mixed convection stagnation-point of Jeffrey fluid flow with slip towards a vertical plate embedded in a porous medium is analyzed. The boundary value problem containing coupled equations in velocity and temperature is solved numerically by shooting technique with Runge-Kutta fourth order using MATLAB. The effects of, Jeffrey parameter λ_1 , Magnetic parameter M , porous medium parameter K , the velocity slip parameter δ , velocity ratio parameter ε , Prandtl number Pr , suction/injection parameter f_w , Eckert number Ec , thermal Radiation parameter R and linear or non-linear parameter m ($m = 1$ or $m = 2$) and buoyancy parameter λ are depicted through graphs on velocity $f'(\eta)$ and

temperature $\theta(\eta)$ profiles with fixed values of $\lambda_1 = 1, M = 2, K = 1, \delta = 1, \varepsilon = 0.5, Pr = 0.7, Ec = 1, f_w = 1, \lambda = 1$ and $m = 1$ or $m = 2$. In order to assure the accuracy of the applied numerical scheme the computed values of Skin friction coefficient $\frac{f''(0)}{1 + \lambda_1}$ and local Nusselt number $-\theta'(0)$ are compared with the available results of Stanford Shateyi and FazleMabood [26] and Wang [14] in Table 1 and have found in excellent agreement.

The numerical results are illustrated graphical in figs.2-17. From figures 2, 3, 4 and 5, it is seen that the effects of Jeffrey parameter λ_1 , the velocity slip parameter δ , velocity ratio parameter ε and Eckert number Ec , on the velocity profiles for both assisting and opposing cases vary with linear ($m = 1$) and non-linear ($m = 2$). It is observed that velocity grows with an increasing of Jeffrey parameter λ_1 , slip parameter δ , velocity ratio parameter ε and Eckert number Ec , for all the cases of linearity ($m = 1$), non-linearity ($m = 2$) vary with assisting flow ($\lambda = 1$) and opposing flow ($\lambda = -1$). And it is observed that the velocity attains the maximum value at $m = 1$ and $\lambda = 1$. The opposite behavior is observed for the Magnetic parameter M from figure 6.

Figures 7 and 8 represent the influence of porous medium parameter K and Prandtl number Pr , on the velocity profiles for both assisting ($\lambda = 1$) and opposing ($\lambda = -1$) cases vary with linear ($m = 1$) and non-linear ($m = 2$). It can be seen that increase of the mixed buoyancy parameter causes the velocity profiles to increase. The velocity decreases with an increasing of porous medium parameter K ($= 0, 1, 2$) and Prandtl number Pr ($= 0.7, 1.7, 2.7$), with non-linearity value ($m = 2$) and the opposite behavior at $\lambda = -1$. The velocity attains the maximum value for the values of $m = 1$ and $\lambda = 1$.

Figures 9 and 10 indicates the effect of suction/injection parameter f_w on the velocity profiles for both assisting and opposing cases vary with linear $m = 1$ and non-linear $m = 2$. It can be observed that increasing the mixed buoyancy parameter causes the velocity profiles to increase. We can also observe that the velocity profiles are significantly influenced by suction/injection parameter f_w . The velocity decreases with an increasing of suction parameter $f_w = 0, 1, 2$ with non-linearity value ($m = 2$) and the opposite behavior with $\lambda = -1$. The velocity attains the maximum value for the values of $m = 1$ and $\lambda = 1$.

In figures 11, 12, 13, 14 and 15 represent the effects of suction $f_w > 0$, injection parameter $f_w < 0$, Prandtl number Pr , thermal Radiation parameter R and the velocity slip parameter δ , on the temperature profiles for both assisting $\lambda = 1$ and opposing $\lambda = -1$ cases vary with linear ($m = 1$) and non-linear ($m = 2$). It can be seen that growing the mixed buoyancy parameter causes the temperature profiles to increase. We can also observe that the temperature profiles are significantly influenced by $f_w > 0, f_w < 0, Pr, R$ and δ . The temperature decreases with an increasing of $f_w > 0, f_w < 0, Pr, R$ and δ with linear ($m = 1$) and non-linearity value ($m = 2$). Here the temperature profile attains the maximum value for the values of $m = 1$ and $\lambda = 1$.

Figure 16, depicts the influence of Eckert number Ec , on the temperature profile for both assisting $\lambda = 1$ and opposing $\lambda = -1$ cases vary with linear ($m = 1$) and non-linear ($m = 2$). It can be illustrated that increase in the mixed buoyancy parameter causes the temperature profiles to increase. We can also observe that the temperature profiles are significantly influenced by Ec . The temperature increases with an increasing of Ec with linear ($m = 1$) and non-linearity value ($m = 2$). It is also observed that the temperature profile attains the maximum value for the values of $m = 1$ and $\lambda = 1$. The effects of linear and non-linear parameter m on temperature is shown in figure 17 for both assisting $\lambda = 1$ and opposing $\lambda = -1$ cases. The temperature increases with an increasing of m ($= 0, 1, 2$) for assisting ($\lambda = 1$) case and the opposite behavior is observed for the case of opposing $\lambda = -1$.

VI. CONCLUSIONS

Numerically investigate the effects of linear or non-linear stretching and suction or injection of MHD mixed convection stagnation-point of Jeffrey fluid flow in a vertical plate embedded in a porous medium with slip. The boundary value problem containing coupled equations in velocity and temperature is solved numerically by shooting

technique with Runge-Kutta fourth order using MATLAB. Further numerical results for the skin friction coefficient and the rate of heat transfer at the surface are in closed agreement with the results which were obtained by earlier researchers in the absence of Jeffrey parameter λ_1 , Porous medium parameter K .

- The governing equations are solved numerically by shooting technique with Runge-Kutta fourth order using MATLAB.
- We conclude that the velocity decreases with increase of $M, K, Pr, f_w > 0$ and $f_w < 0$ as well as the temperature decreases with increasing of $R, m, \delta, Pr, f_w > 0$ and $f_w < 0$. And also the velocity increases with increase of $M, \lambda_1, \delta, \varepsilon$ and Ec as well as the temperature increases with increasing of Ec for different aspects ($\lambda = 1, \lambda = -1$ with $m = 1, 2$).
- Table 1 shows that the skin friction coefficient $f''(0)$ increases with the increasing values of the Jeffrey fluid parameter λ_1 and decreasing with the vales of porous medium K . Further it is observed that the values of the rate of heat transfer $-1/\theta'(0)$ at the surface. From this table it is observed that the rate of heat transfer $-1/\theta'(0)$ decreases with increasing values of Jeffrey fluid parameter λ_1 and porous medium K .

Table 1: Comparison of $-f''(0)$ and $-1/\theta'(0)$ for various values of λ_1 and K . For fixed values of $\lambda_1 = 1, M = 2, K = 1, \delta = 1, \varepsilon = 0.5, Pr = 0.7, Ec = 1, f_w = 1, (m = 1 \text{ or } m = 2)$ and $\lambda = 1$.

λ_1	K	Present study $M = 2, \varepsilon = 0.5, Pr = 0.7$ $f_w = Ec = \delta = 1$		Shateyi and Fazle[26] $\delta = \varepsilon = \lambda = M = Pr = fw = 1,$ $\lambda_1 = 0 K = 0$		Wang [14] $\delta = \varepsilon = \lambda = M = Pr = fw = 0,$ $m = 1$	
		$f''(0)$	$\theta'(0)$	$f''(0)$	$\theta'(0)$	for ε values	$f''(0)$
1	1	0.1872	2.3287	0.0970	1.11964	0	1.2342
2	1	0.3137	1.7872	0.1156	1.0690	0.1	1.1454
3	1	0.5863	1.5289	0.1421	0.9685	0.2	1.0122
1	1	0.7984	2.3487	0.0973	1.1176	0.3	0.9873
1	2	0.8762	1.6562	0.1428	0.8712	0.4	0.8326
1	3	0.6723	1.5262	0.1804	0.7215	0.5	0.7252

- It is obtained that the present results for Skin friction and Nusselt number reduce to the corresponding ones of Shateyi et al. [26] the parameters whereas are taken to $\lambda_1 = 0 K = 0, \delta = \varepsilon = \lambda = M = Pr = fw = 1,$ and Wang [14] the parameters whereas are taken as $\delta = \varepsilon = \lambda = M = Pr = fw = 0, m = 1$.. i.e good agreement is found with the existing results.

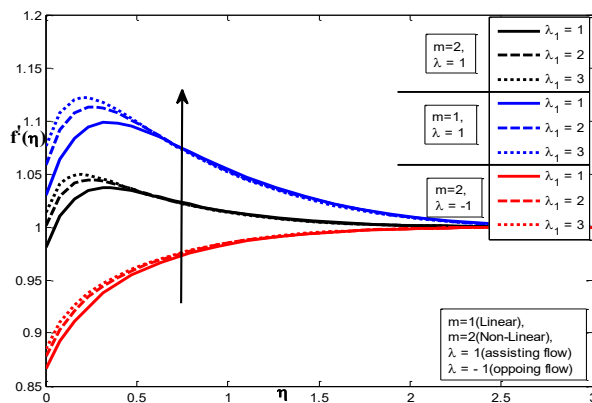


Fig. 2: Velocity profile for different values of Jeffrey fluid parameter λ_1

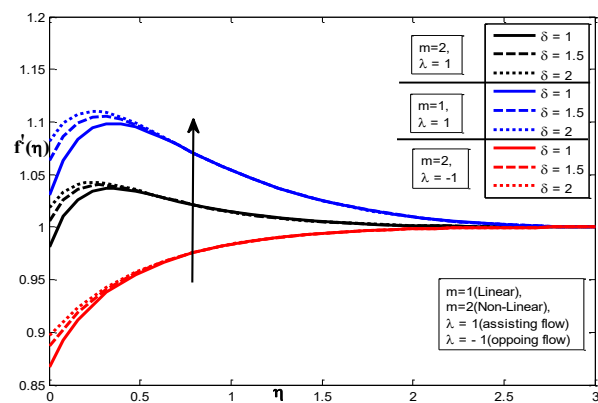


Fig. 3: Velocity profile for different values of the slip velocity parameter δ

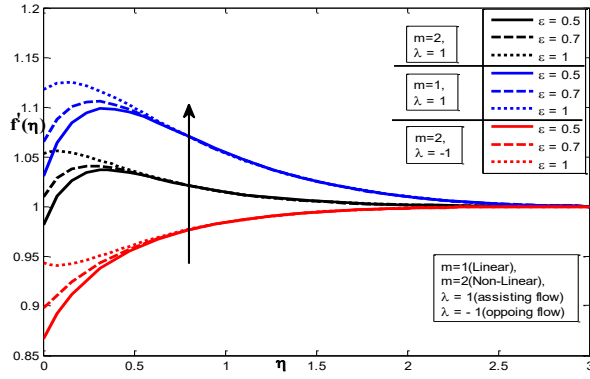


Fig. 4: Velocity profile for different values of velocity ratio parameter ε

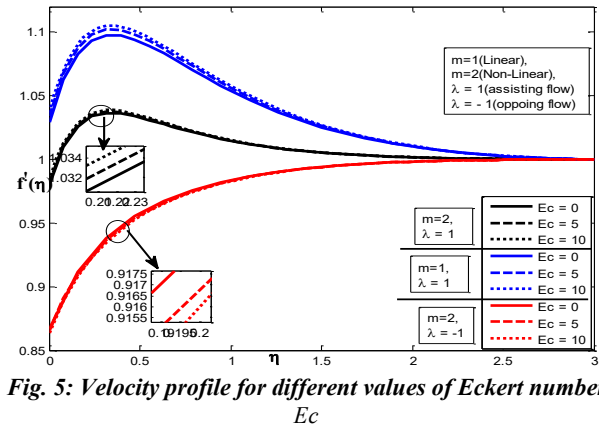


Fig. 5: Velocity profile for different values of Eckert number Ec

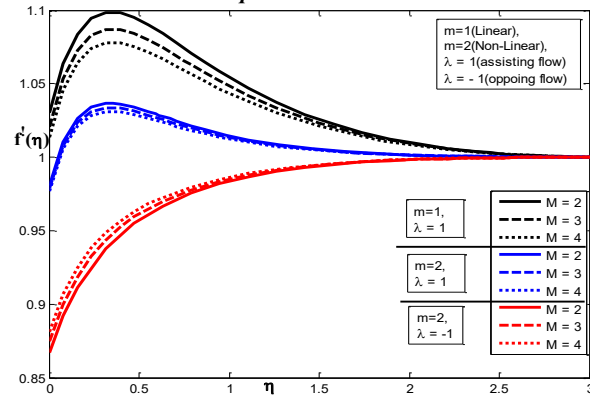


Fig. 6: Velocity profile for different values of magnetic parameter M

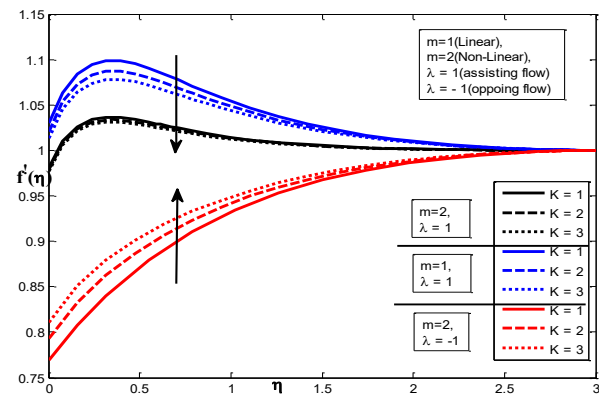


Fig. 7: Velocity profile for different values of porous medium parameter K

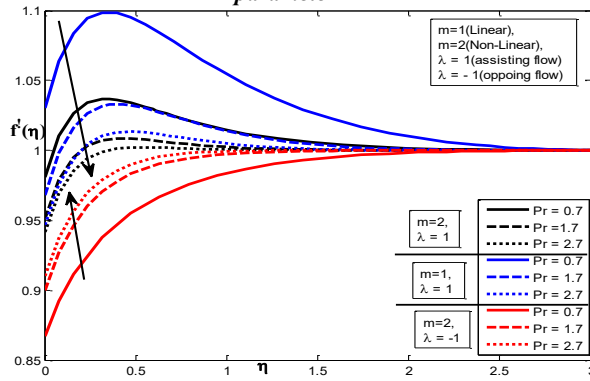


Fig. 8: Velocity profile for different values of Prandtl number Pr

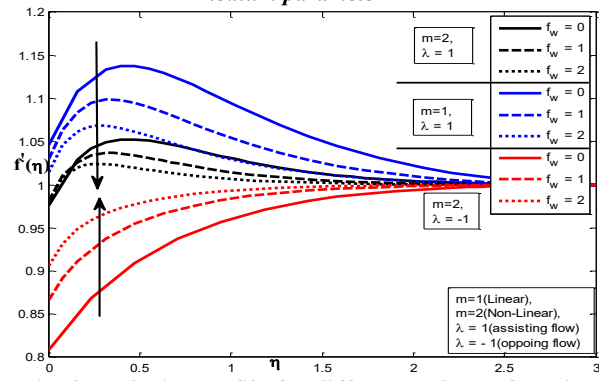


Fig. 9: Velocity profile for different values of suction parameter $f_w > 0$

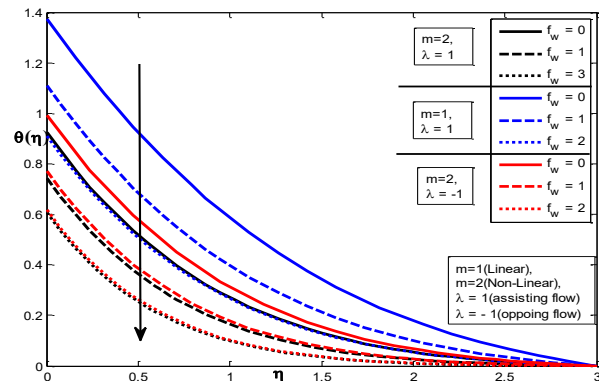
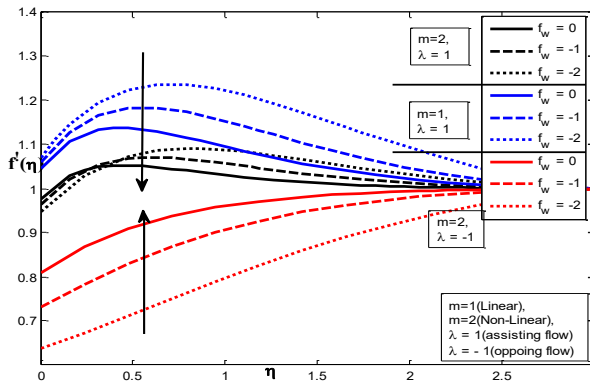


Fig. 10: Velocity profile for different values of Injection parameter $f_w < 0$

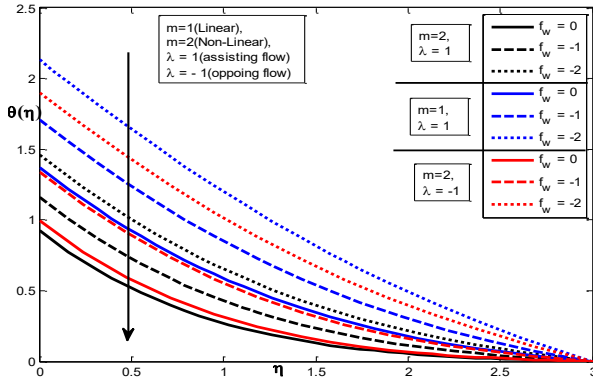


Fig. 12: Temperature profile for different values of Injection parameter $f_w < 0$.

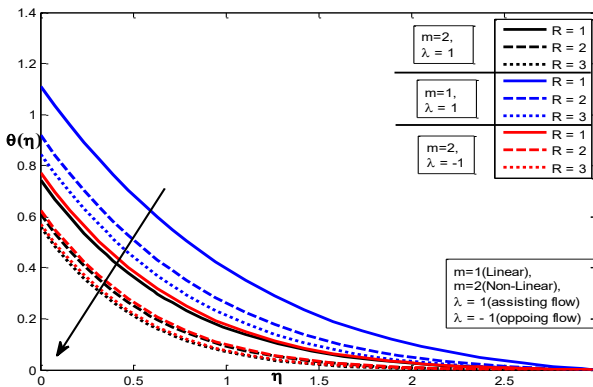


Fig. 14: Temperature profile for different values of Radiation parameter R

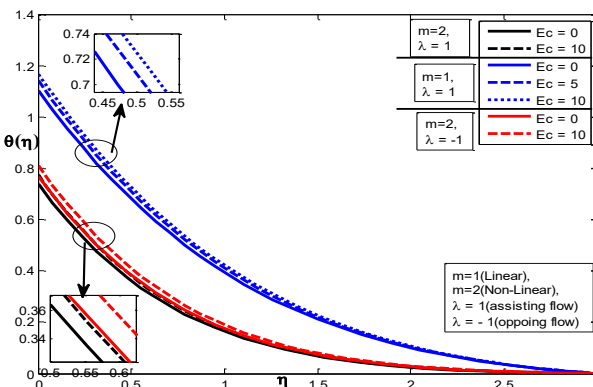


Fig. 16: Temperature profile for different values of Eckert number Ec .

Fig. 11: Temperature profile for different values of suction parameter $f_w > 0$

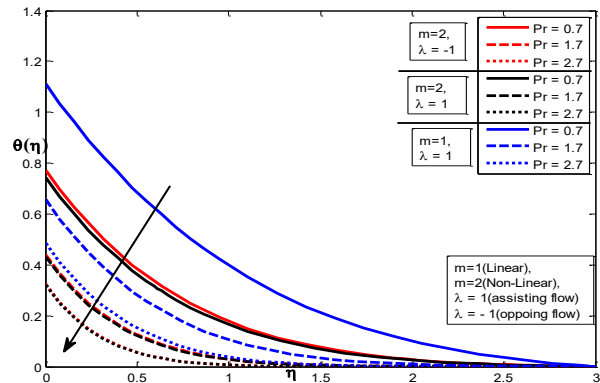


Fig. 13: Temperature profile for different values of Prandtl number Pr

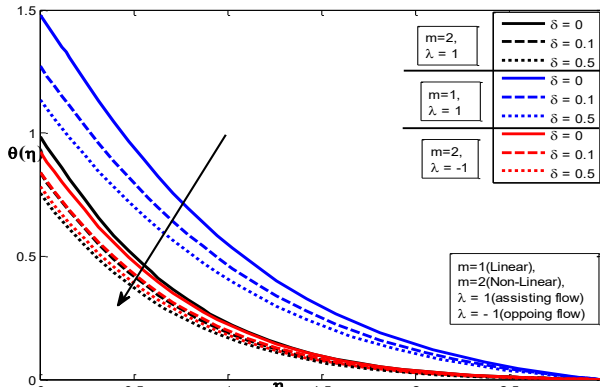


Fig. 15: Temperature profile for different values of the slip velocity parameter δ

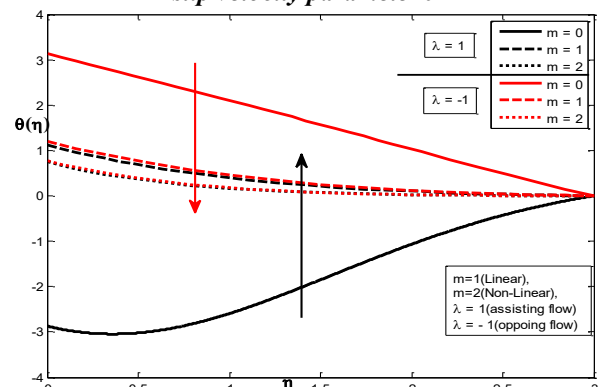


Fig. 17: Temperature profile for different values of the non-linearity parameter m .

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