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A Convective MHD Flow of a Micropolar Fluid Past a Stretched Permeable Surface with Radiation

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Abstract

MHD flow of a micropolar fluid past a stretched permeable surface with heat generation or absorption was considered in this work. The governing partial differential equations were transformed into their equivalent cylindrical coordinate system from its original form (rectangular form). A set of similarity parameters are employed to convert the governing partial differential equations to ordinary differential equations. The obtained self-similar equations are solved using the Adomian Decomposition Method. The effect of various physical parameters on the velocity profile, microrotation and temperature distribution were investigated. The obtained results shows that as the Hartmann number (Ha) increase the velocity profile and the microrotation reduce while the temperature profile increases.

Keywords: Convective, MHD, Adomian decomposition, Micropolar, Radiation.

1.0 Introduction

Micropolar fluids are subset of the micromorphic fluid theory introduced in a pioneering paper by Eringen[1]. Micropolar fluids are those fluids consisting of randomly oriented particles suspended in a viscous medium, which can undergo a rotation that can affect the hydrodynamics of the flow, making it a distinctly non- Newtonian fluid. They constitute an important branch of non-Newtonian fluid dynamics where microrotation effects as well as microinertia are exhibited. Eringen's theory has provided a good model for studying a number of complicated fluids, such as colloidal fluids, polymeric fluids and blood. The effects of radiation on unsteady free convection flow and heat transfer problem have become more important industrially. At high operating temperature, radiation effect can be quite significant. Many processes in engineering areas occur at high temperature and knowledge of radiation heat transfer becomes very important for design of reliable equipments, nuclear plants, gas turbines and various propulsion devices or aircraft, missiles, satellites and space vehicles. Based on these applications, Cogley et al.[2] showed that in the optically thin limit, the fluid does not absorb its own emitted radiation but the fluid does absorb radiation emitted by the boundaries. Hossain and Takhar[3] have considered the radiation effects on mixed convection boundary layer flow of an optically dense viscous incompressible fluid along a vertical plate with uniform surface temperature. Makinde[4] examined the transient free convection interaction with thermal radiation of an absorbing emitting fuid along moving vertical permeable plate. Satter and Hamid[5] investigated the unsteady free convection interaction with thermal radiation of an absorbing emitting plate. Heat and mass transfer effects on unsteady magneto hydrodynamics free convection flow near a moving vertical plate embedded in a porous medium was presented by Das and Jana[6]. Olajuwon[7] examine convection heat and mass transfer in a hydromagnetic flow of a second grade fluid past a semi-infinite stretching sheet in the presence of thermal radiation and thermal diffusion. Haque et al.[8] studied micropolar fluid behavior on steady magneto hydrodynamics free convection flow and mass transfer through a porous medium with heat and mass fluxes. Mahmoud [9] considered thermal radiation effects on MHD flow of a micropolar fluid over a stretching surface with variable thermal conductivity. Aouadi [10] reported a numerical study for micropolar flow over a stretching sheet. Soret and dufour effects on mixed convection in a non- Darcy porous medium saturated with micropolar fluid was studied by Srinivascharya[11]. Olajuwon et,al.[12] investigated the effects of thermo-diffusion and thermal radiation on unsteady heat and mass transfer of free convective MHD micropolar fluid flow bounded by a semi- infinite porous plate in a rotating frame under the action of transverse magnetic field with suction. Oahimire et al[13] investigated the effects of thermal-diffusion and thermal radiation on unsteady heat and mass transfer by free convective MHD micropolar fluid flow bounded by a semi- infinite vertical plate in a slip flow regime under the action of transverse magnetic field with suction. The results shows that the observed parameters have significance influence on the flow, heat and mass transfer. Kedr et al[14] considers steady, laminar, MHD flow of a micropolar fluid past a stretched semi-infinite, vertical and permeable surface in the presence of temperature dependent heat generation or absorption, magnetic field and thermal radiation effects.

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To the best of our knowledge, the use of Adomian Decomposition method to obtain the solution of a convective MHD flow of a micropolar fluid past a stretched permeable surface with radiation has remained unexplored. The objective of the current work is to study the effect of various parameters that may occur on the velocity profile, microrotation and temperature profile.

2.0 Problem Formulation

Consider steady, laminar, convective, MHD boundary –layer flow of a micro polar fluid past a permeable uniformly stretched semi-infinite vertical plate in the presence of heat generation or absorption, thermal radiation and viscous dissipation effects. The fluid is assumed to be viscous and has constant properties. The applied magnetic field is assumed to be constant and the magnetic Reynolds number is assumed to be small so that the induced magnetic field is neglected. No electric field is assumed to exist and the hall effect of magneto hydrodynamics is neglected.

The governing boundary-layer equations may be written as follows:

Continuity equation:

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

Momentum Equation:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\upsilon\frac{\partial^2 u}{\partial y^2}+k_1\frac{\partial N}{\partial y}-\frac{\sigma B^2(x)}{\rho}u+g\beta(T-T_\infty) \tag{2}$$

Angular momentum:

$$G_1\frac{\partial^2 N}{\partial y^2}-2N-\frac{\partial u}{\partial y}=0 \tag{3}$$

Energy equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{\upsilon}{c_p}\left(\frac{\partial u}{\partial y}\right)^2+\frac{Q(x)}{\rho C_p}(T-T_\infty)-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} \tag{4}$$

Subject to boundary conditions:

$$y=0:\ u=U_0x,\quad v=0,\ T=T_w,\ N=0,$$
$$y\to\infty: u\to 0,\quad T\to T_\infty\quad N\to 0, \tag{5}$$

where $B(x)$ magnetic induction, C_p specific heat at constant pressure, $Q(x)$ heat generation or absorption coefficient, Ec Eckert number, f dimensionless stream function, q_r radiative heat flux, T temperature at any point, T_w wall temperature, Ha Hartmann number, T_∞ free stream temperature, U_o stretching velocity, v normal or y-component of velocity, x distance along the plate, y distance normal to the plate, G_1 is the microrotation constant, ρ is the fluid density, k_1 is the coupling constant, α molecular thermal diffusivity, υ fluid apparent kinematic viscosity, ϕ dimensionless heat generation or absorption parameter, σ fluid electrical conductivity, ψ stream function, u is the tangential or x-component of velocity, N is the angular velocity or microrotation, g is the acceleration due to gravity, β is the volumetric coefficient of thermal expansion, θ is the dimensionless temperature, h is the dimensionless microrotation.

In other to transform our equations into cylindrical coordinate, we introduce the following transforms:

$$x=r\cos\Theta,\ y=r\sin\Theta,\ u\ \to u_r,\ v\to u_\Theta$$

$$\frac{\partial}{\partial y}=\frac{1}{r}\frac{\partial}{\partial\Theta},\qquad \frac{\partial}{\partial x}=\frac{\partial}{\partial r} \tag{6}$$

Substituting (6) into (1) to (5) we have the following:

Continuity equation:

$$\frac{1}{r}\left(\frac{\partial(ru_r)}{\partial r}+\frac{\partial u_\Theta}{\partial\Theta}\right)=0 \tag{7}$$

Momentum equation:

$$u_r\frac{\partial u_r}{\partial r}+\frac{u_\Theta}{r}\frac{\partial u_r}{\partial\Theta}=\frac{\upsilon}{r}\frac{\partial}{\partial\Theta}\left(\frac{1}{r}\frac{\partial u_r}{\partial\Theta}\right)+\frac{k_1}{r}\frac{\partial N}{\partial\Theta}-\frac{\sigma B^2(r)}{\rho}u_r+g\beta(T-T_\infty) \tag{8}$$

Angular momentum equation:

$$\frac{G_1}{r}\frac{\partial}{\partial\Theta}\left(\frac{1}{r}\frac{\partial N}{\partial\Theta}\right)-2N-\frac{1}{r}\frac{\partial u_r}{\partial\Theta}=0 \tag{9}$$

Energy equation:

$$u_r\frac{\partial T}{\partial r}+\frac{u_\Theta}{r}\frac{\partial T}{\partial\Theta}=\frac{\alpha}{r^2}\frac{\partial^2 T}{\partial\Theta^2}+\frac{\upsilon}{c_p}\left(\frac{1}{r}\frac{\partial u_r}{\partial\Theta}\right)^2+\frac{Q(r)}{\rho C_p}(T-T_\infty)-\frac{1}{\rho C_p}\frac{1}{r}\left(\frac{\partial q_r}{\partial\Theta}\right) \tag{10}$$

$$\Theta=0: u_r=U_0 r,\quad u_\Theta=0,\quad T=T_w,\quad N=0,$$
$$\Theta\to\infty: u_r\to 0,\quad T\to T_\infty,\quad N\to 0, \tag{11}$$

Using the Rosseland approximation and following El-Arabawy [15], the radiative heat flux is given by:

$$q_r=-\frac{4\sigma_0}{3k^* r}\frac{\partial T^4}{\partial\Theta} \tag{12}$$

Where σ_0 is the Stefan-Boltzmann constant and k^* is the mean absorption coefficient. The temperature differences within the fluid is assumed sufficiently small such that T^4 may be expressed as a linear function of temperature. Expanding T^4 in a Taylors series about T_∞ and neglecting higher order terms, we get:

$$T^4=4TT_\infty^{\,3}-3T_\infty^{\,4} \tag{13}$$

Using (12) and (13) in 10 we have:

$$u_r\frac{\partial T}{\partial r}+\frac{u_\Theta}{r}\frac{\partial T}{\partial\Theta}=\frac{\alpha}{r^2}\frac{\partial^2 T}{\partial\Theta^2}+\frac{\upsilon}{c_p}\left(\frac{1}{r}\frac{\partial u_r}{\partial\Theta}\right)^2+\frac{Q(r)}{\rho C_p}(T-T_\infty)-\frac{1}{\rho C_p}\frac{1}{r^2}\frac{16\sigma_0 T_\infty^{\,3}}{3k^*}\left(\frac{\partial^2 T}{\partial\Theta^2}\right) \tag{14}$$

Defining the dimensional stream function in the usual way such that $u_r=\frac{1}{r}\frac{\partial\psi}{\partial\Theta}$ and $u_\Theta=-\frac{\partial\psi}{\partial r}$ and using the following dimensionless variables:

$$\eta=\Theta\sqrt{\frac{U_0 r}{2\upsilon}}f(\eta),\quad \psi=\sqrt{2\upsilon U_0 r}\,f(\eta),\quad \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty},\ \text{and}\ N=\sqrt{\frac{U_0^{\,3}}{2\upsilon r}}f(\eta) \tag{15}$$

Substituting the expressions in (15) into (8), (9), and (14) we have:

$$f'''+ff''+Lh'-Ha^2f'+G_r\theta=0 \tag{16}$$

$$Gh''-4h-2f''=0 \tag{17}$$

$$(3N_r+4)\theta''+3P_rN_rf\theta'+3\phi N_rP_r\theta+3EcP_rN_rf''^2=0 \tag{18}$$

Where: $Ha=\sqrt{\frac{2\sigma rB^2(r)}{\rho U_0}}$, $G_r=\frac{2rg\beta(T_w-T_\infty)}{U_0^{\,2}}$, $G=\frac{G_1U_0}{r\upsilon}$, $Ec=\frac{U_0^{\,2}}{C_p(T_w-T_\infty)}$,

$L=\frac{k_1}{\upsilon}$, $\phi=\frac{2rQ(r)}{\rho C_pU_0}$, $P_r=\frac{\rho\upsilon C_p}{k}$, $N_r=\frac{kk_0^{\,*}}{4\sigma_0T_\infty^{\,3}}$.

With corresponding boundary conditions:

$$f(0)=0,\quad f'(0)=1,\quad \theta(0)=1,\quad h(0)=0,$$
$$f'(\infty)=0,\quad \theta(\infty)=0,\quad h(\infty)=0. \tag{19}$$

2.1. Adomian decomposition method

For the purpose of illustrating the method of Adomian decomposition we begin with the (deterministic) form $F(u)=g(t)$ where F is a nonlinear ordinary differential operator with linear and nonlinear items. We could represent the linear term Lu where L is a linear operator. We write the linear term $Lu+Ru$ where we choose L as the highest-ordered derivative. Now L^{-1} is simply n-fold integration for an n^{th} order. The remainder of the linear operator is R (in case where stochastic terms are present in linear operator, we can include a stochastic operator term Ru). The nonlinear term is represented by Nu .Thus, $Lu+Ru+Nu=g$ and we write $L^{-1}Lu=L^{-1}g-L^{-1}Ru-L^{-1}Nu$ for initial value problems we conveniently define $L^{-1}=\frac{d^n}{dt^n}$ as the n- fold definite integration operator from 0 to t. For the operator $L=\frac{d^2}{dt^2}$, for example we have,

$L^{-1}Lu=u-u(0)-tu'(0)$

$\therefore\ U=u(0)+L^{-1}g-L^{-1}Ru-L^{-1}Nu$

For the same operator equation but now considering a boundary value problem, we let L^{-1} be an indefinite integral and write $u = A+Bt$ for the first two terms and evaluate A , B from the given condition the first three terms are identified as u_0 in the assumed decomposition

$U=\sum_{n=0}^{r} u_n$

Finally, assuming Nu is analytic, we write

$Nu=\sum_{n=0}^{r} A_n(u_0 \ldots\ldots\ldots\ldots u_n)$

where the A_n are specially generated Adomian polynomials for the specific nonlinearity.

3.0 *Method of solution*

The nonlinear coupled differential equations (16) to (18) with boundary conditions (19) are solved using the ADM methods.

If ADM is applied on (16) to (18) and we defined $L_1 = \dfrac{d^3}{d\eta^3}$, and $L_2 = \dfrac{d^2}{d\eta^2}$, then

$$L_1[f] = -ff'' - Lh' + Ha^2 f' - G_r\theta \tag{20}$$

$$L_2[h] = \frac{2}{G}\left(2h + f''\right) \tag{21}$$

$$L_2[\theta] = \frac{1}{(3N_r+4)}(-3P_rN_rf\theta' - 3\phi N_rP_r\theta - 3EcP_rN_rf''^2) \tag{22}$$

Applying inverse operator on equation (19) to (22), we have

$$L_1^{-1}L_1[f] = -L_1^{-1}[ff''] - L^{-1}{}_1[Lh'] + L_1^{-1}[Ha^2 f'] - L_1^{-1}[G_r\theta] \tag{23}$$

$$L_2^{-1}L_2[h] = \frac{2}{G}L_2^{-1}[(2h + f'')] \tag{24}$$

$$L_2^{-1}L_2[\theta] = \frac{1}{(3N_r+4)}L_2^{-1}[(-3P_rN_rf\theta' - 3\phi N_rP_r\theta - 3EcP_rN_rf''^2)] \tag{25}$$

From the boundary conditions and taking $f''(0)=\alpha, h'(0)=\beta, and\ \theta'(0)=\gamma$, where $L_1^{-1} = \int\int\int(.)d\eta d\eta d\eta$ and $L_2^{-1} = \int\int(.)d\eta d\eta$

The ADM solution is obtained by:

$$\sum_{m=0}^{\infty} f_m(\eta) = \eta + \frac{\eta^2}{2}\alpha - L_1^{-1}[\sum_{m=0}^{\infty} A_m] - L_1^{-1}[\sum_{m=0}^{\infty} Lh'_m] + L_1^{-1}[\sum_{m=0}^{\infty} f'_m] - L_1^{-1}[G_r\sum_{m=0}^{\infty}\theta_m] \tag{26}$$

$$\sum_{n=0}^{\infty} h_n(\eta) = \eta\beta + \frac{2}{G}L_2^{-1}[\sum_{n=0}^{\infty}(2h_n + f''_n)] \tag{27}$$

$$\sum_{n=0}^{\infty}\theta_n(\eta) = 1 + \eta\gamma + \frac{1}{(3N_r+4)}\sum_{n=0}^{\infty}(L_2^{-1}(-3P_rN_rf_n\theta'_n - 3\phi N_rP_r\theta_n - 3EcP_rN_rf_n''^2)) \tag{28}$$

where

$$A_m = \sum_{v=0}^{m} f_{m-v}f''_v \tag{29}$$

$$C_n = \sum_{v=0}^{n} f''_{n-v}f''_v \tag{30}$$

$$F_n = \sum_{v=0}^{n} f_{n-v}\theta'_v \tag{31}$$

from (26) to (28) we have:

$$f_0(\eta) = \eta + \frac{\eta^2\alpha}{2} \tag{32}$$

$$h_0(\eta) = \beta\eta \tag{33}$$

$$\theta_0(\eta) = 1 + \gamma\eta \tag{34}$$

For determination of other components of $f(\eta)$, $h(\eta)$ and $\theta(\eta)$, we have:

$$\sum_{m=0}^{\infty} f_{m+1}(\eta) = -L_1^{-1}[\sum_{m=0}^{\infty} A_m] - L_1^{-1}[\sum_{m=0}^{\infty} Lh_m'] + L_1^{-1}[\sum_{m=0}^{\infty} f'_m] - L_1^{-1}[G_r \sum_{m=0}^{\infty} \theta_m] \quad (35)$$

$$\sum_{n=0}^{\infty} h_{n+1}(\eta) = \frac{2}{G} L_2^{-1}[\sum_{n=0}^{\infty} \left(2h_n + f_n''\right)] \quad (36)$$

$$\sum_{n=0}^{\infty} \theta_{n+1}(\eta) = \frac{1}{(3N_r + 4)} \sum_{n=0}^{\infty} \left(L_2^{-1}[(-3P_r N_r f_n \theta_n' - 3\phi N_r P_r \theta_n - 3EcP_r N_r f_n''^2)]\right) \quad (37)$$

The general solutions are:

$$f(\eta) = \sum_{m=0}^{\infty} f_m(\eta) = f_0 + f_1 + f_2 + \ldots. \quad (38)$$

$$h(\eta) = \sum_{n=0}^{\infty} h_n(\eta) = h_0 + h_1 + h_2 + \ldots \quad (39)$$

$$\theta(\eta) = \sum_{n=0}^{\infty} \theta_n(\eta) = \theta_0 + \theta_1 + \theta_2 + \ldots \quad (40)$$

for conveniences, we used Maple-16 to compute the solutions and by Khedr *et al.* [14]

$\alpha = -0.616542$, $\beta = 0.355330$, $\gamma = -0.249999$.

4.0 Results and Discussion

The system of non-linear coupled ordinary differential equations (16) to (18) with boundary conditions (19) has been solved using the Adomian Decomposition method and the results are in good agreement with that obtained by Khedr *et al.* [14]. The effects of the Physical parameters Ha, G_r, ϕ, N_r, P_r and Ec on the velocity profiles, micro rotations and temperature distributions are shown in Figures 1-11.

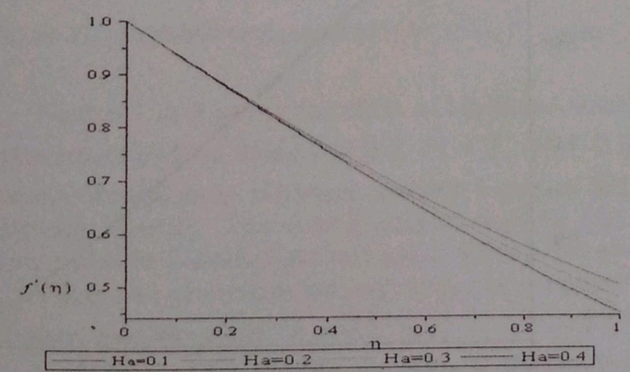

Figure 1: graph of velocity profile $(f'(\eta))$ against η

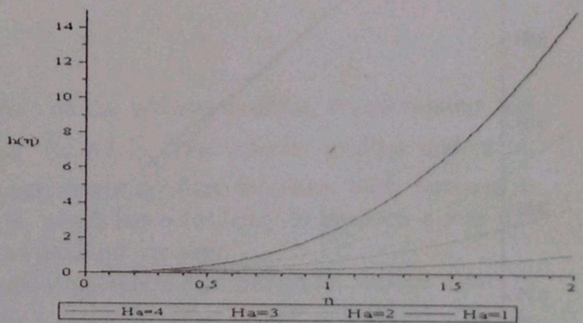

Figure 2: graph of micro rotation $(h(\eta))$ against η

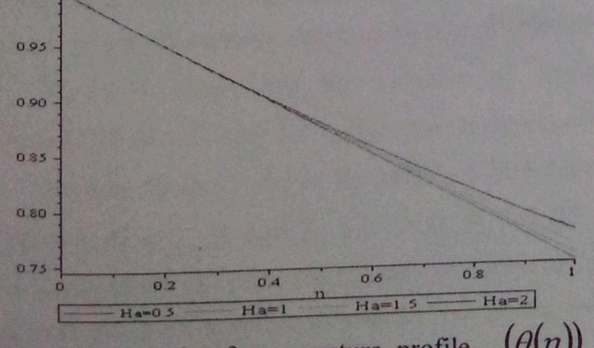

Figure 3: graph of temperature profile $(\theta(\eta))$ against η

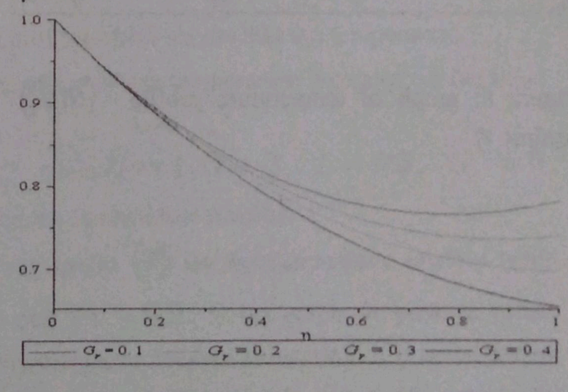

Figure 4: graph of velocity profile $(f'(\eta))$ against η

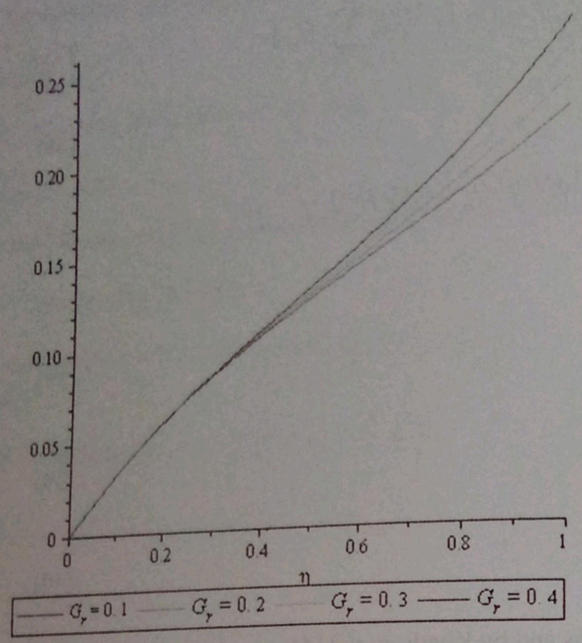

Figure 5: graph of micro rotation $(h(\eta))$ against η

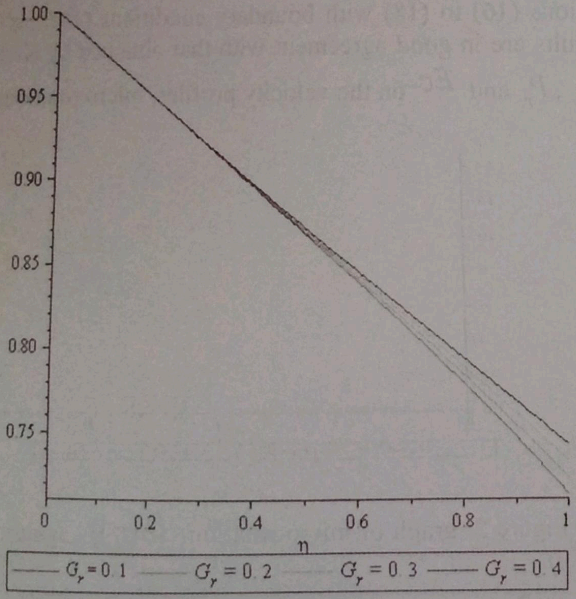

Figure 6: graph of temperature profile $(\theta(\eta))$ against η

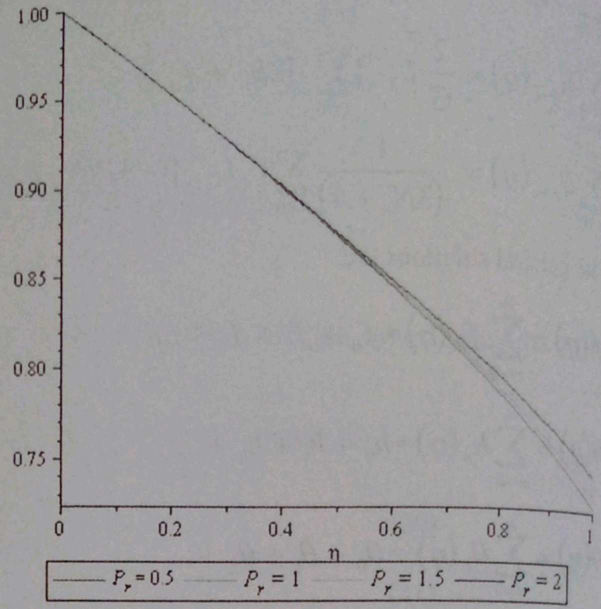

Figure 7: graph of temperature profile $(\theta(\eta))$ against η

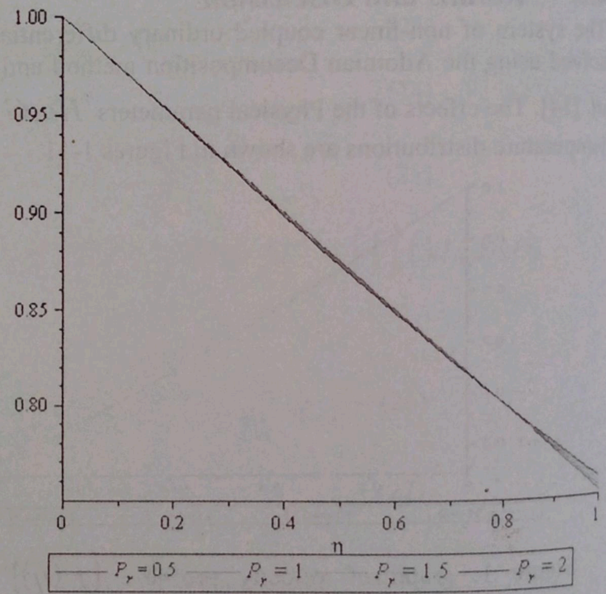

Figure 8: graph of temperature profile $(\theta(\eta))$ against η

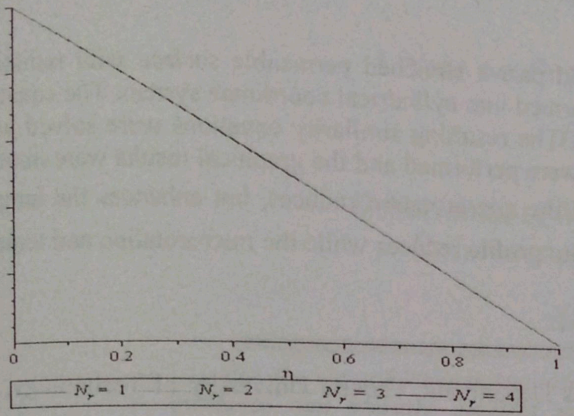

Figure 9: graph of temperature profile $(\theta(\eta))$ against η

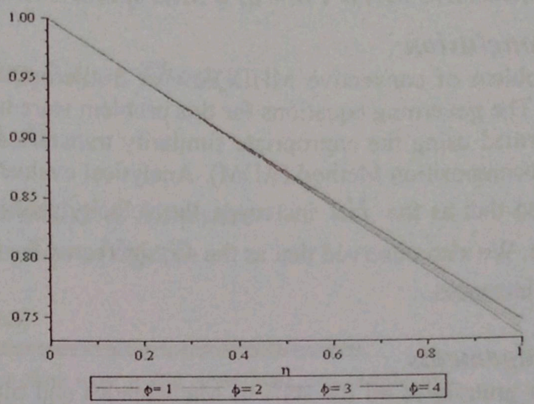

Figure 10: graph of temperature profile $(\theta(\eta))$ against η

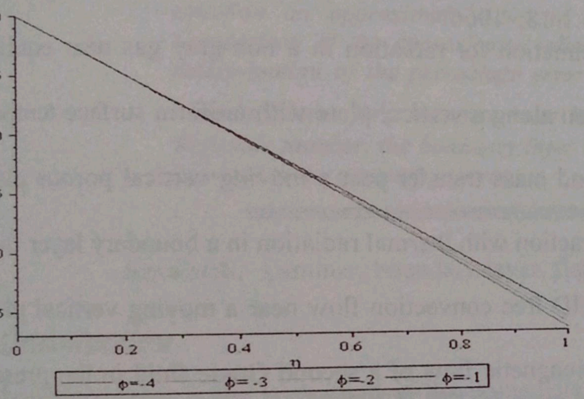

Figure 11: graph of temperature profile $(\theta(\eta))$ against η

Figures 1 to 3 shows the effect of Hartmann number (Ha) on the velocity profiles, micro rotation and temperature profiles where $L=0.2, G=2, P_r=0.05$, and $Ec=1.5$. The velocity profiles and micro rotation decreases as Hartmann number increases and the temperature profiles increases with increase in Hartmann number. This is as a result of magnetic field present, which has a tendency to produce a drag-like force called the Lorentz force that acts in the opposite direction of the fluid's motion.

Figures 4 to 6 presents the velocity profiles, microrotation and temperature distribution for various values of Grashof number while $L=0.2, G=2, P_r=0.05$, and $Ec=0.2, Ha=1, N_r=1, \phi=0$. It was observed that velocity profiles decreases as the Grashof number increases and the microrotation, temperature distributions increases for increased in Grashof number.

Figures 7 to 8 shows the influence of prandtl number for $Ec=0$ and $Ec=0.2$ respectively, while $Ha=1$, $G=2, L=0.2, G_r=0, N_r=1, \phi=0$ on temperature profile; which shows that the temperature increases as the prandtl number increases for $Ec=0$, and the rate at which temperature increases for the same values of prandtl number dropped for $Ec=0.2$.

Figure 9 shows that the variation of Nusselt (N_r) while $Ha=1, G=2, L=0.2, G_r=0$, $P_r=0.05, \phi=0$ and $Ec=0.2$ has no significant effect on the temperature profiles.

Figures 10 to 11 shows the effect of heat generation/ absorption (ϕ) on the temperature profiles while $Ha=1, G=2, L=0.2, G_r=0, P_r=0.05, N_r=1$ and $Ec=0.2$. In the graph the positive values of ϕ represents the presence of heat generation and the negative values represent absorption. It is noted that as ϕ increases from negative to positive values, the temperature as well as the thermal boundary layer thickness increases.

4.0 Conclusion

The problem of convective MHD flow of a micropolar fluid past a stretched permeable surface with radiation was considered. The governing equations for this problem were transformed into cylindrical coordinate system. The equation was also transformed using the appropriate similarity transformations. The resulting similarity equations were solved using the Adomian Decomposition Method (ADM). Analytical evaluations were performed and the graphical results were obtained. It was observed that as the Ha increases, the velocity profile and the microrotation reduces, but enhances the temperature distributions. We also observed that as the G_r increases the velocity profile reduces while the microrotation and temperature distribution increases.

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