Magnetic and Viscous Dissipation Effects on Convection-Radiation in Corrugated Channel with Porous Medium and Uniform Heat Flux

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Abstract: ***This manuscript investigates the influence of Ohmic heating and viscous dissipation on steady free convective MHD fluid flow through a wavy channel; with porous medium in presence of heat generation, bounded by adiabatic-isoflux walls. The fluid is an optically thick non-gray gas. The dimensionless governing coupled nonlinear differential equations obtained; using suitable non-dimensional variables, are linearized by perturbation technique and then solved numerically by the mid-point method with Richardson Extrapolation (MMRE) using the software MAPLE. The velocity, temperature, skin-friction coefficient and the rate of heat transfer for meaningful values of some selected parameters are depicted graphically and discussed. It is noticed that increasing of magnetic parameter increases the temperature and decreases the velocity. It is also observed that the velocity/temperature profile is decreasing/increasing with the increasing values of Eckert number while Ohmic heating exhibits the opposite behavior.***

Keywords: Joule heating, Adiabatic-isoflux walls, Wavy channel, Temperature dependent heat source and Porous medium

1. Nomenclature

A Permeability parameter

B_0 Intensity of the applied magnetic field q_r Radiative heat flux

C_p Specific heat at constant pressure R Radiation parameter

W Distance between the walls S Heat source/sink parameter

E_c Eckert number

J_e Ohmic heating

g Acceleration due to gravity

G_r Grashof number

M magnetic field parameter β_T Thermal expansion coefficient

T_e Temperature in the equilibrium state

(u, v) Dimensionless velocity components

θ Dimensionless fluid temperature

σ_e Electrical conductivity

(x, y) dimensional coordinate

ρ_e Density of the fluid in the equilibrium state

k_w Wave number

$\alpha_{\lambda e}$ Mean absorption coefficient λ Wavelength

$B_{\lambda e}$ Planck's function

2. Introduction

Although the usefulness of corrugated wall(s) components in enhancing heat transfer and, therefore, in reducing the heat exchanger size has been generally understood for some times, but many of its important impacts have been given thoughtful study only in recent times. Its potential applications to physical and engineering devices is mentioned by Vajravelu and Sastri [17]. Vajravelu and Sastri [17] may be considered as the origin of the modern research on the effect of heat transfer on free convection flow in a viscous incompressible fluid. The geometry considered consists of two finitely long (compared to width of the channel) vertical isothermal-isothermal walls; one of which is sinusoidally corrugated, and the other being smooth. Many scholars have shown interest, incorporating various parameters of physical interest (see cf. [1], [5], [6], [7], [8], [9], [10], [11], [16]), for different thermal or thermal and species diffusion conditions, where the flow and transfer processes are caused by buoyancy effect of thermal diffusion only or convection and transfer processes governed by buoyancy mechanisms arising from both thermal and species diffusion.

Of the ten papers, only Taneja and Jain [16] examined slip and constant heat flux (Isothermal-isoflux walls) boundary conditions at the flat wall in presence of temperature dependent heat generation or absorption. Other authors have taken constant heat source or sink into consideration under no-slip condition. Overall, the above papers ignored the modelling of thermal boundary conditions which will be significant when we are concerned with the designing of engineering walls/surfaces for their heat transfer. In a given process, engineer must design materials which will economically remove or added as much heat as possible, while in other cases, the converse is desirable; that is, economically preventing heat from being transferred. Insulators are used in multilayers as a more effective prevention against heat loss, thus made the storage of cryogenic material possible. Thermal insulation is the most effective way of improving comfort and save energy. A study of magnetic hydrodynamic free convective flow past an infinite vertical porous plate with constant heat flux has been considered by Amenya et al. [2]. In all these investigations the problem of the frictional and Joule heating has been omitted.

The viscous dissipation, which appears as a source term in the fluid flow generates appreciable temperature, gives the rate at which mechanical energy is converted into heat in a viscous fluid per unit volume. This effect is of particular importance in natural convection in various devices that are subjected to large variation of gravitational force or that operate at high rotational speeds (see Gebhat [12]). The study of Ohmic heating describes the process where the energy of an electric current converted into heat as it flows through a resistance. Ohmic heating is pertinent to an electrical device's design. This is relevant in terms of electrical systems components, such as conductors in electronics, electric heaters, and fuses. The heating of these structures can cause them to degenerate or even melt. Now engineers can add convection cooling into the design to prevent the components and devices from overheating.

The combined action of viscous and magnetic dissipation on MHD convection flow of heat or heat and mass transfer has received considerable attentions in recent years for its application on heat exchanger designs, and in nuclear engineering in connection with the cooling of reactors. Another vital applications is in various devices which are subjected to large variations of gravitational force. This has been the important subject of many recent research articles, for instance, see Jaber [13], Jabir [14], Loganathan and Sivapoornaprnapriya [15] and Balamurugan [3] studied the problem on different geometries, respectively, stretching plate, stretching porous sheet, vertical plate and moving inclined porous plate, for different thermal or thermal and species diffusion conditions. Yet, the preceding literature survey shows that combined influence of viscous and magnetic dissipations on free convection heat transfer in electrically conducting radiating fluid flowing through a porous medium bounded by thermally insulated wavy wall and isoflux flat wall in the presence of temperature dependent heat source or sink has not being investigated and the present work illustrate the issue. The investigation is based on perturbation of the dimensionless basic equations, wherein the amplitude ε; characterizing the roughness of the wall assumed small, hence the perturbation parameter. The numerical solutions are then obtained using the software MAPLE. Results are presented graphically and discussed quantitatively for parameter values of practical interest from physical point of view.

3. Formulation of the Problem

Here, we consider the steady ($\frac{\partial()}{\partial t'}=0$), two-dimensional ($\vec{u}=(u',v',0)$), laminar free convection flow of a viscous incompressible and electrically conducting fluid through a porous medium bounded by finitely long vertical walls. The channel is characterized by a sinusoidal wavy wall (represented by $y'=\varepsilon^{*}\cos k_w x', \left|\varepsilon^{*}\right|<1$), and an opposite wall being flat (represented by $y'=W$). The wavy wall is considered adiabatic and the constant heat flux is mounted on the flat wall. The $x'-axis$ is taken vertically upwards and parallel to the flat wall and the $y'-axis$ is normal to it. Properties of the fluid are assumed constant except that density change with temperature that brings about the buoyancy forces in a manner corresponding to the equation of state: $\frac{\rho-\rho_e}{\rho_e}=\beta_T(T-T_e)$. There is no applied magnetic field in the y'-direction and magnetic Reynold's number is much less than unit, so that Hall, ions slip current and induced magnetic fields are ignored. $\nabla\ \vec{B}\ \theta$ (Gauss's law of magnetism) gives B_y=constant=B_0 in the flow, thus $\vec{B}=(0,B_0,0)$ and Lorentz force $\vec{F}=\vec{J}\times\vec{B}=\sigma_e\left(\vec{u}\times\vec{B}\right)\times\vec{B}=-\sigma_e B^2 u$, $\nabla\times\vec{B}=\vec{J}$, $\nabla\cdot\vec{E}=0$ and $\vec{J}=\sigma_e\vec{u}\times\vec{B}$ (Ohm's law).

Maxwell currents displacement and free charges are neglected. The volumetric heat sources/sink term in the energy equation is assumed to be proportional to the high temperature differences of the form $Q(T-T_e)$. The Cogley et al. [4] model; showing that the relation $\frac{\partial q_r}{\partial r}=4I\left(T-T_e\right)$ where $I=\int_0^\infty \alpha_{\lambda_e}\left(\frac{\partial B_{\lambda_p}}{\partial T}\right)_e d\lambda$, evaluated at the Temperature T_e, is used to stimulate the effects of thermal radiation. Under these assumptions, the governing equations in dimensionless form are:

$$u_x+u_y=0 \tag{1}$$

$$uu_x+vu_y=-(P-P_e)_x+u_{xx}+u_{yy}-(M+\frac{1}{A})u+G_r\theta \tag{2}$$

$$uv_x+vv_y=-P_y+v_{xx}+v_{yy}-\frac{1}{A}v \tag{3}$$

$$P_r(u\theta_x+v\theta_y)=\theta_{xx}+\theta_{yy}-(R-S)\theta+J_eE_cu^2+P_rE_c\left[u_y^2+v_x^2+2u_yv_x-4u_xv_y\right] \tag{4}$$

Where

$$(x,y)=\frac{1}{W}(x',y'),(u,v)=\frac{W}{\upsilon}(u',v'),T_w>T$$

$$M=\frac{\sigma_eB_0^2W^2}{\rho\upsilon},G_r=\frac{\beta_Tgq_WW^4}{K\upsilon^2},P_r=\frac{\mu C_p}{K},$$

$$S=\frac{QW^2}{K},J_e=\frac{\sigma_eB_0^2W^2C_p}{K},E_c=\frac{\upsilon^2K}{C_pW^3q_w},$$

$$A=\frac{k'}{W^2},R=\frac{4IW^2}{K},\theta=\frac{K(T-T_e)}{q_wW}$$

$$P=\frac{p'W^2}{\rho\upsilon^2},P_e=\frac{p_e'W^2}{\rho\upsilon^2},\lambda=k_wW,\varepsilon=\frac{\varepsilon^*}{W}$$

The boundary conditions are:

$$u=0, v=0, \frac{\partial\theta}{\partial y}=0 \text{ at y = } \cos\lambda x \quad (5)$$

$$u=0, v=0, \frac{\partial\theta}{\partial y}=-1 \text{ at y = 1}$$

4. Method of Solution

Since the roughness of the wavy wall is assumed small, we seek a perturbation solution for small ε, where the limit ε=0 is, of course, the limit of a smooth flat wall. We now take the flow field and the temperature to be:

$$u(x,y)=u_0(y)+\varepsilon u_1(x,y), v(x,y)=\varepsilon v_1(x,y)$$

$$P(x,y)=P_0(x)+\varepsilon P_1(x,y),$$

$$\theta(x,y)=\theta_0(y)+\varepsilon\theta_1(x,y) \quad (6)$$

Put (6) in (1)-(5), equating $\varepsilon^0, \varepsilon^1$ and neglecting 0(ε^2), zeroth- and perturbed quantities denoted by the subscripts 0 and 1, respectively, obtained. Eliminate dimensionless P_1 and employ stream function Ψ_1 defined by

$$.u_1(x,y)=-\Psi_{1,y}, v_1(x,y)=\Psi_{1,x} \quad (7)$$

Assume wave-like solutions:

$$\Psi_1(x,y)=\varepsilon e^{i\lambda x}\psi(\lambda,y), \theta_1(x,y)=\varepsilon e^{i\lambda x}\phi(\lambda,y) \quad (8)$$

(7) becomes $u_1=-\varepsilon e^{i\lambda x}\psi'(y), v_1=\varepsilon i e^{i\lambda x}\psi(y)$

In term of stream function, perturbed quantities reduce to

$$\psi^{iv}+\lambda^2(\frac{\psi}{A}-2\psi^{''})-\frac{\psi^{''}}{A}-M\psi^{''}-G_r\phi^{'}$$

$$=i\lambda(u_0\psi^{''}-u_o^{''}\psi) \quad (9)$$

$$\phi^{''}-R\phi+S\phi+2J_eE_cu_0\psi^{'}-\lambda^2\phi$$

$$2P_rE_cu_0^{'}(-\psi^{''}-\lambda^2\psi=i\lambda P_r(u_0\phi+\theta_0^{'}\psi) \quad (10)$$

i is the complex unit.

If λ is much less than unity or ($k_w <<1$), we write

$$\psi(\lambda,y)=\sum_{j=0}^{\infty}\lambda^j\psi_j, \phi(\lambda,y)=\sum_{j=0}^{\infty}\lambda^j\phi_j, (j=0,1,2,...) \quad (11)$$

Putting (11) into (9) and (10) in terms of ψ_j, comparing the like-power terms of λ to the order of λ^2, overall set of coupled nonlinear set of ordinary differential equations and the boundary conditions for this work:

$$u_0^{''}-(M+\frac{1}{A})u_0=-G_r\theta_0 \quad (12)$$

$$\theta_0^{''}-(R-S)\theta_0+J_eE_cu_0^2+P_rE_c(u_0^{'})^2=0 \quad (13)$$

$$\psi_0^{iv}-(M+\frac{1}{A})\psi_0^{''}=G_r\phi_0^{'} \quad (14)$$

$$\phi_0^{''}-(R-S)\phi_0+2J_eE_cu_0\psi_0^{'}-2P_rE_cu_0^{'}\psi_0^{''}=0 \quad (15)$$

$$\psi_1^{iv}-(M+\frac{1}{A})\psi_1^{''}=G_r\phi_1^{'}+u_0\psi_0^{''}-u_0^{'}\psi_0 \quad (16)$$

$$\phi_1^{''}-(R-S)\phi_1+2J_eE_cu_0\psi_1^{'}-u_0\phi_0= 2P_rE_cu_0^{'}\psi_1^{''}+\psi_0\theta_0 \quad (17)$$

$$\psi_2^{iv}-(M+\frac{1}{A})\psi_2^{''}+\frac{\psi_0}{A}=2\psi_0^{''}+G_r\phi_2^{'} -u_0\psi_1^{''}+u_0^{''}\psi_1 \quad (18)$$

$$\phi_2^{''}-(R-S)\phi_2+2J_eE_cu_0\psi_2^{'}-\phi_0+u_0\phi_1= 2P_rE_cu_0^{'}\psi_2^{''}+2P_rE_cu_0^{'}\psi_0+\psi_1\theta_0^{'} \quad (19)$$

and

$u_0=0, \theta_0^{'}=0$ at $y=0$, $u_0=0, \theta_0^{'}=-1$ at y = 1

$\psi_0^{'}=u_0^{'}, \psi_0=0, \phi_0^1=-\theta_0^{''}$ at y = 0

$\psi_0^{'}=0, \psi_0=0, \phi_0^1=0$ at y = 1

$\psi_1^{'}=0, \psi_1=0, \phi_1^1=0$ at y = 0

$\psi_1^{'}=0, \psi_1=0, \phi_1^1=0$ at y = 1

$\psi_2^{'}=0, \psi_2=0, \phi_2^1=0$ ay y = 0

$\psi_2^{'}=0, \psi_2=0, \phi_2^1=0$ at y = 1

5. Results and Discussion

The numerical solutions for the velocity u, temperature θ, skin friction coefficient C_f and the rate of heat transfer N_u are computed for physical parameters E_c, J_e, S, A, M and R. The Prandtl $P_r=0.71$ corresponds to the air at temperature 20^oC and one atmospheric pressure. The values of A, M and R are chosen arbitrarily. G_r and E_c take negative values, which corresponds to heating of the wall (heat flux, that is, transferred heat from the wall to the fluid). S=-1 corresponds to heat absorption and we have S = 0 in the absence of heat generation while S = 1, 2 give heat generation. Geometric parameters characterizing the roughness of wall; amplitude ε=0.025 (characteristic of dilated channel), wavelength λ = 0.01 and $\lambda x=\frac{\pi}{2}$. The default parameter used throughout the numerical computations, M = 2.5, R = 3, E_c = -1.5, S = 2, A = 0.3, G_r = -2, J_e = -1.5. Fig. 1, Fig. 2 and Fig. 3 gives velocity profiles at varying values of E_c, R, and M, respectively. It is observed that velocity decreases with increasing values of E_c, R, and M. Increase in J_e, S and A increases the velocity of the fluid throughout the channel as observed in Fig. 4 to Fig. 6, respectively. Fig. 3 asserts that as M increases the velocity of the fluid decrease; attributed to the presence of the transverse magnetic field normal to the walls which gives rise to Lorentz force which is resistive to the flow hence decelerating the flow of the fluid.

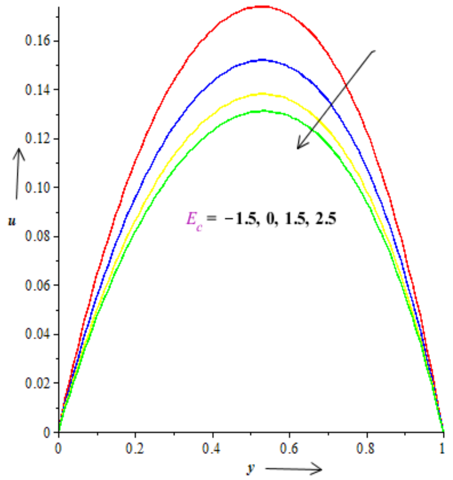

Figure 1: u vs. y with E_c

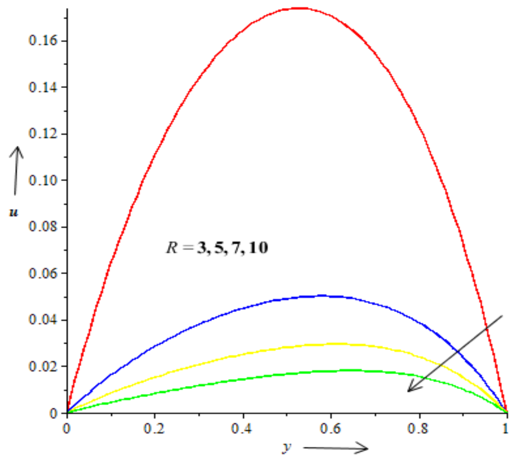

Figure 2: u vs. y with R

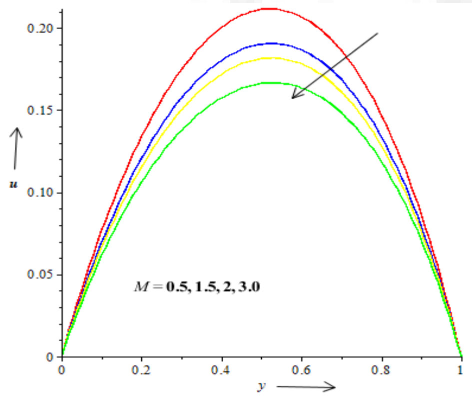

Figure 3: u vs. y with M

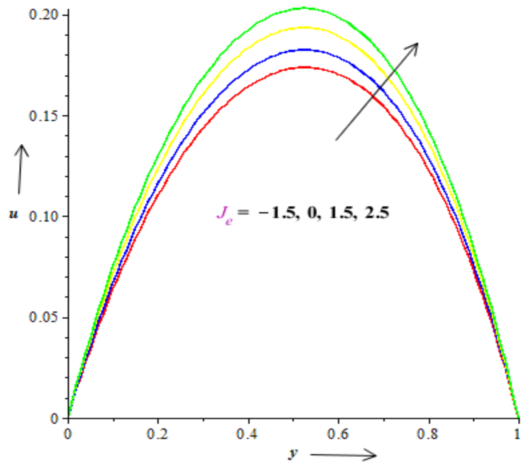

Figure 4: u vs. y with J_e

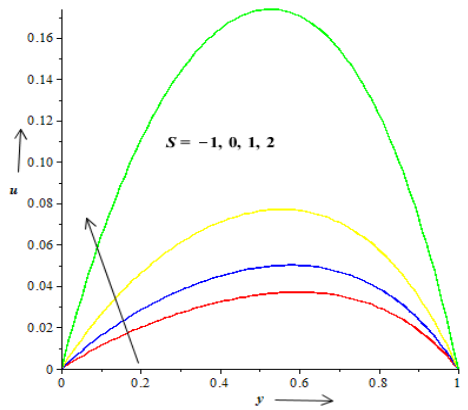

Figure 5: u vs. y with S

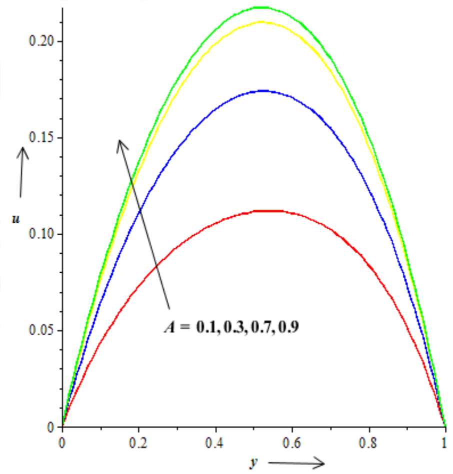

Figure 6: u vs. y with A

The velocity of the fluid decreases or increases as one moves away from the walls at a given values of governing parameters making the velocity of the fluid to be maximum at the Centre of the channel. This satisfies the natural situation since fluids flow in such a way that the velocity is maximum at the Centre position of the channel. This is due to the interaction of fluid molecules with wall molecules hence reducing its velocity near the walls.

In the Fig. 7 – Fig. 12, the temperature field θ is plotted against y for different variations in governing parameters E_c, R, M, J_e, S and M, respectively. The temperature θ becomes negative throughout the channel for all variations. This is justified due to the fact that the flat wall is being heated and the wavy wall is insulated. It is being observed that when E_c, R and M (Fig. 7 – Fig. 9) are increased, temperature θ is increased but the phenomena reverses for the case of J_e, S and A (Fig. 10 – Fig. 12).

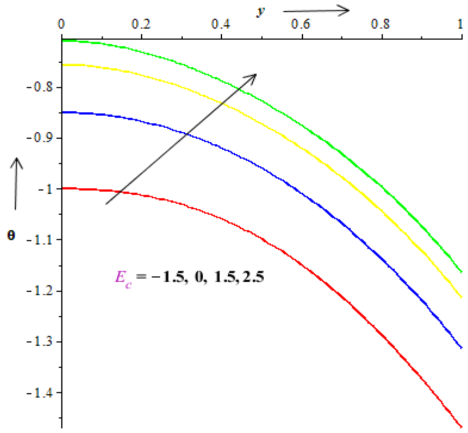

Figure 7: θ vs. y with E_c

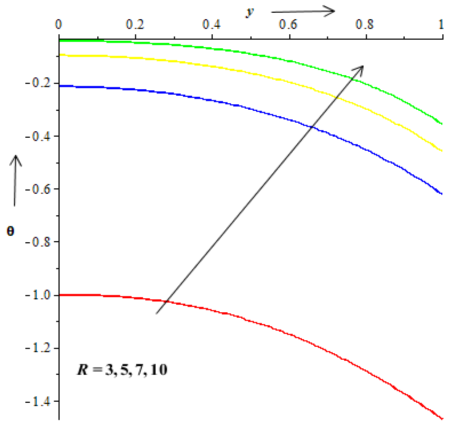

Figure 8: θ vs. y with R

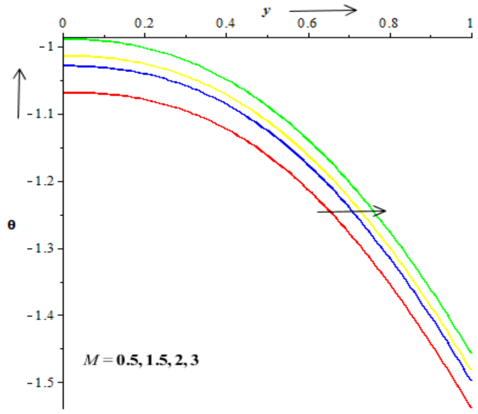

Figure 9: θ vs. y with M

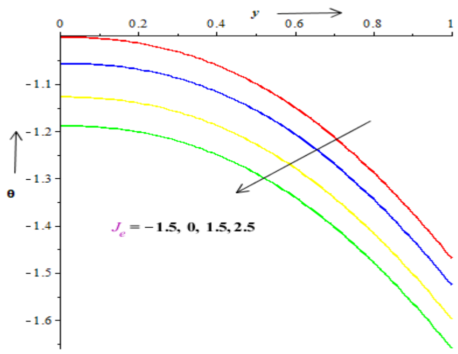

Figure 10: θ vs. y with J_e

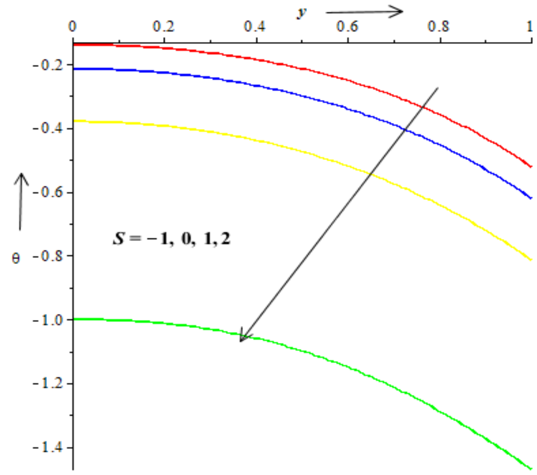

Figure 11: θ vs. y with S

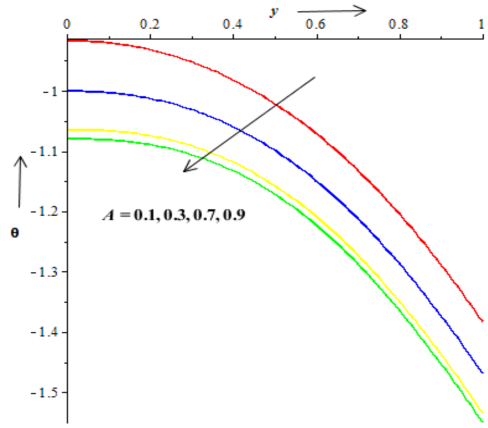

Figure 12: θ vs. y with A

Fig. 13 to Fig. 18 demonstrate the effect of values of stated relevant parameters on the skin friction C_f . The effects of E_c , R and M are displayed in Fig. 13, Fig. 14 and Fig. 15, respectively. For the growth of E_c , R and M , the shearing stress experiences a declination to the position y = 0.5 and then becomes constant for all values of E_c , R and M , that is, the value of skin friction coefficient decreases but as from this point to the heated flat wall accelerating upward and increases. The influence of J_e , S and A is shown in Fig. 16, Fig. 17 and Fig. 18, respectfully. However, the skin friction shows opposite pattern due to the change of J_e , S and A as depicted in Fig. 16 to Fig. 18. It is being observed that increasing the embedded parameters cause reversal flow towards the heated wall, that is, skin friction becomes negative near the heated flat wall while it remains positive near the insulated wavy wall.

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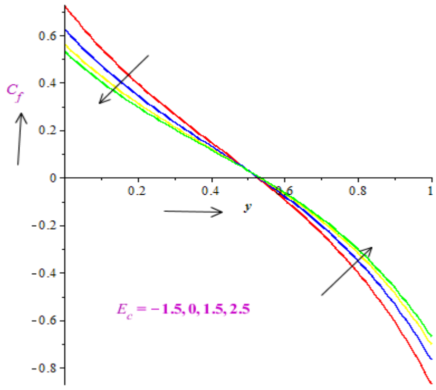

Figure 13: C_f vs. y with E_c

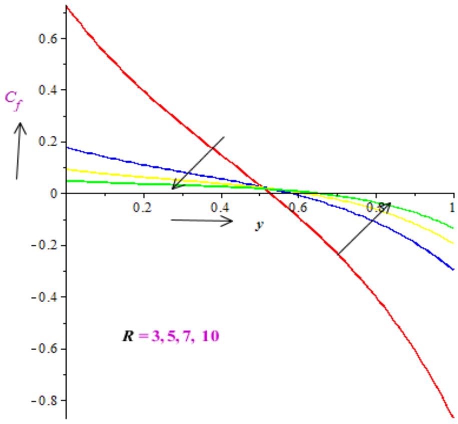

Figure 14: C_f vs. y with R

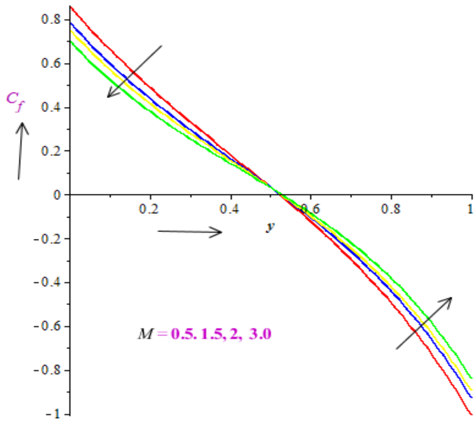

Figure 15: C_f vs. y with M

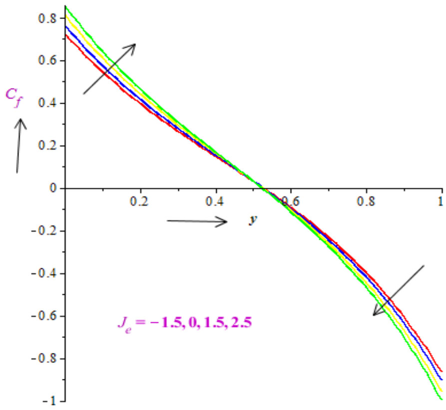

Figure 16: C_f vs. y with J_e

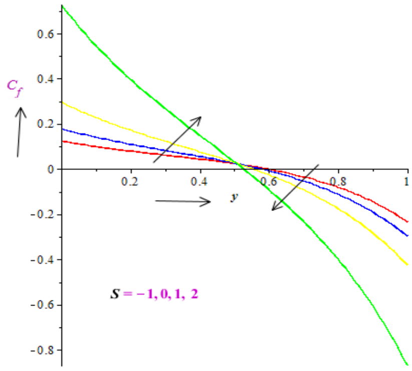

Figure 17: C_f vs. y with S

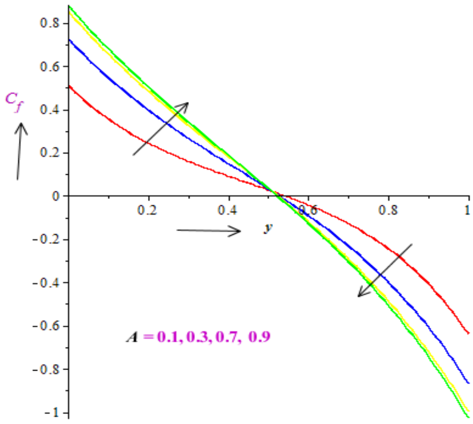

Figure 18: C_f vs. y with A

The Nusselt number N_u which measures the rate of heat transfer is shown in Fig. 19 to Fig. 24. It becomes negative as a result of the heating of the flat wall. The Nusselt number slow down significantly (Fig. 19) for higher values of E_c to the position y = 0.5, where it becomes constant, then accelerated upward and increases. E_c exert stronger effect on the rate of heat transfer in comparison with Joule heating (Fig. 22). Fig. 20 reveals an increasing trend of the rate of heat transfer with the enhancement of the radiation parameter but the Fig. 23 exhibits an opposite trend of rate of heat transfer with increase in heat source parameter, for heated wall (G_r <0). Fig. 21 and Fig. 24 revealed that Nusselt number against M exhibits the opposite behavior against A.

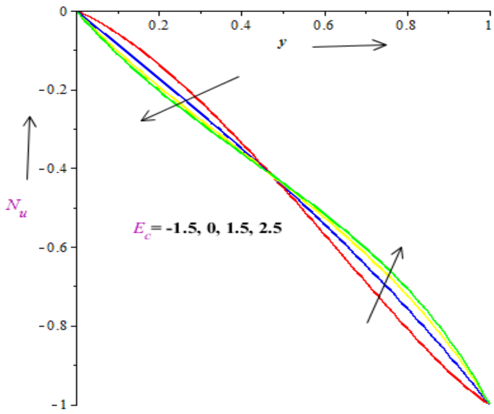

Figure 19: N_u vs. y with E_c

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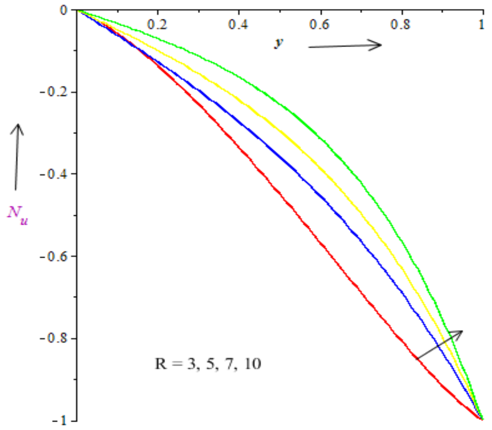

Figure 20: N_u vs. y with R

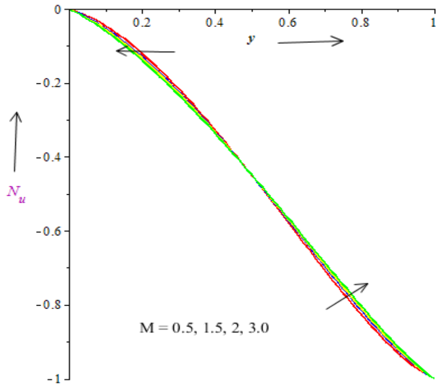

Figure 21: N_u vs. y with M

6. Conclusions

An analysis of steady MHD free convective flow with heat transfer through porous medium bounded by thermally insulated wavy wall and uniformly heated flat wall in presence of Ohmic heating and viscous dissipation has been presented for different values of Eckert number E_c, Ohmic heating J_e in combination of other flow parameters.

The investigation create the circumstances to make the following results:

- Enhancement in E_c, R and M cause the fluid temperature to rise while fall in the fluid temperature observed with an increase in J_e, S and A, towards the heated flat wall.
- Velocity decreases with increasing values of E_c, R and M while velocity increases as J_e, S and A increase.
- Damping of the velocity noted in increasing the magnetic field strength is the Hartmann result.
- With the enhancement of E_c, R and M, skin friction shows a diminishing trend and exhibits opposite trend for J_e, S and A.
- The Nusselt number diminishes with the increasing values of Eckert number.

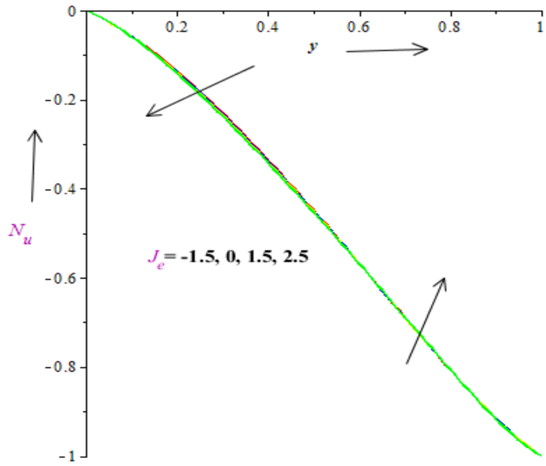

Figure 22: N_u vs. y with J_e

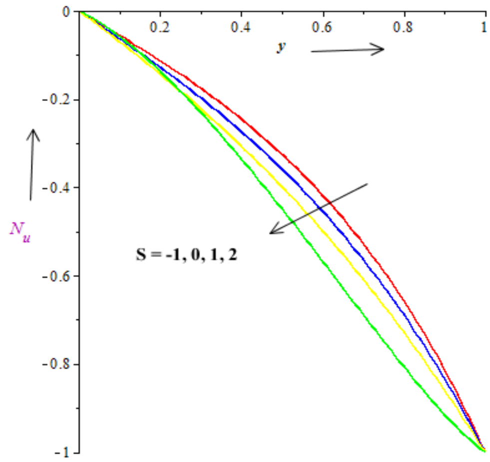

Figure 23: N_u vs. y with S

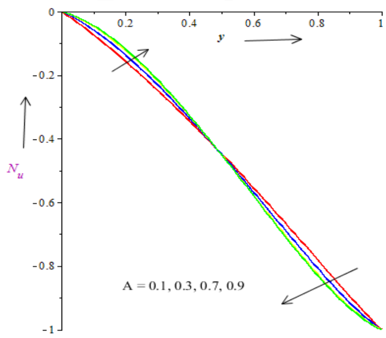

Figure 24: N_u vs. y with A

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