Analysis of Heat and Mass Transfer on MHD flow of Nanofluid over a Semi Infinite moving Surface with Diffusion Thermo

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Abstract: **The flow problem presented in the paper is boundary-layer flow of nanofluids over a moving surface in the presence of Diffusion thermo(Dufour), radiation absorption and chemical reaction. The numerical solutions of the boundary layer equations are assumed of oscillatory type. Constant velocity U0 is considered. Temperature and concentration are assumed to be fluctuating with time harmonically from a constant mean at the plate surface. We have solved the model equations using two-term perturbation technique. Comprehensive numerical computations are conducted for various values of the parameters describe the flow characteristics and results are illustrated graphically. Skin-friction coefficient and Nusselt number are discussed in detail. The findings of this investigation may be useful in catalysis, biomedicine, magnetic resonance imaging, data storage and environmental remediation. Hence, the subject of nanofluids is of great interest worldwide for basic and applied research.**

Key words: Nanofluids, Boundary layer flow, Heat and Mass Transfer, Diffusion Thermo.

1. INTRODUCTION

Pheat transfer in presence of magnetic field has received much attention by many researchers due to its potential used in science, engineering and industrial applications such as nuclear power plants, cooling of transmission lines and electric transformer etc. Accordingly, effect of radiation on MHD is of considerable interest because of its wider applications in space technology and others. When the difference between the surface and the ambient temperature is large, the radiation effect becomes important. On the other hand, the magnetohydrodynamic (MHD) nanofluid has key importance in engineering, physics and chemistry. Specifically such fluids have wide coverage in the optical modulators, tunable optical fiber filters, optical grating, optical switches, polymer industry, stretching of plastic sheets and metallurgy. Several metallurgical processes involve the cooling of continuous strips or filaments by drawing them through a nanofluid. Such strips in processes of drawing, thinning of copper wires and annealing are sometimes stretched. The quality and desired characteristics of a final product in such cases strongly depend upon the cooling rate by drawing such strips in an electrically conducting fluid. The magnetic nanoparticles are also useful in the construction of loudspeakers, magnetic cell separation, hyperthermia, drug delivery etc. Recently, the nanofluids in view of their enhanced thermal characteristics have been attracted by the scientists and engineers. It is known well established fact that the nanofluids improve the heat transfer performance of many engineering applications. The study of heat and mass transfer with chemical reaction in the presence nanofluids is of immense realistic significance to engineers and scientists because of its almost universal incidence in many branches of science and engineering. B.venkateswarulu et al., [1] have been aimed to study the effects of radiation absorption and chemical reaction in a rotating frame of reference. Shateyi and Prakash [2] investigated themagnetohydrodynamic boundary layer flow of a nanofluid over a moving surface in the presence of thermal radiation. Bhaskar Reddy et al. [3] studied the influence of variable thermal conductivity and partial velocity slip on hydromagnetic two-dimensional boundary layer flow of a nanofluid with Cu nanoparticles over a stretching sheet with convective boundary condition and also concluded that the velocity decreases as the magnetic parameter increases. Krishnamurthy et al. [4] investigated the radiation and chemical reaction effects on the steady boundary layer flow of MHD Williamson fluid through porous medium toward a horizontal linearly stretching sheet in the presence of nanoparticles and concluded that magnetic parameter decreases the velocity and also causes increase in its temperature.Sheikholeslami et al. [5] studied the free convection of magnetic nanofluid by considering MFD viscosity effect. Nanofluid is described as a fluid containing nanometer-sized particles, called nanoparticles within the length scale of 1-100 nm diameter and 5% volume fraction of nanoparticles. These fluids are suspended in engineering colloidal system of nanoparticles in a base fluid. As oil, ethylene glycol and water are poor heat transfer fluids, because they have low thermal conductivities or low heat transfer properties. The nanoparticles can be used in metals such as (Ag, Cu), oxides (Al_2O_3), nitrides (AlN, SiN), carbides (SiC) or nonmetals (graphite, carbon nano-tubes). Nanotechnology has been widely used in heat transfer including microelectronics, pharmaceutical processes, fuel cells and hybrid-powered engines. Nanofluid term was first introduced by Choi [6]. Sheikholeslami et al. [7] investigated effect of electric field on hydrothermal behavior of nanofluid in a complex geometry. Makinde and Aziz [8], Ibrahim et al. [9], Bachok et al. [10] studied the boundary layer problems of stagnation point flow over a stretching or shrinking sheet. Sheikholeslami and Rashidi [11], Sheikholeslami and Ganji [12] were investigated heat transfer effects on nanofluids and in presence of magnetic field. Hamad et al. [13] investigated the magnetic field effects on free convection flow of past a vertical semi-infinite flat plate of a nanofluid. In the similar analysis Sheikholeslami et al. [14] investigated heat transfer on $Al2O3$ water nanofluid flows in a semi annulus enclosure using Lattice Boltzmann method. Rashidi et al. [15] analyzed the buoyancy effect on MHD flow over a stretching sheet of a nanofluid in the effect of thermal radiation using RK iteration scheme

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In the present study, we investigate the flow and heat transfer phenomena over a semi infinite moving plate with velocity, temperature and concentration at the boundary conditions. The problem is solved by perturbation technique. The effects of different flow parameters on the velocity and temperature profiles were sketched and analyzed. Skin-friction coefficient and Nusselt number are discussed in detail.

2. ANALYSIS OF THE FLOW OF THE PROBLEM

An unsteady natural conventional flow of a nanofluid past a vertical permeable semi-infinite moving plate with constant heat source is considered. The flow is assumed to be in the x-direction which is taken along the plate and y-direction is normal to it. A uniform external field of strength B0 is taken to be acting along the y-direction. It is assumed that the induced magnetic field and the external electric field due to polarization of charges are negligible. The plate and the fluid are the same temperature $T_\infty^{'}$ and concentration $C_\infty^{'}$ in a stationary condition, when t ⩾ 0, the temperature and concentration at the plate fluctuate with time harmonically from a constant mean. The fluid is a water based nanofluid containing Ag(silver). The nano particles are assumed to have a uniform shape and size. Moreover, It is assumed that both the fluid phase nanoparticles are in thermal equilibrium state. Due to semi-infinite plate surface assumption, further more the flow variables are functions of y and t only.

Under the above boundary layer approximations, the governing equations for the nanofluid flow are given by

$$\frac{\partial v'}{\partial y'} = 0 \tag{1}$$

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = \frac{\mu_{nf}}{\rho_{nf}}\frac{\partial^2 u'}{\partial y'^2} + \frac{(\rho\beta)_{nf}}{\rho_{nf}} g(T' - T_\infty ') - \frac{\mu_{nf}}{\rho_{nf}}\frac{u'}{K'} - \frac{1}{\rho_{nf}}\sigma B_0^2 u' \tag{2}$$

$$(\rho C_p)_{nf}\left(\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'}\right) = \alpha_{nf}(\rho C_p)_{nf}\frac{\partial^2 T'}{\partial y'^2} - Q'(T' - T'_\infty) + Q_l^{'}(\rho C_p)_{nf}(C' - C'_\infty) + \frac{D_m K_T}{C_s}\frac{\partial^2 C'}{\partial y'^2} \tag{3}$$

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D_B\frac{\partial^2 C'}{\partial y'^2} - K_l(C' - C'_\infty) \tag{4}$$

The relevant boundary conditions for the problem are given by

$$\begin{aligned} &t' < 0, \quad u'(y',t') = 0, \quad T' = T'_\infty, C' = C'_\infty \\ &t' \geq 0, \quad u'(y',t') = U_0, \\ &T' = T'_w + \varepsilon e^{iw't'}(T'_w - T'_\infty), \\ &C' = C'_w + \varepsilon e^{iw't'}(C'_w - C'_\infty) \qquad at\ y' = 0 \\ &u'(y',t') = 0, \quad T' = T'_\infty, C' = C'_\infty\ as\ y' \to \infty \end{aligned} \tag{5}$$

The dimension less parameters feature in Equations (1) – (5) and are defined as:

$\Pr = \frac{v_f}{\alpha_f}$ (Prandtl number);

$K = \frac{K'\rho_f U_0^2}{v_f^2 \mu_{nf}}$ (permeability parameter);

$S = \frac{V_0}{U_0}$ (the suction(S > 0) or injection(S < 0) parameter);

$M = \frac{\sigma B_0^2 v_f}{\rho_f U_0^2}$ (Magnetic parameter);

$Sc = \frac{v_f}{D_B}$ (Schmidt number);

$Gr = \frac{(\rho\beta)_f g v_f (T'_w - T'_\infty)}{\rho_f U_0^2}$ (Grashof number);

$Du = \frac{D_m K_T (C'_w - C'_\infty)}{k_f C_s (T'_w - T'_\infty)}$ (Diffusion-thermo parameter);

$u = \frac{u'}{U_0}$ (dimensional velocity component);

$y = \frac{U_0 y'}{v_f}$ (normal coordianate);

$t = \frac{U_0^2 t'}{v_f}$ (dimensional time);

$\theta = \frac{(T'-T'_\infty)}{(T'_w - T'_\infty)}$ (dimensionless temperature),

$Q_L = \frac{Q'_l(C'_w - C'_\infty)}{U_0^2(T'_w - T'_\infty)}$ (radiation absorption parameter);

$Kr = \frac{K_l v_f}{U_0^2}$ (Chemical reaction parameter);

$\psi = \frac{(C'-C'_\infty)}{(C'_w - C'_\infty)}$ (dimensional velocity component);

$\mu_{nf} = \rho_f v_f$ (dimensional velocity component);

In equations (2) – (4) with the boundary conditions (5) we obtain

$$\frac{\partial u}{\partial t} - S\frac{\partial u}{\partial y} = \frac{D}{A}\frac{\partial^2 u}{\partial y^2} + \frac{B}{A}Gr\theta - \left(M + \frac{1}{K}\right)u \qquad (6)$$

$$\frac{\partial \theta}{\partial t} - S\frac{\partial \theta}{\partial y} - Q_L\psi = \frac{1}{C\Pr}\left(E\frac{\partial^2\theta}{\partial y^2} - Q\theta\right) + \frac{Du}{C\Pr}\frac{\partial^2\psi}{\partial y^2} \qquad (7)$$

$$Sc\frac{\partial \psi}{\partial t} - Sc\,S\frac{\partial \psi}{\partial y} = \frac{\partial^2\psi}{\partial y^2} - ScKr\psi \qquad (8)$$

The corresponding boundary conditions are

$$\begin{aligned} &t < 0 : u = 0, \theta = 0, \psi = 0 \\ &t \geq 0 : u = 1, \theta = 1 + \varepsilon e^{iwt}, \psi = 1 + \varepsilon e^{iwt} \quad at \quad y = 0 \\ &\qquad u = 0, \theta = 0, \psi = 0 \quad as \quad y \to \infty \end{aligned} \qquad (9)$$

3. NUMERICAL SOLUTIONS BY TWO TERM PERTURBATION TECHNIQUE

Equations (6) – (8) are coupled non-linear partial differential equations whose solutions in closed-form are difficult to obtain. To solve these equations by converting into ordinary differential equations, the unsteady flow is superimposed on the mean steady flow, so that in the neighborhood of the plate, the expressions for velocity, temperature and concentration are assumed as

$$u(y) = u_0(y) + \varepsilon\, e^{iwt}u_1(y) + O(\varepsilon^2) \qquad (10)$$

$$\theta(y) = \theta_0(y) + \varepsilon e^{iwt}\theta_1(y) + O(\varepsilon^2) \qquad (11)$$

$$\psi(y) = \psi_0(y) + \varepsilon e^{iwt}\psi_1(y) + O(\psi^2) \qquad (12)$$

Where $\varepsilon << 1$ is a perturbation parameter.

Now substituting equations (10) – (12) into equations (6) – (8) and equating the harmonic and non-harmonic terms and neglecting higher order terms, using relevant boundary conditions, we obtain the expressions for velocity, temperature and concentration as

$$\begin{aligned} u(y,t) &= (L_5 e^{-m_5 y} + L_3 e^{-m_3 y} + L_4 e^{-m_1 y}) \\ &+ \varepsilon e^{iwt}(L_8 e^{-m_6 y} + L_6 e^{-m_4 y} + L_7 e^{-m_2 y}) \end{aligned} \qquad (13)$$

$$\begin{aligned} \theta(y,t) &= (L_1 e^{-m_3 y} + A_1 e^{-m_1 y}) \\ &+ \varepsilon e^{iwt}(L_2 e^{-m_4 y} + A_2 e^{-m_2 y}) \end{aligned} \qquad (14)$$

$$\psi(y,t) = e^{-m_1 y} + \varepsilon e^{iwt}e^{-m_2 y} \qquad (15)$$

The dimensionless skin-friction coefficient, rate of heat transfer and rate of mass transfer are given by

$$\begin{aligned} \tau = -\left(\frac{\partial u}{\partial y}\right)_{y=0} &= (L_5 m_5 + L_3 m_3 + L_4 m_1) \\ &+ \varepsilon e^{iwt}(L_8 m_6 + L_6 m_4 + L_7 m_2) \end{aligned} \qquad (16)$$

$$\begin{aligned} Nu = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} &= (L_1 m_3 + A_1 m_1) \\ &+ \varepsilon e^{iwt}(L_2 m_4 + A_2 m_2) \end{aligned} \qquad (17)$$

$$Sh = -\left(\frac{\partial \psi}{\partial y}\right)_{y=0} = m_1 + \varepsilon e^{iwt}m_2 \qquad (18)$$

4. RESULTS AND DISCUSSIONS

In order to bring out the silent features of the flow, heat and mass transfer characteristics with nanoparticles, the results are presented in Figures 1-15 and Tables 2 - 3 The influences of nanoparticles on the velocity, the temperature and the concentration distributions as well as on the skin-friction, the heat transfer rate and mass transfer rate are discussed numerically. We have assumed here ε = 0.001, t = 1, ω = 1 and Pr = 0.71, while the remaining parameters are varied over a range.

Table 1 Thermo physical properties of fluid and nanoparticles given by Oztop and Abu-Nada[16].

Physical Properties	Water	Ag
C_p(J/kgK)	4179	235
ρ(kg/m^3)	997.1	10500
k(W/mK)	0.613	429
$\beta X10^{-5}$	21	1.89

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_s;$$

$$(\rho C_p)_{nf} = (1-\phi)(\rho C_p)_f + \phi(\rho C_p)_s;$$

$$(\rho\beta)_{nf} = (1-\phi)(\rho\beta)_f + \phi(\rho\beta)_s;$$

$$K_{nf} = K_f\left(\frac{K_s + 2K_f - 2\phi(K_f - K_s)}{K_s + 2K_f + 2\phi(K_f - K_s)}\right);$$

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}};$$

$$\alpha_{nf} = \frac{K_{nf}}{(\rho C_p)_{nf}};$$

$$A = \left((1-\phi) + \phi\left(\frac{\rho_s}{\rho_f}\right)\right);$$

$$B = \left((1-\phi) + \phi\left(\frac{(\rho\beta)_s}{(\rho\beta)_f}\right)\right);$$

$$C = \left((1-\phi) + \phi\left(\frac{(\rho C_p)_s}{(\rho C_p)_f}\right)\right);$$

$$D = \frac{1}{(1-\phi)^{2.5}};$$

$$E = \frac{K_{nf}}{K_f} = \left(\frac{(1+2\phi) + 2(1-\phi)\left(\frac{K_f}{K_s}\right)}{(1+2\phi) + 2(1+\phi)\left(\frac{K_f}{K_s}\right)}\right).$$

Fig.1 demonstrates the effect of suction parameter S on fluid velocity u for nano fluid (ϕ ≠ 0). As out put of figure, it is seen that the velocity of the fluid across the boundary layer by decreases as the suction parameter S increases for nano fluid with Nano particles Ag. Fig.2 witnessed the influence of schmdit number Sc on velocity distribution. It is clear from the figure that velocity increase with increase of Sc. Fig.3 portrays the influence of heat source parameter Q on velocity distribution. It is clear from the figure that velocity decrease with increase of Q. Fig.4 exhibites the effect of prandtl number Pr on velocity distribution. It is clear from the figure that velocity decrease with increase of Pr. Fig.5 shows the influence of volumetric fraction parameter ϕ on velocity distribution. It is clear from the figure that velocity decrease with increase of ϕ. The magnetic parameter M on velocity profiles for Nano particles Ag are shown in Fig.6. From this graph, it is obvious that nanofluid velocity of the fluid decelerates with an increase in the strength of magnetic field. The influences of a transverse magnetic field on an electrically, conducting fluid give rise to a resistive-type force called the Lorentz force. This force has the tendency to slow down the motion of the fluid in the boundary layer. Also it is clear that the nanofluid velocity is lower for the regular fluid. Fig.7 shows the effect of the permeability of the porous medium parameter Kon the velocity distribution. As shown, the velocity is increasing with the increasing dimensionless porous medium parameter. The effect of the dimensionless porous medium becomes smaller as increase. Physically, this result can be achieved when the holes of the porous medium may be neglected. It is observed that an increase in the Grashof number leads to increase in the velocity For various values of Grashof number the velocity profiles are plotted in Fig.8 The Grashof number signifies the relative effect of the thermal buoyancy force to the viscous hydrodynamic force in the boundary layer. As expected, it is observed that there is a rise in the velocity due to the enhancement of thermal buoyancy force. Fig.9 portrays the influence of Diffusion thermo parameter Du on velocity distribution. It is clear from the figure that velocity decrease with increase of Du. Fig.10 demonstrates the effect of suction parameter S on fluid temperature for nano fluid (ϕ ≠ 0). As out put of figure, it is seen that the temperature of the fluid across the boundary layer by increases as the suction parameter S increases for nano fluid with Nano particles Ag. Fig.11 witnessed the influence of schmdit number Sc on temperature distribution. It is clear from the figure that temperature increase with increase of Sc. Fig.12 portrays the influence of heat source parameter Q on temperature distribution. It is clear from the figure that temperature decrease with increase of Q. The graphical representation of prandtl number Pr on temperature profiles as depicted in Fig.13 with in boundary layer. It is observed that the growing Pr increases the temperature boundary layer. For different values of destructive chemical reaction parameter Kr the temperature profiles are plotted in Fig.14. An increase in chemical reaction parameter will suppress the temperature of the fluid. The temperature distribution decreases at all points of the flow field with the increase in the chemical reaction parameter.The influence of Diffusion Thermo parameter Du on the temperature distribution for Ag -water nano fluid is portrayed in Fig.15 with in boundary layer. With the increasing values of Du, the temperature of nanofluid is found to increase the thermal boundary layer thickness. The numerical values of the skin-friction coefficient for the nanoparticles Ag are in Table 2. From this table, it is seen that the skin-friction coefficient increases with increase values of S, M, K while decrease with increase values of Du,Sc,Pr and ϕ for the nanoparticle Ag.Table 3. denotes the numerical values of heat transfer rate for different fluid flow parameters S, Q, Sc, Du, ϕ, and Q_L for Ag water nanofluid. From this table it is clear that the heat transfer rate increases withS,kr, ϕ and Q, while decreases withSc, Du and Q_L

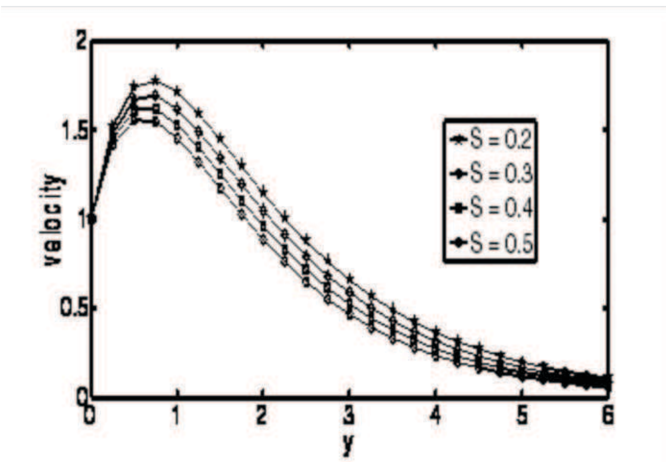

Fig.1 Plot of Suction parameter(S) on velocity profile with Ag-water.

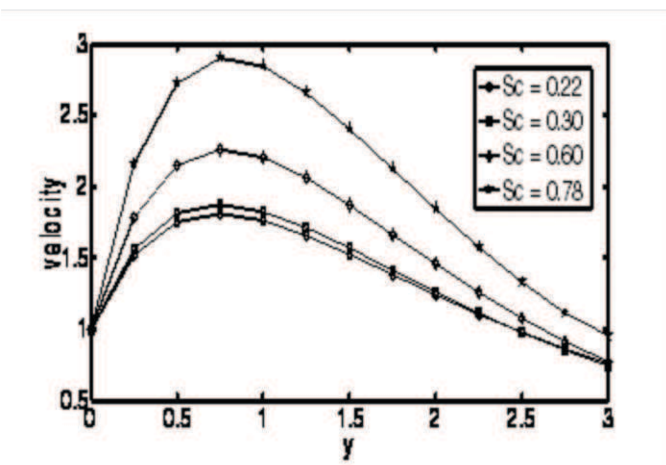

Fig.2 Plot of Schmdit number(Sc) on velocity profile with Ag-water.

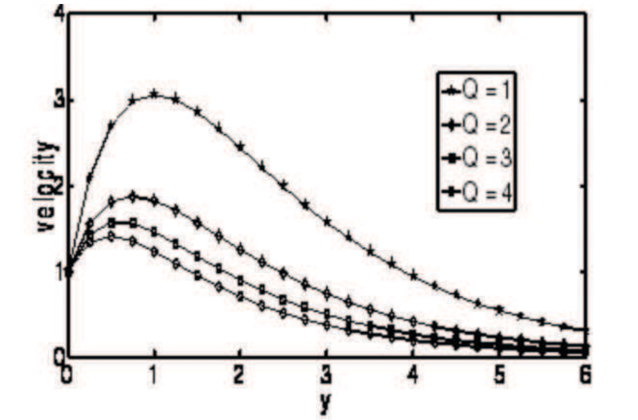

Fig.3 Plot of Heat source parameter(Q) on velocity profile with Ag-water

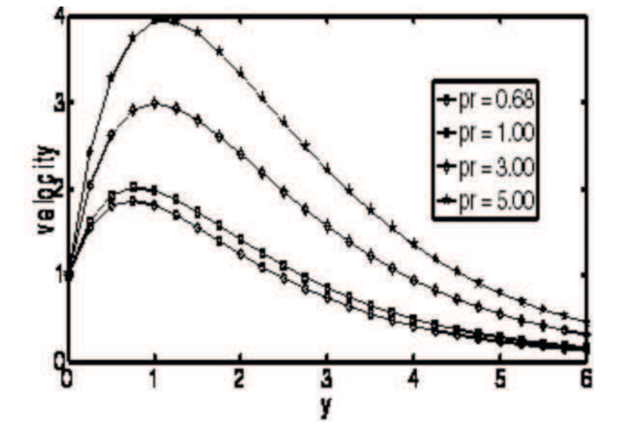

Fig.4 Plot of Prandtl number(Pr) on velocity profile with Ag-water.

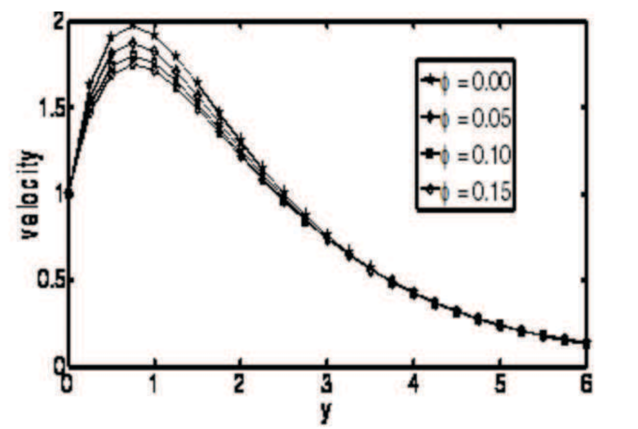

Fig.5 Plot of volumetric fraction number(ϕ) on velocity profile with Ag-water.

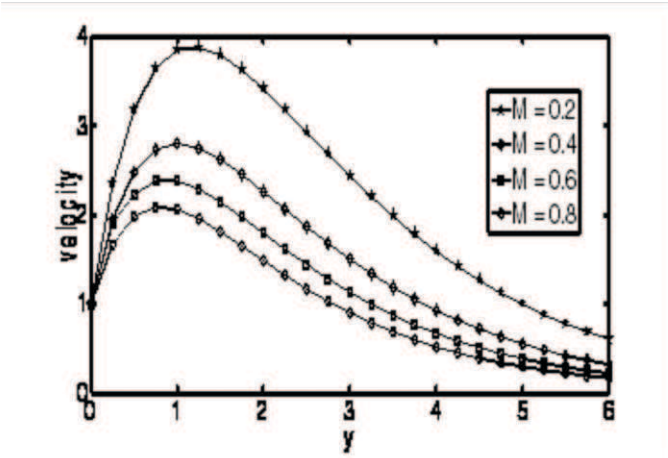

Fig.6 Plot of magnetic parameter(M) on velocity profile with Ag-water

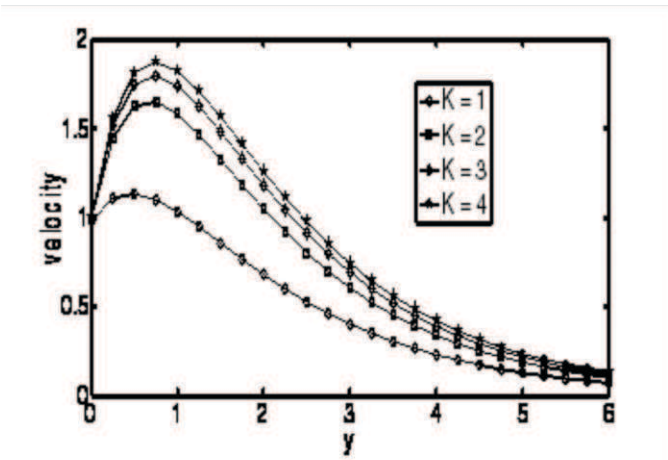

Fig.7 Plot of permeability parameter(K) on velocity profile with Ag-water.

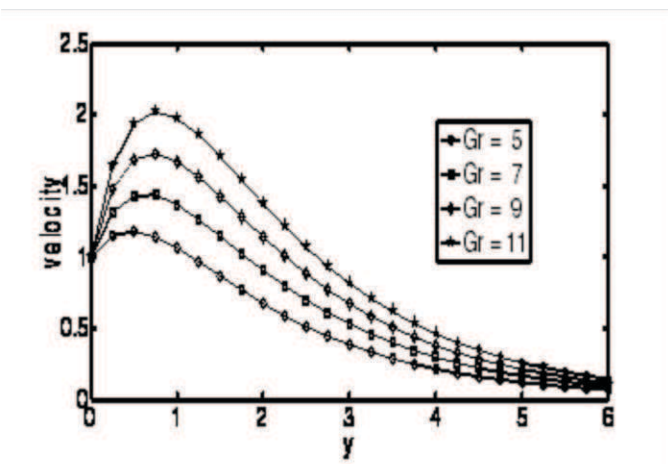

Fig.8 Plot of Grashof number(Gr) on velocity profile with Ag-water.

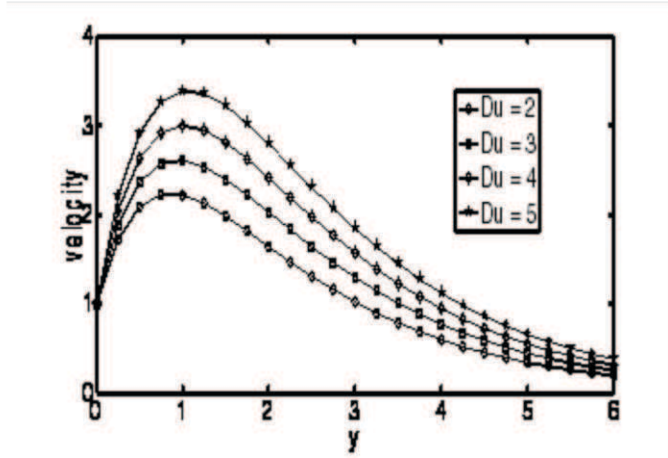

Fig.9 Plot of Diffusion-thermo parameter(Du) on velocity profile with Ag-water

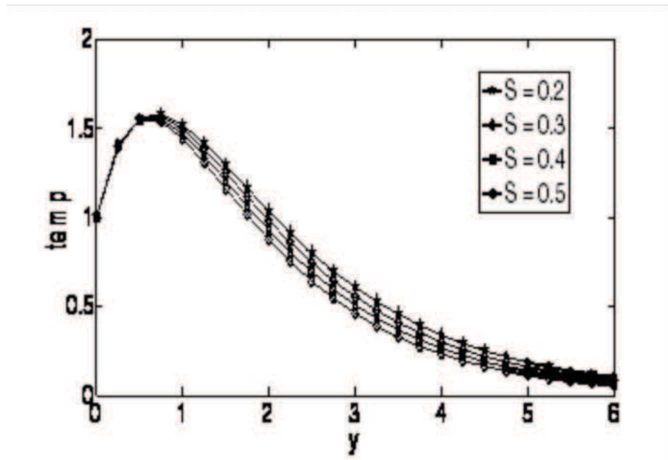

Fig.10 Plot of Suction parameter(S) on temperature profile with Ag-water

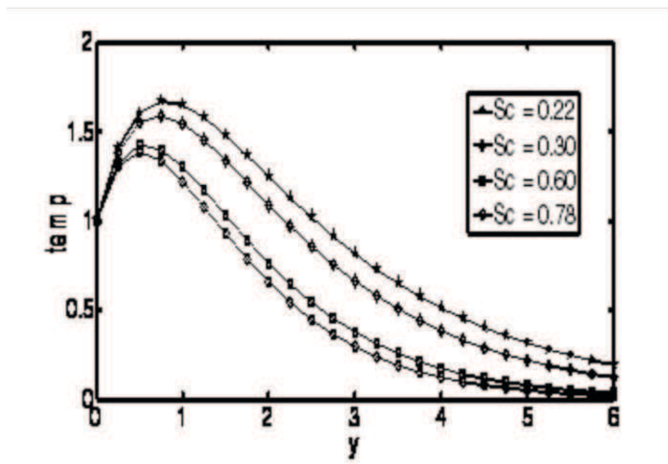

Fig.11 Plot of Schmdit number (Sc) on temperature profile with Ag-water.

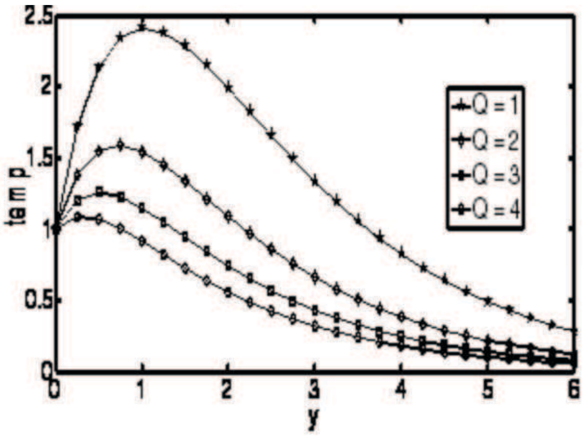

Fig.12 Plot of Heat source parameter(Q) on temperature profile with Ag-water.

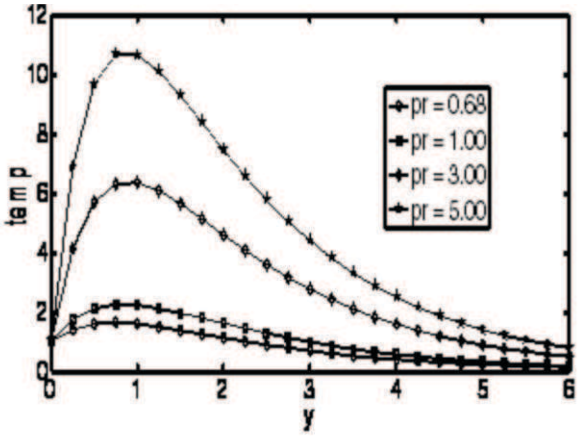

Fig.13 Plot of Prandtl number(Pr) on temperature profile with Ag-water.

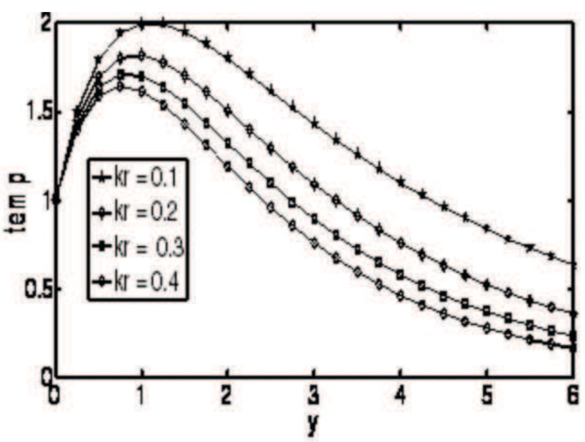

Fig.14 Plot of Chemical reaction parameter(kr) on temperature profile with Ag-water.

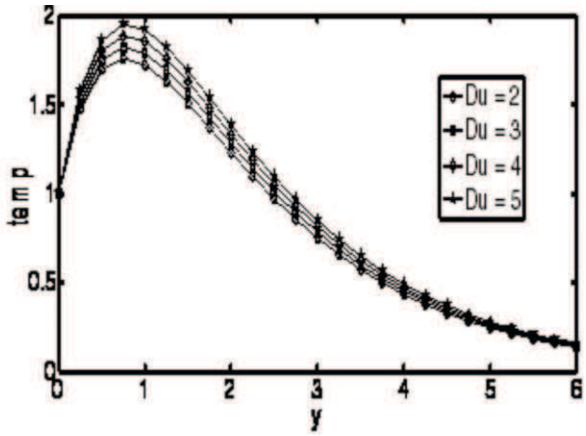

Fig.15 Plot of Diffusion-thermo parameter(Du) on temperature profile with Ag-water.

Table2:. Skin-friction coefficient values of Ag water Nanofluid

S	Du	M	Sc	Pr	K	ϕ	Ag(sk)
0.2	1	1	0.30	0.71	1	0.05	1.4449
0.3	1	1	0.30	0.71	1	0.05	1.8529
0.4	1	1	0.30	0.71	1	0.05	2.2681
0.1	2	1	0.30	0.71	1	0.05	0.8278
0.1	3	1	0.30	0.71	1	0.05	0.6318
0.1	4	1	0.30	0.71	1	0.05	0.4357
0.1	1	2	0.30	0.71	1	0.05	0.9408
0.1	1	3	0.30	0.71	1	0.05	1.3378
0.1	1	4	0.30	0.71	1	0.05	1.6281
0.1	1	1	0.22	0.71	1	0.05	1.0812
0.1	1	1	0.60	0.71	1	0.05	0.7227
0.1	1	1	0.78	0.71	1	0.05	0.4226
0.1	1	1	0.30	1	1	0.05	0.8704
0.1	1	1	0.30	2	1	0.05	0.5971
0.1	1	1	0.30	3	1	0.05	0.4322
0.1	1	1	0.30	0.71	2	0.05	0.5346
0.1	1	1	0.30	0.71	3	0.05	0.4091
0.1	1	1	0.30	0.71	4	0.05	0.3502
0.1	1	1	0.30	0.71	1	0.10	0.9422
0.1	1	1	0.30	0.71	1	0.15	0.9077
0.1	1	1	0.30	0.71	1	0.20	0.8837

Table2:. Skin-friction coefficient values of Ag water Nanofluid

S	kr	Q	Sc	Du	QL	ϕ	Ag(nu)
0.2	0.5	2	0.30	1	2	0.05	0.5830
0.3	0.5	2	0.30	1	2	0.05	0.5963
0.4	0.5	2	0.30	1	2	0.05	0.6082
0.1	0.1	2	0.30	1	2	0.05	0.5724
0.1	0.2	2	0.30	1	2	0.05	0.5838
0.1	0.3	2	0.30	1	2	0.05	0.5834
0.1	0.5	3	0.30	1	2	0.05	1.0227
0.1	0.5	4	0.30	1	2	0.05	1.3767
0.1	0.5	5	0.30	1	2	0.05	1.6741
0.1	0.5	2	0.22	1	2	0.05	0.5807
0.1	0.5	2	0.60	1	2	0.05	0.4882
0.1	0.5	2	0.78	1	2	0.05	0.4245
0.1	0.5	2	0.30	2	2	0.05	0.3908
0.1	0.5	2	0.30	3	2	0.05	0.2131
0.1	0.5	2	0.30	4	2	0.05	0.0354
0.1	0.5	2	0.30	1	0	0.05	1.3079
0.1	0.5	2	0.30	1	1	0.05	0.9382
0.1	0.5	2	0.30	1	3	0.05	0.1987
0.1	0.5	2	0.30	1	2	0.10	0.5834
0.1	0.5	2	0.30	1	2	0.15	0.5983
0.1	0.5	2	0.30	1	2	0.20	0.6132

CONCLUSIONS

We have peformed Analysis of Heat and Mass Transfer on MHD flow with Ag Water Nanofluid over a Semi Infinite Flat Surface. In this article we considered Ag-water nanofluid. We have solved the model equations using perturbation technique. The following conclusions can be made from the present investigation.

- The silver (Ag) nanoparticles proved to have the maximum cooling recital for this vertical porous plate problem. This is due to the high thermal conductivity of Ag.
- The velocity profile increases with an increase inpermeability parameter.
- The temperature profile decreases with an increase in Dufour number.
- Due to chemical reaction, the temperature of the fluid decreases. This is because the consumption of chemical species leads to fall in the species temperature field.

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NOMENCLATURE

‘u- velocity component along x-axis, ‘v - velocity component along y-axis, ϕ- the solid volume fraction of the nanoparticles,K_{nf}- the thermal conductivity of the base fluid, Ks- the thermal conductivity of the solid, β_f- the coefficient of the thermal expansion of the fluid, β_C- the coefficient of the thermal expansion of the solid, ρ_f- the density of the fluid fraction, ρ_C- the density of the solid fraction, β_{nf}- the coefficient of thermal expansion of nanofluid, σ- the electric conductivity of the fluid, ρ_{nf}- the density of the nanofluid, μ_{nf}- the viscosity of nanofluid, $(\rho C_p)_{nf}$- the heat capacitance of nanofluid, g- the acceleration due to gravity, K'- the permeability porous medium, T'- the temperature of the nanofluid, Q- the temperature dependent volumetric rate of the heat source, α_{nf}-

the thermal diffusivity of the nanofluid, U_0 - uniform reference velocity, ε- perturbation parameter, u- velocity components in the x-axis, v- velocity components in the y-axis, C- Nanoparticle concentration, f- Fluid, w- condition at wall, ∞ - Ambient Condition, T'_w- Temperature at the surface, T'_∞- Ambient temperature, C_f- skin friction coefficient, Cp – specific heat at constant pressure, C'_∞- Ambient concentration, nf- nanofluid, σ- electrical conductivity of the fluid.

APPENDIX

$$m_1 = \left(\frac{SSc + \sqrt{(SSc)^2 + 4KrSc}}{2} \right);$$

$$m_2 = \left(\frac{SSc + \sqrt{(SSc)^2 + 4Sc(i\omega + Kr)}}{2} \right);$$

$$m_3 = \left(\frac{\Pr CS + \sqrt{(\Pr CS)^2 + 4EQ}}{2} \right);$$

$$m_4 = \left(\frac{\Pr SC + \sqrt{4E(Q + i\omega \Pr C)}}{2E} \right);$$

$$m_5 = \left(\frac{AS + \sqrt{(AS)^2 + 4D\left(M + \frac{1}{K}\right)}}{2D} \right);$$

$$m_6 = \left(\frac{AS + \sqrt{(AS)^2 + 4D\left(Ai\omega + \left(M + \frac{1}{K}\right)\right)}}{2D} \right);$$

$$L_1 = 1 - A_1 \quad ; \quad L_2 = 1 - A_2 \quad ;$$

$$L_3 = -\left(\frac{BL_1 Gr}{Dm_3^2 - ASm_3 - \left(M + \frac{1}{K}\right)} \right);$$

$$L_4 = -\left(\frac{BA_1 Gr}{Dm_1^2 - ASm_1 - \left(M + \frac{1}{K}\right)} \right);$$

$$L_5 = 1 - L_3 - L_4;$$

$$L_6 = -\left(\frac{BL_2 Gr}{Dm_4^2 - ASm_4 - \left(Ai\omega + M + \frac{1}{K}\right)} \right);$$

$$L_7 = -\left(\frac{BGrA_2}{Dm_2^2 - ASm_2 - \left(Ai\omega + M + \frac{1}{K}\right)} \right);$$

$$L_8 = -L_6 - L_7;$$

$$A_1 = -\left(\frac{m_1^2 Du + \Pr Q_L C}{Em_1^2 - \Pr CSm_1 - Q} \right);$$

$$A_2 = \left(\frac{m_2^2 Du + C \Pr Q_L}{Em_2^2 - C \Pr m_2 - (Q + i\omega C \Pr)} \right).$$

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