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EFFECTS OF RADIATION AND ABSORPTION ON THREE DIMENSIONAL MAGNETOHYDRODYNAMIC (MHD) UPPER-CONVECTED MAXWELL NANO-FLUID FLOW

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The present paper deals with the study of the MHD upper-convected Maxwell nano-fluid flow through a bidirectional stretchable surface. The influence of heat absorption and thermal radiation has been studied. Governing non-linear partial differential equations, controlling the mass conservation, momentum conservation, energy conservation, and species concentration, are transformed into ordinary differential equations with the help of an appropriate similarity transformation, which are then solved numerically by using the bvp4c routine of MATLAB. The impact of various physical parameters on the velocity, temperature, and concentration distributions is described briefly with the help of graphs. The skin-friction, rate of heat and mass transfers at the plate are computed numerically and displayed through the table. able. Such a fluid flow problem may find applications in heat transfer mechanisms/devices.
Keywords: *Maxwell Nano-fluid; MHD; Heat absorption; Thermal radiation*
PACS: 47.11.-j, 47.10.ab, 02.30.Jr

List of Symbols (Nomenclature)

a, b:	dimensional constants	Rd:	thermal radiation parameter
B_0:	Magnetic field strength	Re_z:	Reynolds number
C:	Concentration of fluid	Sh_z:	Sherwood number
C:	stretching ratio parameter	T:	temperature of fluid
c_p:	Specific heat at constant pressure	Tw:	wall temperature
C_w:	concentration on wall	T_∞:	ambient temperature
C_∞:	ambient concentration	(u,v,w):	velocity components
D_B:	Brownian diffusion coefficient	α:	Thermal diffusivity
D_T:	Thermophoretic diffusion coefficient	λ:	fluid relaxation time
$f' g'$:	Non-dimensional velocity	ν:	Kinetic viscosity coefficient
j_w:	mass flux	θ:	Non-dimensional temperature
K:	Thermal conductivity	σ:	Stefan- Boltzman constant
Le:	Lewis number	τ:	ratio of nanoparticle heat and base
M:	Magnetic parameter	η:	similarity variable
Nb:	Brownian diffusion coefficient (non-dimensional)	ρ:	density of fluid
Nt:	Thermophoretic diffusion coefficient (non-dimensional)	ϕ:	Non-dimensional concentration
Nu_z:	Nusselt number	θ_w:	temperature ratio parameter
Pr:	Prandtl number	Q_0:	Heat absorption coefficient
q_r:	Radiative heat flux	Q:	Heat absorption parameter
q_w:	surface heat flux		

1. INTRODUCTION

Maxwell Nanofluid is used in cooling and heating systems. It enhances the rate of heat transfer by 15%. It is used in chillers, heat pumps, energy recovery systems, pumps, fans and terminal units. In a Maxwell Nanofluid, submicron Aluminum Oxide particles are suspended in the base fluid. Sajid et al. [1] studied the “Darcy-Forchheimer flow of Maxwell Nanofluid flow with nonlinear thermal radiation and activation energy”. Increasing the Deborah number leads to decrease in the velocity profile. When the thickness of the wall, Prandtl number and linear thermal radiation is increased then the Nusselt number also increases and decreases when the thermophoresis parameter, magnetic parameter, Lewis number and thermal conductivity is increased. Further it is observed that the Nusselt number increases when the temperature difference parameter, Deborah number, porosity parameter, reaction rate constant and fitted rate constant is increased then the Nusselt number also increases. Due to the presence of the Lorentz force there is a higher rate of collision of the molecules. The velocity profile seems to be going uphill as the magnetic parameter is increased. Bilal et al. [2] studied the “Maxwell Nanofluid flow individualities by way of rotating cone”. Kumara et al. [3] studied the “numerical simulation of heat transport in Maxwell nanofluid flow over a stretching sheet considering magnetic dipole effect”. In their investigation they kept the Prandtl number constant. For both the type of fluids the radial velocity profile kept decreasing as the ferromagnetic

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interaction parameter was increasing while the surface drag force kept increasing. The rate of heat transfer increased as the scalar potential value increased. Thermal distribution is disrupted by increasing the thermal relaxation parameter. The rate of heat transfer is better in the Newtonian liquid compared to the Maxwell liquid when the magnetic value is increased. Biswas et al. [4] studied the "computational treatment of MHD Maxwell Nano fluid flow across a stretching sheet considering higher order chemical reaction and thermal radiation". The velocity of the nanofluid is enhanced by increasing its thermal buoyancy whereas the velocity of the nanofluid falls down due to the resistive force produced by magnetic field and the porosity. The Brownian motion and thermophoresis affect helps the nanoparticles to move about freely due to which the temperature is increased. In the convection mode the rate of heat transfer is enhanced by increasing the Nusselt number. The Lewis number increases as the solutal diffusivity decreases. Shuguang et al. [5] studied the "modelling and analysis of heat transfer in MHD stagnation point flow of Maxwell Nano fluid over a porous rotating disc". The radial velocity and the azimuthal velocity drop down as the Deborah number increased whereas the axial velocity hiked up. When the value of magnetic parameter was increasingly high, increased the viscosity of the fluid which in turn reduced the radial velocity remarkably. The centrifugal force leads to an increased tangential velocity and axial velocity when the thermal biot number value increases the temperature at the boundary layer increases. For higher values of Reynolds number, the concentration profile increased. As the Prandtl number, Brownian motion, thermophoresis effect and the thermal biot number values increased the Nusselt number profile decreased gradually. Adem and Chanie [6] studied the "inclined magnetic field on mixed convection Darcy-Forchheimer Maxwell Nano fluid flow over a permeable stretching sheet with variable thermal conductivity: The numerical approach". In the hot surface the mixed convection parameter increases when the fluid velocity is increased, while it is the opposite in case of the cold surface. There is a negative effect in the magnetic field parameter, inertia coefficient and the angle of inclination when the fluid velocity increases. The Prandtl number is directly proportional to the temperature and concentration profiles. When the activation energy increases the concentration profile also increases. As the radiation parameters steadily increases the temperature spikes up. Faizan et al. [7] studied the "bio convection Maxwell Nano fluid through Darcy-Forehheimer medium due to rotating disc in the presence of MHD". It has been observed the velocity across the radius and tangent increases whereas across the axis it tends to decrease when the magnetic parameter is increased. There is a fall in all the velocity when the Deborah number is increased. When the thermal biot number is increased the polymeric movement is enhanced. The motility of the microorganisms reduces as the bioconvective Lewis number increases. By increasing the Darcy-Forchheimer and Deborah number the skin friction coefficient is increased.

The heat transfer rate of nanofluid is greater due to greater thermal activities as compared to the ordinary base fluids. Rashid et al. [8] studied "the shape effects of nano size particles on magnetohydrodynamic Nano fluid flow and heat transfer over a stretching sheet with Entropy generation". They used Ag-water Nano fluid. Three differently shaped nano particles that is sphere, blade and lamina was used for the study. They used Prandtl number = 6.2 for the experiment. The laminar shaped Nano particles performed better than the other shaped particles in the temperature profile, heat transfer whereas the sphere-shaped Nano particle gave the least performance. Sadiq [9] studied "the heat transfer of a Nano liquid thin film over a stretching sheet with a surface temperature and internal heat generation". He used copper, Alumina and Titanium with water-based fluid. The temperature profile can be increased if the Nano particle volume fraction is increased. When the Nano particle volume parameter and unsteadiness parameter is increased there is a decline in the film thickness parameter. When the Nano particle volume fraction is increased the thermal boundary layer increases. Sarada et al. [10] studied "the effect of magnetohydrodynamics on heat transfer behavior of a non-Newtonian fluid flow over a stretching sheet under a local thermal non-equilibrium condition". They considered their study on Jeffrey and Oldroyd-B fluid. The heat transfer in the liquid and solid phase of both the fluid decreases as the thermophoresis parameter decreases. Qureshi [11] studied "the MHD driven Prandtl-Eyring hybrid nano fluid flow over a stretching sheet with thermal jump condition". He used the Engine oil as his base fluid and the nano particles copper and zirconium dioxide. The heat transfer rate is better when the hybrid nano fluid is used in comparison to the traditional nano fluid. When the size of the nano particles is increased the rate at which the heat is transferred is also increased. The thermal conductivity is better in the Prandtl-Eyring hybrid nano fluid. By increasing the thermal radiative flow, Reynolds number, magnetic field, Brinkman number and Size parameter the entropy of the system increases. Anusha et al. [12] studied "the MHD of nano fluid flow over a porous stretching / shrinking plate with mass transportation and Brinkman ratio". Copper and alumina Nano particles suspended in water as the base fluid was used to carry out the investigation. They found out that when the porosity parameter is increased the transverse velocity will decrease. A similar effect takes place even with the magnetic field. Abbas [13] studied "heat transfer enhancement of copper ethylene glycol based nano particle on radial stretching sheet." Differently shaped nano particle such as cylinder, platelet and sphere shape was used. The maximum flow was recorded when the platelet shaped copper nano particle was used. The minimum heat transfer occurred in the case of sphere-shaped particle. Rao and Deka [14] studied "the analysis of the MHD bi-convection flow of a hybrid nano fluid containing motile micro-organisms over a porous stretching sheet". They used water-based Nano-fluid having motile organisms and copper and alumina nano particles. The nano fluid having the motile micro-organisms showed a better result in heat transfer in comparison to the nano fluid without motile micro-organisms. When the magnetic field is increased there is an increase in the concentration of nano particles and microbes, also the temperature profile while the velocity profile decreases. Same is the effect of porosity parameter the velocity profile increases when the volume fraction of copper and alumina is increased.

When the energy is transferred through a space or medium in the form of waves or particles is called radiation. When the temperature between two sources is different radiation takes place. In the field of medical science radiation is used for the diagnosis as well as the treatment for many diseases. It is also used in the system of communication etc. Shoaib et al. [15] studied “the numerical investigation for rotating flow of MHD hybrid nanofluid with thermal radiation over a stretching sheet”. The velocity profile decreases and the temperature profile increases for higher values of magnetic parameter and rotation parameter. Both the velocity and temperature profiles increase when the Biot number and concentration of nanoparticles are increased. Higher values of magnetic parameter and concentration of the particle decrease the skin friction. Sreedevi et al. [16] studied “the heat and mass transfer analysis of unsteady hybrid nanofluid flow over a stretching sheet with thermal radiation”. They have used carbon nanoparticles and silver nanoparticles combinedly and the base fluid considered is water. Fatunmbi et al. [17] studied the “entropy analysis of nonlinear radiative Casson nanofluid transport over an electromagnetic actuator with temperature dependent properties”. As and when there is an appreciation in the magnitude of caption fluid perimeter viscosity variation parameter mass section term and nanoparticles concentration flux terms there is a shrinkage in the hydrodynamic boundary layer, thus decelerating the fluid flow. Increasing the Hartmann number and Richardson number accelerates the fluid flow. The temperature field soars high as the wall heating parameter, thermophoresis, thermal conductivity, Brownian movement, viscose dissipation shoots up. Whereas there is an opposite action by mass suction and Prandtl number parameter. Amplification of viscose dissipation and suction leads to hike in entropy generation parameter. It is lowered when the thermophoresis and Richardson numbers steps up. Yaseen et al. [18] $s$tudied “the system and opposing flow of MHD hybrid nanofluid flow past a permeable moving surface with heat source/ sink and thermal radiation”. They have made their study on hybrid nanofluid (SiO_2 - MoS_2 / water). Hussain and Sheremet [19] studied “the convective analysis of the radioactive Nano fluid flow through porous media over a stretching surface with inclined magnetic field”. The thermal profile is intensified as the nanoparticle concentration increases. The fluid velocity and magnitude of drag coefficient diminishes as the Hartmann’s number rises. Jagdeesh et al. [20] studied “the convective heat and mass transfer rate on 3D Williams and nanofluid flow via linear stretching sheet with thermal radiation and heat absorption”. When there is an upsurge in the magnetic parameter the velocity of the Williamson fluid is higher than that of Nano fluid. The skin friction coefficient is higher in the absence of Williamson parameter. The temperature is high in non-Newtonian fluid. Williamson fluid has higher fluid velocity in comparison to nanofluid motion due to the electrical conductivity.

Absorption is a process in which the substances get absorbed in the solid/liquid/gaseous phase. In the process of absorption, the Nernst distribution law is used. Gopal et al. [21] studied “the impact of thermal stratification and heat generation /absorption on MHD Carreau nanofluid flow over a permeable cylinder”. They found out that the curvature parameters led to more friction. Krishna et al. [22] studied “the radiation absorption on MHD convective flow of nanofluids through vertically travelling absorbent plate”. They used Al_2O_3-water based and TiO_2-water based nanofluid for their study. The radiation absorption parameter when increased, there is also an increase in the temperature and velocity. The radiation parameter works like a catalyst for the velocity profile. Nemati et al. [23] $s$tudied “the MHD natural convection in a cavity with different geometrics filled with a nanofluid in the presence of heat generation/absorption using lattice Boltzmann method”. They used Cu-water based nanofluid for their study in a which the particles are shaped as diagonal, smooth and curve. Dahab et al. [24] studied “the double diffusive peristaltic MHD Sisko nanofluid flow through a porous medium in presence of non-linear thermal radiation, heat generation/ absorption and Joule heating”. The velocity about the axis first increased and then gradually decreased when the magnetic parameter, heat Grashof number, Darcy number, Nano particle Grashof number, rotation and solutal Grashof number increased. The solutal Grashof number, heat Grashof number nano particle Grashof number, all these parameters, when increased led the pressure gradient distribution to rise then fall after a while. When the non-linear thermal radiation and the temperature ratio parameters are increased, the distribution of the temperature declines gradually. Asghar et al. [25] studied “the magnetized mixed convection hybrid nanofluid with effect of heat generation/ absorption and velocity slip condition”. They found out that when the volume fraction of the solute was high, the rate of heat transfer increased also helping in the separation of the boundary layer. Mahmood et al. [26] studied “the numerical analysis of MHD tri- hybrid nanofluid over a non-linear stretching/ shrinking sheet with heat generation /absorption and slip conditions”. In their investigation they found that the tri -hybrid nanofluid showed up the best result and the conventional nanofluid showed the least result when compared for the profiles, Nusselt number, velocity, skin friction and temperature. When the volume fraction was increased all the three types of fluid showed an increasing graph for the velocity profile as well as the temperature profile. The rate of heat transfer soar high as the suction parameter was increased. The velocity increased and the temperature decreased for all the three types of fluid when the stretching parameter was increased. Muzammal et al. [27] studied “the transportation of melting heat in stratified Jeffrey fluid flow with heat generation and magnetic field”. In their findings they got to know that for higher values of Deborah number, velocity profile and the temperature profile increased. As the stratified parameter increased the temperature profile showed a downhill curve. Also, the temperature of the fluid kept falling when the melting parameter rose high. But higher Eckert number helped to increase the temperature of the fluid. Many researchers [28-32] have contributed in this area of research.

Going through the above cited articles, authors are motivated to investigate the effects of nonlinear thermal radiation and heat absorption on three dimensional MHD upper-convected Maxwell nano-fluid flow past a bidirectional stretching surface. Governing equations are solved, numerically, by using bvp4c routine of MATLAB. The influence of key physical parameters on velocity, temperature, and concentration profiles is analyzed and illustrated through graphical results. Additionally, numerical values for the Nusselt number, and Sherwood number are computed and presented in tabular form. This investigation is relevant to various engineering applications involving heat and mass transfer processes in complex fluids.

2. MATHEMATICAL MODEL

A steady state, viscous, incompressible, upper-convected Maxwell nano-fluid flow through a bilinear stretchable surface parallel to $xy-$plane is considered for the study. A uniform magnetic field of strength B_0 is applied normal to the surface i.e. parallel to z-direction. Furthermore, nonlinear thermal radiation and heat absorption are incorporated into the formulation of the energy equation. The stretching surface velocities in the x and y - directions are defined as $U_w(x) = ax$ and $V_w(Y) = by$, respectively, as illustrated in Fig. 1.

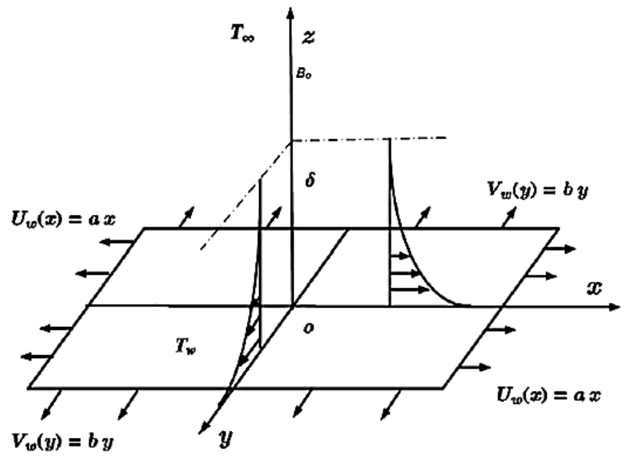

Figure 1. Schematic diagram of the physical configuration

The governing equations for velocity, temperature, and nanoparticle concentration in the described problem are given as follows [33–36]:

Based on the assumptions aforementioned, equations governing to the present problem are:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}+\lambda\left(u^2\frac{\partial u^2}{\partial x^2}+v^2\frac{\partial u^2}{\partial y^2}+w^2\frac{\partial u^2}{\partial z^2}+2uv\frac{\partial^2 u}{\partial x\partial y}+2uw\frac{\partial^2 u}{\partial x\partial z}+2vw\frac{\partial^2 u}{\partial y\partial z}\right)$$

$$=\upsilon\frac{\partial^2 u}{\partial z^2}-\frac{\sigma B_0^{\,2}}{\rho}\left(u+\lambda w\frac{\partial u}{\partial z}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+\lambda\left(u^2\frac{\partial v^2}{\partial x^2}+v^2\frac{\partial v^2}{\partial y^2}+w^2\frac{\partial v^2}{\partial z^2}+2uv\frac{\partial^2 v}{\partial x\partial y}+2uw\frac{\partial^2 v}{\partial x\partial z}+2vw\frac{\partial^2 v}{\partial y\partial z}\right)$$

$$=\upsilon\frac{\partial^2 v}{\partial z^2}-\frac{\sigma B_0^{\,2}}{\rho}\left(v+\lambda w\frac{\partial v}{\partial z}\right) \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\frac{\partial^2 T}{\partial z^2}-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial z}+\tau\left(D_B\frac{\partial C}{\partial z}\frac{\partial T}{\partial z}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial z}\right)^2\right)+\frac{Q_0}{\rho c_p}\left(T-T_\infty\right) \tag{4}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+w\frac{\partial C}{\partial z}=D_B\frac{\partial^2 C}{\partial z^2}+\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial z^2} \tag{5}$$

The following boundary conditions regulate the current circumstance:

$$\left.\begin{array}{ll} u=U_w=ax,\ v=V_w=by,\ w=0,\ T=T_\infty,\ C=C_w, & \text{at } z=0 \\ u,\ v\to 0,\ T\to T_\infty,\ C\to C_\infty, & \text{as } z\to\infty \end{array}\right\} \tag{6}$$

where symbols have their usual meaning (see "List of Symbols").

Introducing similarity and dimensionless variables as follows:

$$q_r = -\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial z},\ u = axf'(\eta),\ \ v = ayg'(\eta),\ \ w = -\sqrt{a\upsilon}\left(f(\eta)+g(\eta)\right)$$
$$\theta(\eta) = \frac{T-T_\infty}{T_w-T_\infty},\ \ \phi(\eta) = \frac{C-C_\infty}{C_w-C_\infty},\ \ \eta = \sqrt{\frac{a}{\upsilon}}z\ ,\ T = T_\infty\left((\theta_w-1)\theta+1\right)$$
$$q_r = -\frac{16\sigma^*}{3k^*}T_\infty^{\ 3}\left((\theta_w-1)\theta+1\right)^3\frac{\partial T}{\partial z} \tag{7}$$

Using equation (7), the mass conservation (1) is satisfied. Also, together with the B.Cs. (6), governing equations (2), (3), (4) and (5) assume the form:

$$f''' - f'^2 + \left(M^2K+1\right)(f+g)f'' + K\left(2f'(f+g)f'' - (f+g)^2 f'''\right) - M^2 f' = 0 \tag{8}$$

$$g''' - g'^2 + \left(M^2K+1\right)(f+g)g'' + K\left(2g'(f+g)g'' - (f+g)^2 g'''\right) - M^2 g' = 0 \tag{9}$$

$$\theta'' + \left(4/3\right)Rd\left[\left(1+(\theta_w-1)\theta\right)^3\theta'' + 3(\theta_w-1)\left(1+(\theta_w-1)\theta\right)^2\theta'^2\right] + \Pr(f+g)\theta' + \Pr Nt\theta'^2 + Q\Pr\theta + \Pr Nb\theta'\phi' = 0 \tag{10}$$

$$\phi'' + \frac{Nt}{Nb}\theta'' + \Pr Le(f+g)\phi' = 0 \tag{11}$$

$$f(0)=0,\quad f'(0)=1,\quad g(0)=0,\quad g'(0)=c,\quad \theta(0)=1,\quad \phi(0)=1,$$
$$f'(\infty)=0,\quad g'(\infty)=0,\quad \theta(\infty)=0,\quad \phi(\infty)=0 \tag{12}$$

Non-dimension parameters are defined as

$$\left.\begin{aligned} &K=\lambda a,\ M^2=\frac{\sigma B_0^{\ 2}}{\rho a},\ \Pr=\frac{\upsilon}{\alpha}=\frac{\rho c_p\upsilon}{k},\ Rd=\frac{4\sigma^* T_\infty^{\ 3}}{kk^*},\ \theta_w=\frac{T_w}{T_\infty},\ Q=\frac{Q_0}{a\rho c_p}\\ &Nb=\frac{\tau D_B}{\upsilon}\left(C_w-C_\infty\right),\ Nt=\frac{D_T}{T_\infty}\frac{\tau}{\upsilon}\left(T_w-T_\infty\right),\ Le=\frac{\alpha}{D_B},\ c=\frac{b}{a},\ k=\alpha\rho c_p \end{aligned}\right\} \tag{13}$$

The most important physical quantities for the problem in engineering point of view are the local Nusselt and Sherwood numbers, which are defined by the following relations:

$$Nu_z = \frac{xq_w}{k\left(T_w-T_\infty\right)},\qquad Sh_z = \frac{xj_w}{D_B\left(C_w-C_\infty\right)} \tag{14}$$

where, heat and mass fluxes are defined by

$$q_w = -\left(\frac{\partial T}{\partial z}\right)_{z=0},\qquad j_w = -D_B\left(\frac{\partial C}{\partial z}\right)_{z=0} \tag{15}$$

Thus the non-dimensional Local Nusselt and Sherwood numbers are as follows:

$$\mathrm{Re}_z^{-1/2}Nu_z = -\left[1+\frac{4}{3Rd\theta^3_{\ w}}\right]\theta'(0),\ \ \mathrm{Re}_z^{-1/2}Sh_z = -\phi'(0) \tag{16}$$

In equations (8) - (16), symbols have their usual meaning (see “List of Symbols”).

3. RESULTS AND DISCUSSION

Non-linear ordinary differential equations are found from the controlling non-linear partial differential equations (1) - (5) with the help of suitable similarity transformation. These equations (8) - (11) together with boundary conditions (12) are solved, numerically, through MATLAB’s bvp4c routine.

To gain some physical insight into the flow pattern, the effects of different physical parameters on the velocity ($f'(\eta)$), temperature ($\theta(\eta)$) and nanoparticle concentration ($\phi(\eta)$) profiles have been plotted in the form of graphs (Figures 2 - 28). Figures 2-8 display the effects of various physical parameters on the fluid velocity. It is observed from the Figs. 2-8 that the profiles of fluid velocity are getting increased on increasing thermophoresis parameter, thermal radiation parameter and Lewis number. These concludes that the thermal radiation parameter, thermophoretic diffusion and Lewis number have the tendency to enhance the fluid velocity at the vicinity of the plate. It is also observed that fluid velocity is getting decreased on increasing the Deborah number, magnetic parameter, stretching ratio parameter and Prandtl number. As we know, increase in Deborah number increases viscosity of the fluid and hence the velocity decreases as shown in Fig. 2. This indicates that the fluid relaxation time, magnetic field, stretching ratio have the tendency to retard the fluid velocity. Since we know that Prandtl number represents the strength of thermal diffusion, on increasing Prandtl number the strength of thermal diffusion is getting reduced and vice-versa. Hence, we can conclude that the thermal diffusion has the tendency to enhance the fluid velocity.

Figures 9 to 18 explain the temperature profiles of the nano-fluid and the influence of flow parameters. It is clearly seen from Figs. 9-18 that with the increase in K, M, Rd, θ_w, Nt, Nb and Q the fluid temperature is getting increased while the fluid temperature is getting decreased on increasing C, Pr and Le. This shows that the Deborah number, magnetic field, thermal radiation, temperature ratio, thermophoretic diffusion, Brownian diffusion, thermal diffusion and heat absorption are the cause for rise in fluid temperature whereas stretching ratio and Lewis number are the cause for fall in fluid temperature. By increasing the magnetic parameter M, a drag force known as Lorentz force also increases which resultantly reduces the velocity of fluid (Fig. 3) and hence rate of heat transfer is reduced (Table - 1) and this leads to an increment in temperature (Fig. 10).

Figures 19 to 28 illustrate the impact of various flow parameters on species concentration. It is evident from Figs. 19-28 that with the increase in K, M, Rd, θ_w and Q there is an increment in the concentration profile, where there is a decrement in the concentration profile with the increase in C, Nt, Nb, Pr and Le. This signifies that the Deborah number, magnetic field, Radiation temperature ratio, heat absorption and thermal diffusion have the tendency to accelerate the concentration of the fluid while stretching ratio, thermophoretic diffusion and Lewis number have opposite effect on this.

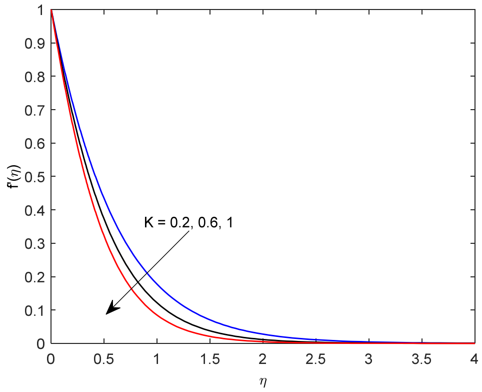

Figure 2. Velocity profiles for K

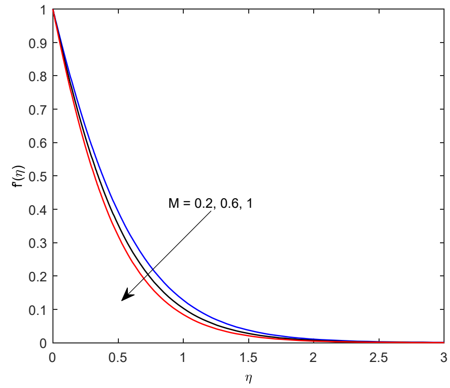

Figure 3. Velocity profiles for M

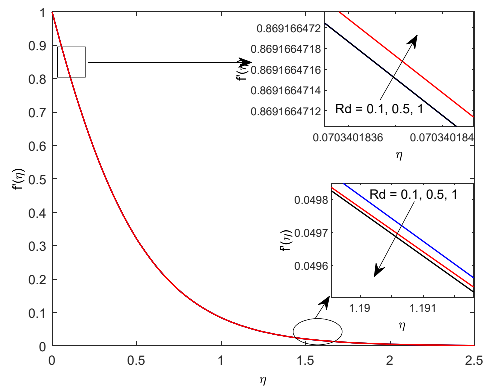

Figure 4. Velocity profiles for Rd

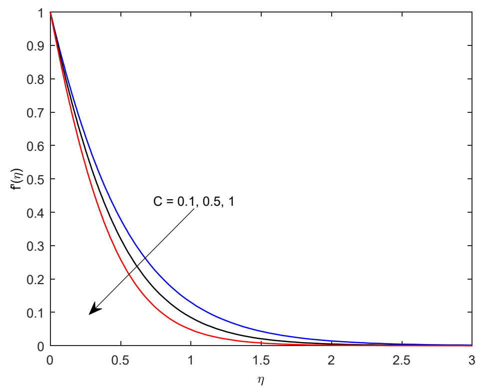

Figure 5. Velocity profiles for c

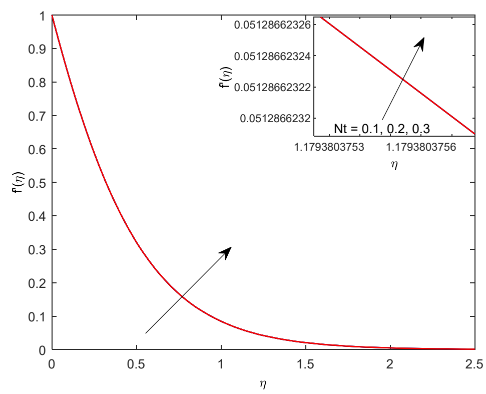

Figure 6. Velocity profiles for Nt

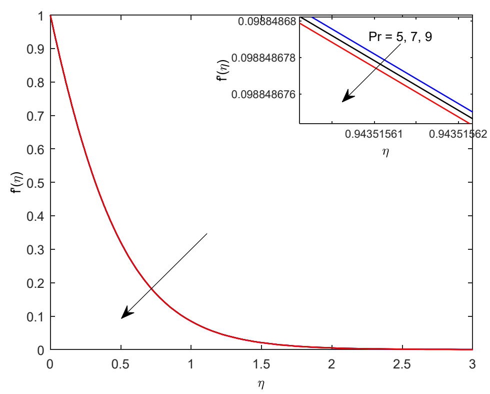

Figure 7. Velocity profiles for Pr

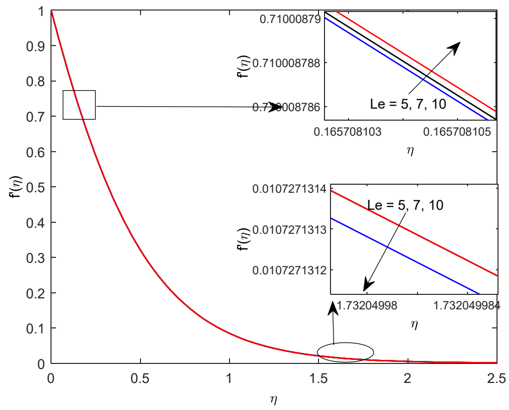

Figure 8. Velocity profiles for *Le*

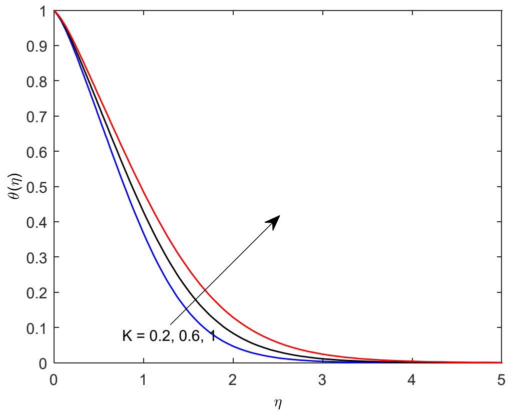

Figure 9. Temperature profiles for K

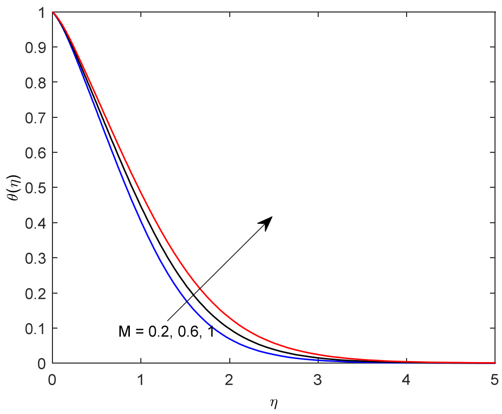

Figure 10. Temperature profiles for M

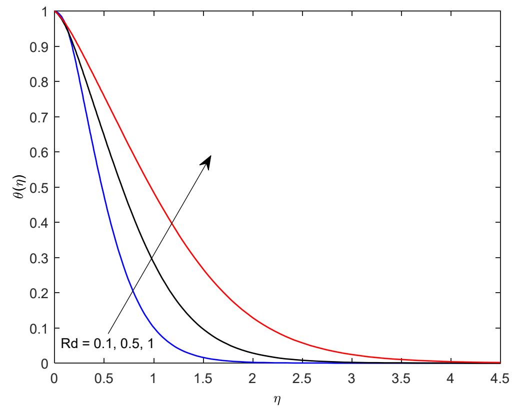

Figure 11. Temperature profiles for Rd

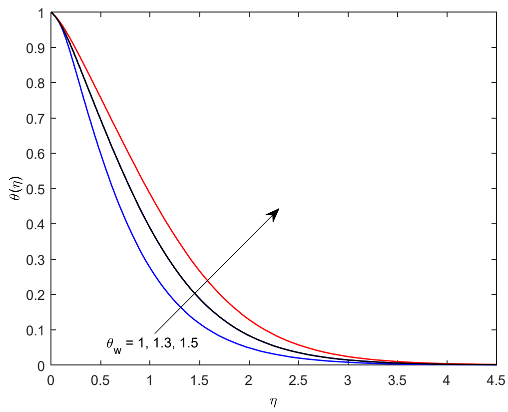

Figure 12. Temperature profiles for θ_w

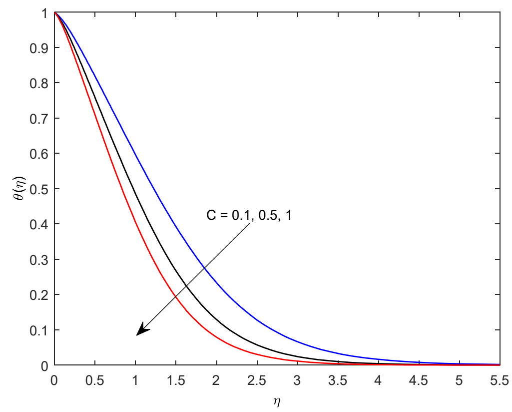

Figure 13. Temperature profiles for C

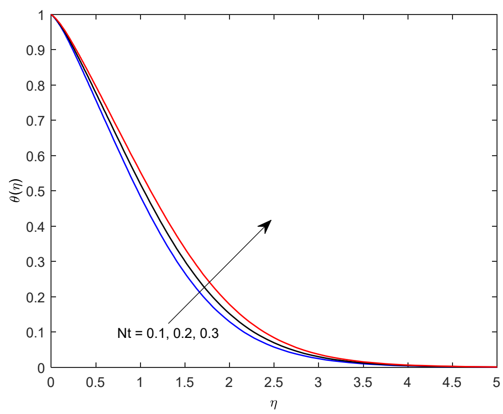

Figure 14. Temperature profiles for Nt

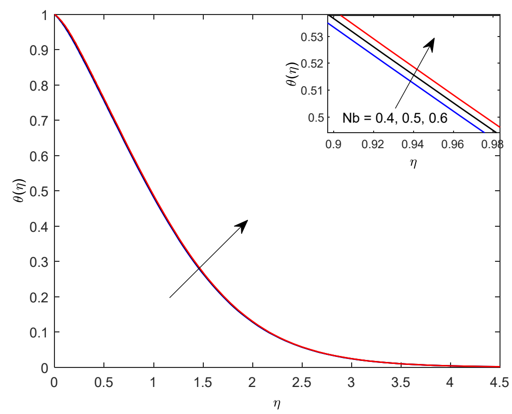

Figure 15. Temperature profiles for Nb

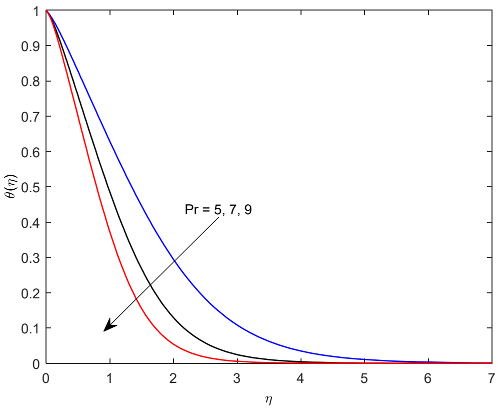

Figure 16. Temperature profiles for Pr

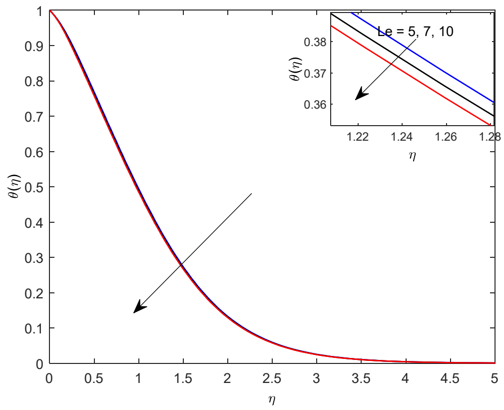

Figure 17. Temperature profiles for Le

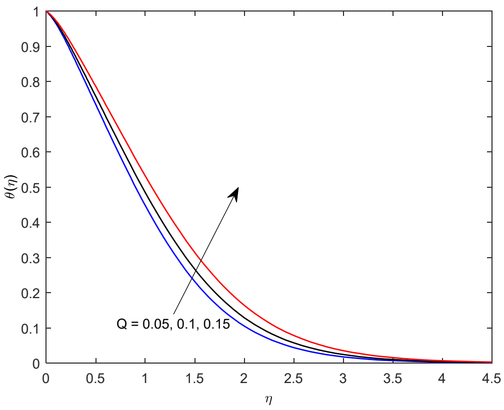

Figure 18. Temperature profiles for Q

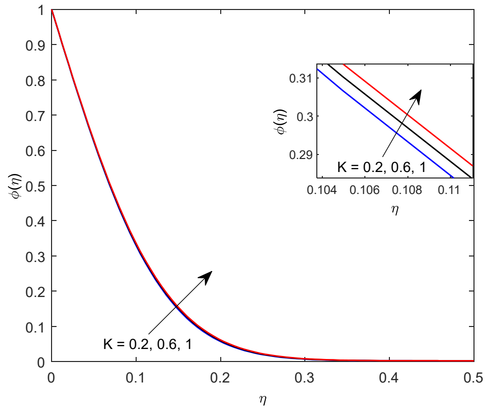

Figure 19. Concentration profiles for K

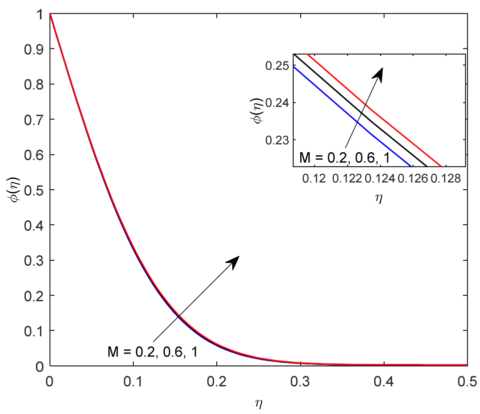

Figure 20. Concentration profiles for M

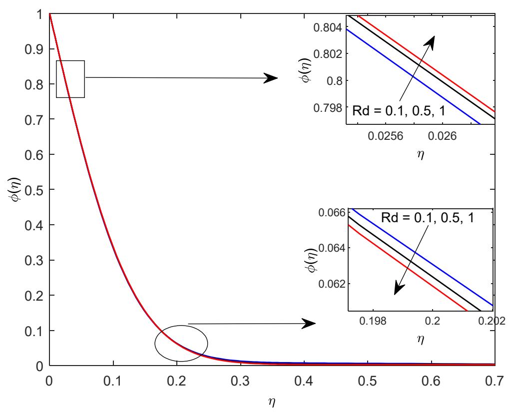

Figure 21. Concentration profiles for Rd

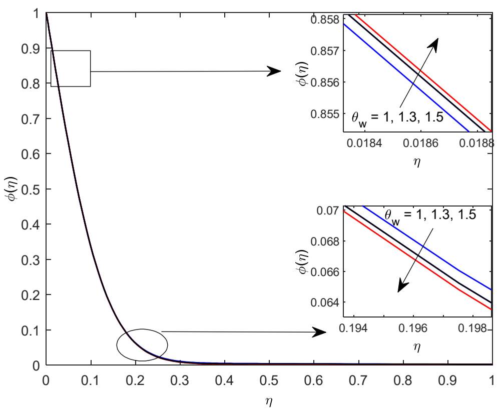

Figure 22. Concentration profiles for θ_w

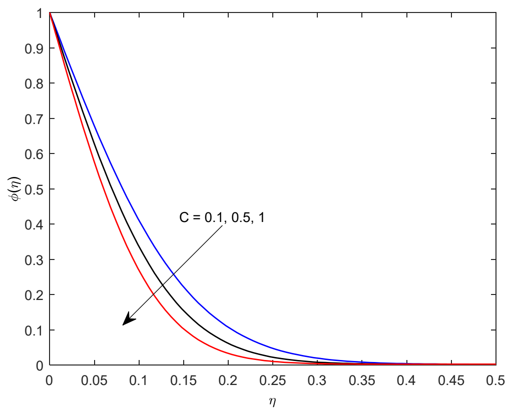

Figure 23. Concentration profiles for C

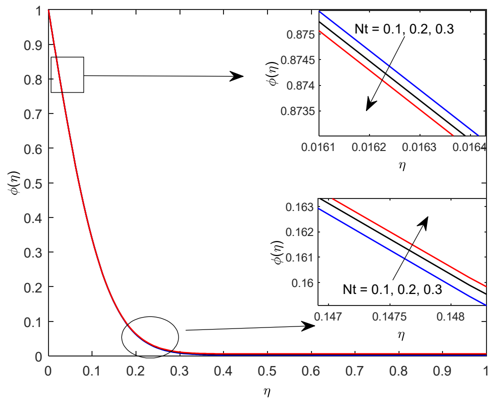

Figure 24. Concentration profiles for *Nt*

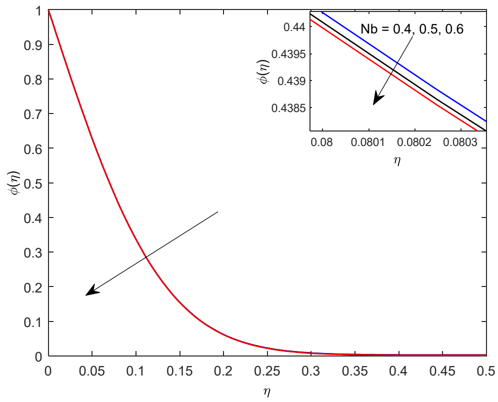

Figure 25. Concentration profiles for Nb

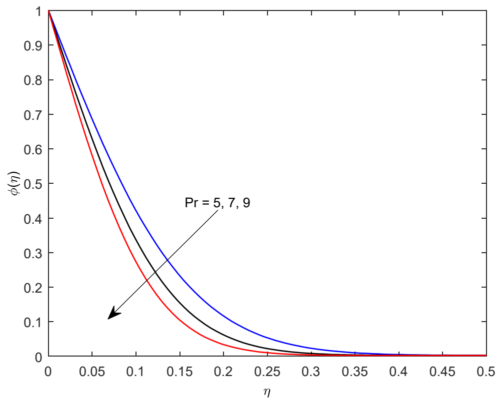

Figure 26. Concentration profiles for Pr

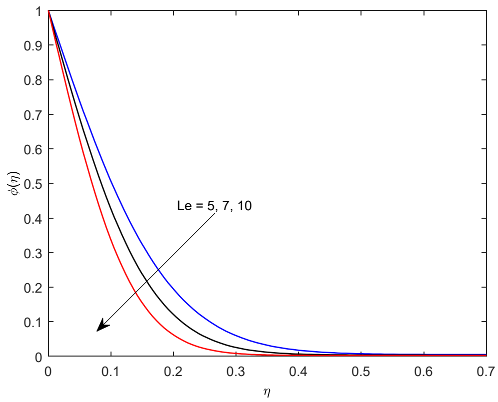

Figure 27. Concentration profiles for *Le*

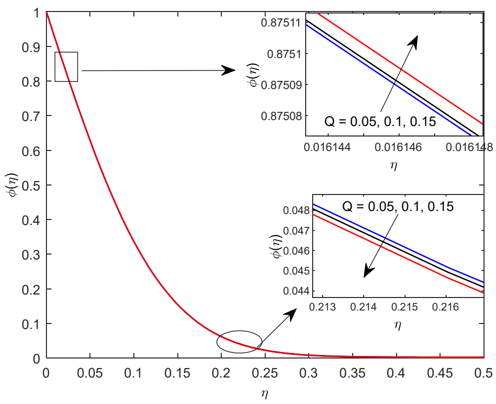

Figure 28. Concentration profiles for *Q*

To visualize the effects of various physical entities on the rate of heat transfer and rate of mass transfer, a numerical result has been displayed in a tabular form in Table 1. It is noticed from Table 1 that the rate of heat transfer at the surface is getting enhanced by thermal radiation parameter, temperature ratio, stretching ratio and Lewis number, while it is getting reduced by the fluid relaxation time, magnetic field, thermophoretic diffusion, Brownian diffusion, thermal diffusion and heat absorption. It is also visualized from the table 1 that stretching ratio, thermophoretic diffusion, Brownian diffusion and Lewis number are the inducive agent for the rate of mass transfer at the surface while fluid relaxation time, magnetic field, thermal radiation, temperature ratio, thermal diffusion and heat absorption serve as a reducing agent for the rate of mass transfer at the surface.

Table 1. Numerical values of the Nusselt number and Sherwood number against different values of flow parameters

K	M	Rd	θ_w	c	Nt	Nb	Pr	Le	Q	$Re_z^{-1/2} Nu_z$	$Re_z^{-1/2} Sh_z$
0.2										1.66974664	7.86824129
0.6										1.50948141	7.81943062
1										1.35790927	7.77406945
	0.2									1.57854902	7.86103299

K	M	Rd	θ_w	c	Nt	Nb	Pr	Le	Q	$\mathrm{Re}_z^{-1/2} Nu_z$	$\mathrm{Re}_z^{-1/2} Sh_z$
	0.6									1.46355607	7.81540597
	1									1.35790927	7.77406945
		0.1								0.14818961	7.84184626
		0.5								0.77939	7.79639224
		1								1.35790927	7.77406945
			1							0.49470041	7.81019105
			1.3							1.00056998	7.78539034
			1.5							1.35790927	7.77406945
				0.1						1.01893114	6.63511542
				0.5						1.35790927	7.77406945
				1						1.63307299	8.97380238
					0.1					1.35790927	7.77406945
					0.2					1.22993982	7.78864098
					0.3					1.11422449	7.8013766
						0.4				1.54494505	7.77329499
						0.5				1.35790927	7.77406945
						0.6				1.19313544	7.77410782
							5			1.17361175	6.49367177
							7			1.35790927	7.77406945
							9			1.38784655	8.88283191
								5		1.35594007	5.36581493
								7		1.35686267	6.43219245
								10		1.35790927	7.77406945
									0.05	1.53680377	7.77435377
									0.1	1.35790927	7.77406945
									0.15	1.14720189	7.7735382

4. CONCLUSIONS

A detailed study has been carried out on steady state, viscous, incompressible, upper-convected Maxwell nano-fluid flow through a bilinear stretchable surface considering the effects of nonlinear thermal radiation and heat absorption. The significant results are summarized as follows:

- "Non-linear thermal radiation, thermophoretic diffusion, thermal diffusion and Lewis number are acting as an inducive agent for fluid velocity near the plate while fluid relaxation time, magnetic field, stretching ratio are acting as a reducing agent for the same".
- "Deborah number, magnetic field, thermal radiation, temperature ratio, thermophoretic diffusion, Brownian diffusion, thermal diffusion and heat absorption are the cause for rise in fluid temperature whereas stretching ratio and Lewis number are the cause for fall in fluid temperature".
- "The Deborah number, magnetic field, radiation, temperature ratio, heat absorption and thermal diffusion have the tendency to accelerate the concentration of the fluid while stretching ratio, thermophoretic diffusion and Lewis number have opposite effect on this".
- "Rate of heat transfer at the surface is getting enhanced by thermal radiation parameter, temperature ratio, stretching ratio and Lewis number, while it is getting reduced by the fluid relaxation time, magnetic field, thermophoretic diffusion, Brownian diffusion, thermal diffusion and heat absorption."
- "Stretching ratio, thermophoretic diffusion, Brownian diffusion and Lewis number are the inducive agent for the rate of mass transfer at the surface while fluid relaxation time, magnetic field, thermal radiation, temperature ratio, thermal diffusion and heat absorption serve as a reducing agent for the rate of mass transfer at the surface".

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ВПЛИВ ВИПРОМІНЮВАННЯ ТА ПОГЛИНАННЯ НА ТРИВИМІРНИЙ МАГНІТОГІДРОДИНАМІЧНИЙ (МГД) ПОТІК НАНОРІДИНИ МАКСВЕЛЛА З ВЕРХНЬОЮ КОНВЕКЦІЄЮ

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У цій статті досліджується МГД-потік нанорідини Максвелла з верхньою конвекцією через двоспрямовану розтяжну поверхню. Було досліджено вплив поглинання тепла та теплового випромінювання. Нелінійні диференціальні рівняння з частинними похідними, що контролюють закони збереження маси, збереження імпульсу, збереження енергії та концентрацію частинок, перетворюються на звичайні диференціальні рівняння за допомогою відповідного перетворення подібності, які потім розв'язуються чисельно за допомогою процедури bvp4c у MATLAB. Вплив різних фізичних параметрів на розподіл швидкості, температури та концентрації коротко описується за допомогою графіків. Тертя поверхні, швидкість тепло- та масоперенесення на пластині обчислюються чисельно та відображаються у таблиці. Така задача потоку рідини може знайти застосування в механізмах/пристроях теплопередачі.

Ключові слова: *нанорідина Максвелла; МГД; поглинання тепла; теплове випромінювання*