Flow and Heat Transfer Analysis of Nanofluid (CuO/water) Subject to Inclined Magnetic Field and Thermal Radiation: A Numerical Approach

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ABSTRACT: *Nanofluids play an important role in order to augment of the heat transfer characteristics in many energy systems. As compared to usual fluids, nanofluids comprise better physical strength and thermal conductivity. Our aim in studying this work is to numerically interpret the flow and heat transfer features of copper oxide (CuO) nanoparticles in the coexistence of thermal radiation and inclined magnetic fields. The model equations are first simplified by the similarity transformations and then finite difference discretization is used to apply the numerical technique known as the successive over-relaxation method. We have mainly examined that how much the thermal radiation and inclined magnetic field affect the nanofluid flow. The impacts of involved parameters are overlooked with the help of tabular and graphical representations. The consequences evidently point out that the effect of inclination is to devaluate the heat transfer and elevate the skin friction on the surface. The thermal radiation phenomenon is responsible for an increase in the temperature.*

KEYWORDS: *Nanofluids; Copper oxide; Inclined magnetic field; Thermal radiation; Finite difference.*

INTRODUCTION

In the modern period, scientists have been experimenting with various fluid kinds to obtain more effective results. Base fluids have a crucial role as host fluids when mixed in nanoparticles. Formerly, researchers had solely focused on basic simple fluids, but for a few decades, the preference for nanofluids had already been brought up for discussion. *Choi* and *Eastman* [1] conducted a pioneering analysis of the thermophysical characteristics of nanofluid. When compared to the fundamental solvents of single-phase base fluid, they found that the heat transfer and thermal conductivity of nanofluids had improved. Nanofluid is the name for the fluid that contains nanoscale particles. Oxides, carbides, and metallic elements are typically utilized in order to prepare nanofluids in a highly

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volatile liquid (e.g. ethylene glycol, paraffin, oil, water). Researchers are now assembling nanoparticles that have specifically to achieve efficacious thermal conductivity since the variation of particle selection, basic medium, and size have an impact on conductivity. The uses of adaptable nanofluids are in advanced industries like electronic cooling, automotive cooling, and heating systems, surfactants, lubricants, metal welding, medical production, solar heating, cooling equipment, integrated engines, cooling integrated circuits (ICs), and heat transfer to nuclear reprocessing. They have a wide range of applications including car engines, generators, cooling systems, and much more that are emerging and appealing to scientists. Later, numerous scientists studied these fluids. *Cui et al.* [2] carried out a statistical analysis of a three-dimensional mathematical model having bioconvective boundaries.

The magnetic field plays a vital role in applied research, particularly in fluid dynamics. Due to its unique and extraordinary qualities, experts have been researching it for decades. Studies have been done on aspects of fluid transfer including heat transmission, fluid properties, and other aspects. Most research only produces numerical and theoretical results, but there hasn't been much experimental work done on heat transfer and magnetic exchange. In the modern world, specifically, we need experimental data that benefit industries. The most crucial issues in all industries where heat transmission has been involved are cooling devices like air conditioners, refrigerators, etc. In these circumstances, the application of cutting-edge cooling technology is envisaged. When we upgrade the majority of heat transfer appliances, we must expand their surface area, which results in an increase in their size and volume. Therefore, we require new coolers that are more efficient if we have to solve these issues. There are two techniques to investigate the issues with the effect of magnetic field on the minor heat transfer of nanofluids that nanofluids are bringing to the field. Multi-physical transport can be effectively converted and managed thermally by using well-controlled magnetic fields. The fluid's speed is altered by the fixed magnetic field. The transport process is incredibly challenging due to the numerous physical factors involved, including the porous surface and nanofluid. Because of this, the magnetic field-based control method is well-accepted in many contemporary systems, and its application is expanding quickly across a range of technical and industrial domains. Williamson's nanofluid was affected numerically by an affiliated magnetic field, as noted by Srinivasulu and Goud [3]. They discovered that as the aligned angle grew, fluid velocity reduced.

Thermal conduction and particles also their fractional volume of nanofluid all affect thermal efficiency. Numerous studies have found that the thermal effectiveness of nanofluids can also be influenced by random particle movement, size, temperature, and the nature of nanoparticles. Mathematical descriptions of the thermal applications of hybrid nanofluids caused by stagnation points through stretching cylinders were provided by *Kolsi et al.* [4]. They came up with a numerical solution using the MATLAB BVP4C method.

Radiation plays a key role in many different industrial applications in the construction of furnaces and the manufacture of glass, as in space technology like direction-finding systems, spacecraft, aerodynamics aircraft, plasma physics, burning methods, solar radiation, in the flow of atomic plants structures, compressors of the ship, and core combustion engines. *Ahmad et al.* [5] evaluated the impact of thermal radiation over magnetohydrodynamic flow but *Mohyud-Din et al.* [6] investigated the impact of thermal radiation on the free convection magnetohydrodynamic flow across a flat infinite plate. *Shehzad et al.* [7] research on the 3D MHD flow on Jeffrey nanofluid also discussed the generation of radiation. *Lv-Yu et al.* [8] investigated the impacts of radiation (thermal) and abnormality of heat source/sink along with the Hall effect on the flow of nanofluid in a channel having rotating effects. *Khader et al.* [9] investigated thermal radiation and the amelioration method of heat transfer.

Chamkha et al. [10, 11] numerically explored the hybrid and nanofluid flow within a slant and Gamma-shaped porous cavities using Successive under Relaxation and finite volume method respectively. *Kargarsharifabad et al.* [12-14] investigated the heat transfer phenomenon in several geometries e.g. cubic enclosure, cavity, and tube taking different fluids. *Alagumalai et al.* [15] developed a framework to understand the commercialization of nanofluids. *Rashidi et al.* [16] employed a high-order compact scheme to numerically interpret the flow of hybrid nanofluid under the impact of magnetic field. A lid-driven square cavity was taken as the geometry through which the fluid was flowing. The comprehensive analysis regarding the nanofluid flow was presented by

Turkyilmazoglu [17-19] taking into account, respectively, the effects of thermal radiation, suction, and magnetic field. The nanofluid flows under the influence of entropy generation and magnetohydrodynamics was studied by *Riaz et al.* [20, 21]. The flow was taken within a cylindrical enclosure and between two non-concentric pipes. *Ijaz et al.* [22] and *Vaidya et al.* [23] featured the characteristics of nanofluids with the coexistence of heat generation/absorption and slip effects respectively. The articles by *Sheikholeslami* [24-27] provide assistance in understanding the recent advancement in nanofluids. Further recent studies which are relevant to the concerned topic can be seen in refs. [28-35].

The above-mentioned literature served as inspiration for the research on the influence of an angled magnetic field on nanofluid flow. We investigated how radiation and inclination angle affect the nanofluid. PDEs have been converted to ODEs by the similarity transformation technique, and the numerical solutions have been obtained by the Successive over-relaxation method. In this paper, several aspects and effects of parameters such as angle change and others are examined. To increase heat transfer, however, nano-colloidal dispersion offers a highly encapsulated technique. That is why it is unquestionably vital to investigate such a fluid. Also the discussion on the impact the magnetic field has on these thermophysical properties. We believe that the upcoming nanoscience technology will improve our extraordinary effort from both a scientific and practical standpoint.

THEORETICAL SECTION

Mathematical formulation

Let us assume an incompressible, laminar, steady, and viscous nanofluid flow that is electrically conducted over a surface. We have applied the uniform magnetic field strength at the angle that is inclined in position on the *x*-axis. In this research, we have employed a specific nanofluid, in which two dissimilar particles allocate the composition of the base liquid. In our mathematical segment, we have set some supposition that no chemical reaction will take place between the base solution and nanoparticles. There will be no jump in temperature between base fluid and nanosized particles, and viscous dissipation has been waived. In addition, thermal equilibrium has been maintained by base liquid and nanoparticles. The magnetic field which has been created by induction is very small and it is negligible as compared to the magnetic field that is applied.

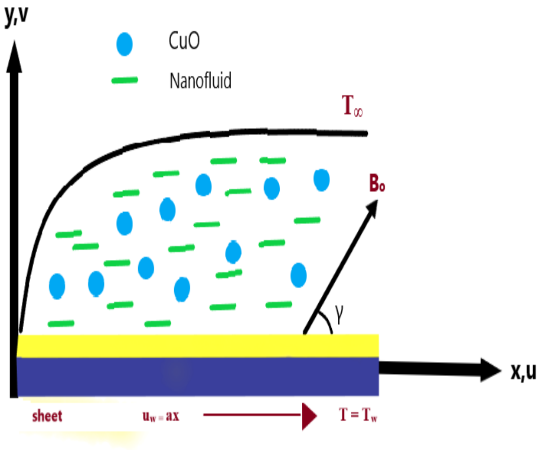

Fig. 1: Physical Model.

By using the approximations of the boundary layer along with the order of the magnitude analysis, we can prescribe the equations which govern the flow, such as (*Acharya* [36]; *Ahmad et al.* [37]):

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

$$v\left(\frac{\partial u}{\partial y}\right) + u\left(\frac{\partial u}{\partial x}\right) = \frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 u}{\partial y^2}\right) - \mu_{nf}\frac{1}{\rho_{nf} k^*}u - \sigma_{nf}\frac{1}{\rho_{nf}}B_0^2 u \sin^2(\gamma) \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k_{nf}}{(\delta c_p)_{nf}}\frac{\partial^2 T}{\partial y^2} - \frac{1}{c_p}\frac{\partial q_r}{\partial y} \tag{3}$$

So, here are the boundary conditions at the surface of the sheet:

$$\left.\begin{array}{llll} v = v_w, & u = u_w, & T = T_w & \text{at} \quad y = 0 \\ T \to T_\infty, & u \to 0, & & \text{at} \quad y \to \infty \end{array}\right] \tag{4}$$

Thermophysical features

In this research, we use water as an ordinary fluid and CuO to make it nanofluid. We construct the equations to obtain the hydrothermal features as described by *Acharya et al.* (2019b) and *Devi* and *Devi* (2016). In Table 1 those formulations have been shown. Also, in Table 2 nanoparticle's thermophysical data has been enlisted.

Table 1: The Thermophysical Properties.

Properties	Nanofluid (*CuO/Water*)
Heat capacity	$(\rho C_p)_{nf} = \phi(\rho C_p)_s + (1-\phi)(\rho C_p)_f$
Density	$\rho_{nf} = \phi\rho_s + (1-\phi)\rho_f$
Viscosity	$\mu_{nf} = \mu_f \dfrac{1}{(1-\phi)^{2.5}}$
Electrical conductivity	$\dfrac{\sigma_{nf}}{\sigma_f} = \dfrac{3\phi(\sigma-1)}{(\sigma+2)-\phi(\sigma-1)}+1$ Where $\sigma = \dfrac{\sigma_s}{\sigma_f}$
Thermal conductivity	$\dfrac{k_{nf}}{k_f} = \dfrac{(n-1)k_f + k_s - \phi(k_f - k_s)(n-1)}{\phi(k_f - k_s) + k_f(n-1) + k_s}$

Table 2: The thermophysical properties of nanoparticles and base fluid.

Physical properties	*CuO*	Water
$C_p(K\, {}^{j}\!/_{kg})$	5.356×10^2	4.180×10^3
$\rho(kg\, {}^{1}\!/_{m^3})$	6.500×10^3	9.97×10^2
$\kappa(W\, {}^{1}\!/_{mK})$	2.0×10	6.071×10^{-1}
$\sigma(S\, {}^{1}\!/_{m})$	5.96×10^7	5.5×10^{-6}

Similarity transformation

We perform similarity transformation in need to establish nonlinear ODE from the preceding PDEs (1)-(3) along with their boundary conditions (4).

The essential renovations are:

$$\left.\begin{array}{l} u = ax\left(f'(\eta)\right), \qquad u = \left(\dfrac{\partial\psi}{\partial y}\right), \\ v = -\left(\sqrt{a\nu_f}\right)f(\eta) \ , \ v = -\left(\dfrac{\partial\psi}{\partial x}\right) \\ \psi = \sqrt{a\nu_f}\ x\left(f(\eta),\right) \quad \eta = \left(\sqrt{\dfrac{a}{\nu_f}}\right)y, \\ \theta(\eta) = \dfrac{T-T_w}{T_w-T_\infty} \end{array}\right\} \tag{5}$$

The required equations are as follows:

$$f'''(\eta) - \frac{A_5}{A_4}M\sin^2(\gamma)f'(\eta) + \frac{A_1}{A_4}\left[f(\eta)f''(\eta) - f'^2(\eta)\right] = 0 \tag{6}$$

$$\left(\frac{A_3}{A_2} + R\right)\theta'' + f\,\Pr\theta' = 0 \tag{7}$$

Where

$$A_1 = \frac{\delta_{nf}}{\delta_f}\ ,\ A_2 = \frac{(\delta c_p)_{nf}}{(\delta c_p)_f}\ ,\ A_3 = \frac{k_{nf}}{k_f}\ ,\ A_4 = \frac{\mu_{nf}}{\mu_f}$$

$$A_5 = \frac{\sigma_{nf}}{\sigma_f}$$

$$M = \frac{B_0}{a}\frac{\sigma_{nf}}{\delta_f}\quad ,\quad P_r = \frac{\mu_f(\delta c_p)_f}{\delta_f k_f} = \frac{1}{\nu_f}\frac{(\delta c_p)_f}{k_f}$$

Also, boundary conditions remodeled as

$$\left.\begin{array}{llll} f = S, & f' = 1, & \theta = 1 & \text{at } \eta = 0 \\ f' = 0, & \theta \to 0 & & \text{as } \eta \to \infty \end{array}\right\} \tag{8}$$

Physical Quantities

The physical quantities of engineering interest are skin friction, Nusselt number, reduced skin friction & reduced Nusselt number which are respectively defined as:

$$C_f = \frac{2\mu_{nf}\left(\frac{\partial u}{\partial y}\right)_{y=0}}{\rho_{nf}u_w^2}\ ,\ Nu = \frac{1}{\kappa_f\left(T_w - T_\infty\right)}\left(\kappa_{nf}\frac{\partial T}{\partial y}\right)_{y=0}$$

$$C_{fr} = \sqrt{Re_x}.C_f = \left(\frac{\sqrt{2}(1-\phi_1)^{-2.5}.(1-\phi_2)^{-2.5}}{(1-\phi_2)\{(1-\phi_1)+\phi_1.\left(\frac{\rho_{s_2}}{\rho_f}\right)\}+\phi_2.\left(\frac{\rho_{s_2}}{\rho_f}\right)}\right)f''$$

$$\mathrm{Nu}_r = \frac{\mathrm{Nu}}{\sqrt{\mathrm{Re}_x}} = -\frac{\kappa_{nf}}{\kappa_f}\theta'(0)$$

Numerical procedure

The nonlinear DE's (6) and (7) subject to boundary conditions (8) are very difficult to solve analytically. So numerical approach is the best approach for us to solve them. We will use Successive over Relaxation techniques to solve them. We will take the help of MATLAB software to make and run our algorithm script. To do the solution numerically we firstly need to discretize ODEs By putting $f' = q$. So dimensionless form is

$$q'' - \frac{A_5}{A_4} M \sin^2(\gamma) q + \frac{A_1}{A_4}\left[f q^{/} - q^{2} \right] = 0 \qquad (9)$$

Now by using finite difference the eq. (9) and eq. (7) may be written as

$$q_i\left(\frac{-2}{h^2} - \frac{A_5}{A_4} M \sin^2\gamma - \frac{A_1}{A_4} q_i\right) + q_{i-1}\left(\frac{1}{h^2} - \frac{f_i}{2h}\right) + \qquad (10)$$

$$q_{i+1}\left(\frac{1}{h^2} + \frac{f_i}{2h}\right) = 0$$

$$\theta_i\left(\frac{-2}{h^2}\frac{A_3}{A_2} - \frac{2R}{h^2}\right) + \theta_{i-1}\left(\frac{A_3}{A_2 h^2} + \frac{R}{h^2} - \frac{f_i \Pr}{2h}\right) + \qquad (11)$$

$$\theta_{i+1}\left(\frac{A_3}{A_2 h^2} + \frac{R}{h^2} + \frac{f_i \Pr}{2h}\right) = 0$$

Where boundary conditions are,

$$\left.\begin{array}{llll} f = S, & q = 1, & \theta = 1 & \text{at } \eta = 0 \\ q = 0, & \theta \to 0 & & \text{as } \eta \to \infty \end{array}\right\} \qquad (12)$$

The efficiency of the present numerical code is appraised by a numerical comparison provided in Table 3. The results are in a good agreement with those presented by *Acharya et al.* [38] under limiting conditions e.g. $M_0 = S_0 = \gamma = Rn = 0$.

RESULTS AND DISCUSSION

Table 4 describes the Hartmann number M_0 (magnetic parameter) and its effects on the rate of heat transfer and shear stress. We can see that when M_0 rises, the rate of heat transfer decreases while the shear stress rises. Figs. 2-4 show the effects of M_0 over the velocity $F(\xi)$ and $F'(\xi)$ and temperature. Figs. 2 and 3 demonstrate that there is a definite retardation in velocities in the domain of flow. Magnetic field generates the Lorentz force due to the motion of fluid which is electrically conducted. The fluid's surface resistance contributes to the improvement of temperature as appeared in Fig. 4.

Table 3: Comparison with heat transfer $\theta'(0)$ for various values of Pr.

Pr	*Acharya et al.* [38]	Present Results
0.7	0.453962	0.453196
2.0	0.911397	0.911278
7.0	1.895420	1.894310
20.0	3.353861	3.353752

Suction parameter *S* affects the streamwise velocity as shown in Fig. 5 while the temperature effect is portrayed in Fig. 6. Both profiles show decreasing behavior for *S*. When we get a surface that is impermeable we will obtain the highest temperature and maximum velocity. Illustrations of numerics of shear stress as well as the rate of heat transfer are in Table 5. They increase with an increment in S.

Velocity profile does not change for *Rn* and *Pr* but temperature $\theta(\xi)$ faces retardation as we increase the *Rn* and *Pr* which could clearly be noticed in Figs. 7 & 8. When we notice the effect of heat transfer from Table 6 over *Rn* and *Pr* it is noticed that *Pr* shows the direct relationship with heat transfer while *Rn* shows the inverse relation.

Figs. 9 and 10 show an impression of γ over velocities. This demonstrates a large impact on streamwise and normal velocity. As in magnetic strength, a trigonometric function factor has been used which results in magnetic strength risings with the growth of the angle between. $0 \to 90$. Thus, the factor $Msn^2(\gamma)$aids in retarding velocities. From Table 7 we noticed that there is an increase in heat transfer rate with increment in γ while heat transfer rate retards.

CONCLUSIONS

This study deals with the nanofluid flow of copper oxide nanoparticles involving thermal radiation and an inclined magnetic field. The successive Relaxation method has been utilized to determine the numerical solution of the problem. Flow and thermal features of the problem are analyzed for the prominent effects of applied

Table 4: Effect of M_0 on shear stress and heat transfer rate.

M_0	Shear stress	Heat transfer rate
3	-2.004646	-1.517170
6	-2.516216	-1.479554
9	-2.933463	-1.452322
12	-3.293405	-1.431025

Table 5: Effect of S_0 on shear stress and heat transfer rate.

S_0	Shear stress	Heat transfer rate
1.0	-2.279277034308806	-2.336422685018273
1.5	-2.592558444532426	-3.204712434963764
2.0	-2.940336836141263	-4.097831576351604
2.5	-3.316634693362490	-5.003844872756291

Table 6: Effect of Pr and Rn parameter on heat transfer rate.

Pr	Heat transfer rate	Rn	Heat transfer rate
1	-0.359612286930067	0.0	-1.600212095313077
3	-0.830952896772789	0.6	-1.377560537750415
5	-1.278034962037618	1.2	-1.216528193743146
7	-1.694509470174251	1.8	-1.095248844977300

Table 7: Effect of γ on shear stress and heat transfer rate.

γ	Shear stress	Heat transfer rate
30^0	-1.658627575251311	-1.545526555971540
45^0	-2.000360928195437	-1.517506839267990
60^0	-2.213455619461099	-1.501218333819621
75^0	-2.379903652847763	-1.489099933594451

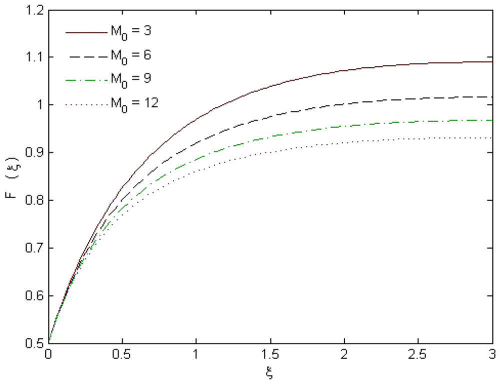

Fig. 2: Illustrates the normal velocity on different values of M_0.

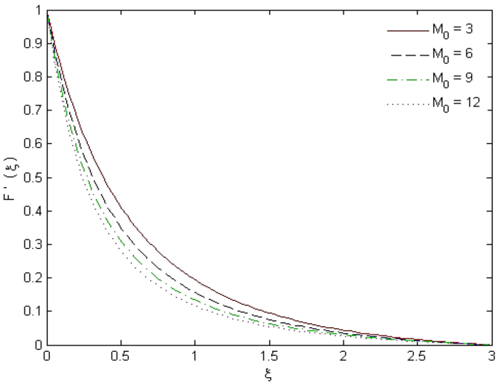

Fig. 3: Illustrates the steam velocity on different values of M_0 .

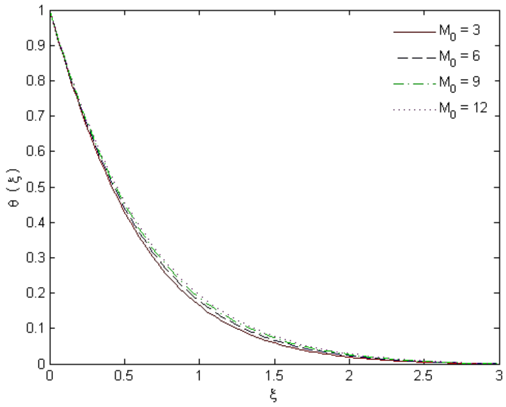

Fig. 4: Illustrates the temperature on different values of M_0.

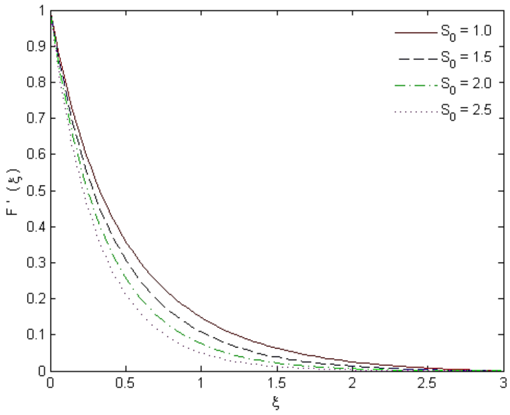

Fig. 5: Illustrates the steam velocity on different values of S_0 .

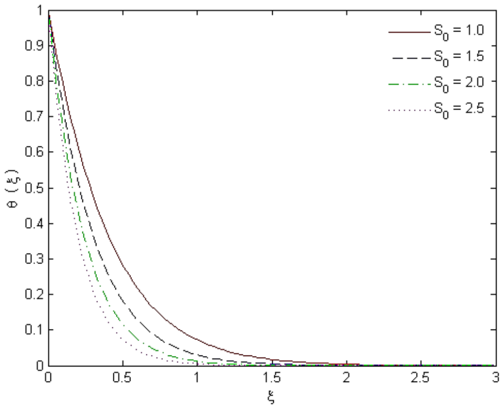

Fig. 6: Illustrates the temperature on different values of S_0.

magnetic field, inclined magnetic field, chemical reaction, suction and thermal radiation. The main consequences are labeled as:

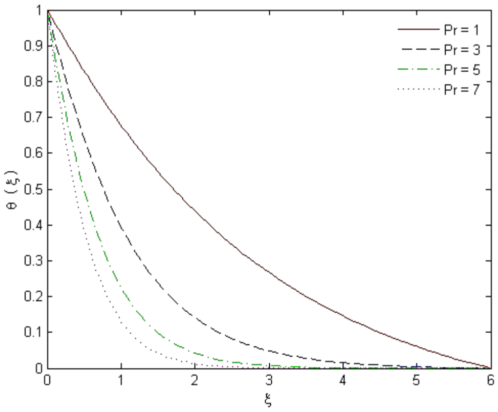

Fig. 7: Illustrates the temperature on different values of Pr.

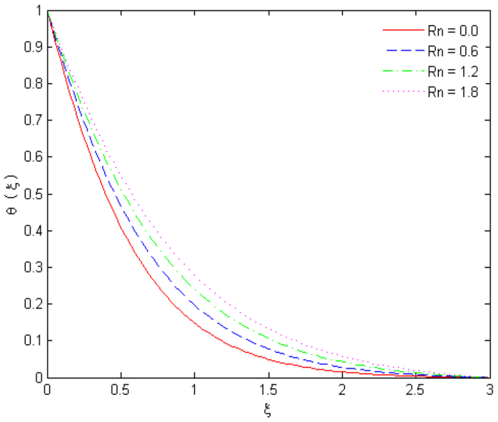

Fig. 8: Illustrates the temperature on different values of Rn.

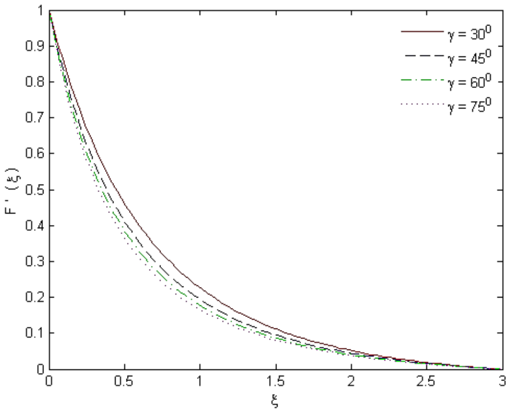

Fig. 9: Illustrates the stream velocity on different values of γ.

- A decrease in heat transfer rate is due to an increase in the values of thermal radiation parameter whereas the Prandtl number causes an increase in the heat transfer rate.

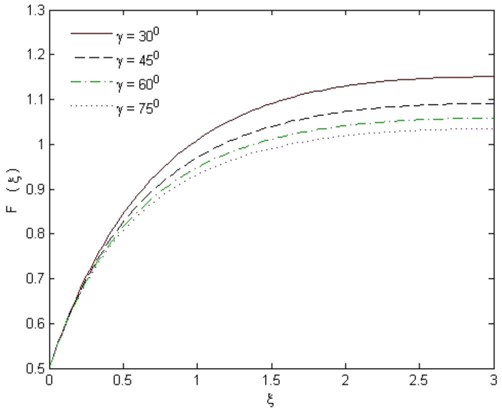

Fig. 10: Illustrates the normal velocity on different values of γ.

- Inclination angle parameter tends to devaluate heat transfer rate but elevates shear stress on the surface of sheet.
- Magnetic field interaction parameter enhances temperature but reduces both velocities e.g. normal and streamwise.
- The temperature and velocity of fluid has got escalation with the effect of Suction parameter.

Nomenclature

x,y	Cartesian coordinates, m
(u,v)	Velocity components, m/s
t	Time, s
u_w	Stretching velocity, m/s
a	Stretching rate, s^{-1}
T_w	The temperature of the surface, K
T_∞	Temperature far away from surface, K
ρ	Density, kgm^3
μ	Dynamic viscosity, kg/m.s
κ	Thermal conductivity, W/m.K
Pr	Prandtl number
M	Hartmann number
Nu	Nusselt number
C_f	Skin friction
Nu_r	Reduced Nusselt number
C_{fr}	Reduced skin friction
Re_x	Local Reynolds number
ρC_p	Capacitance of heat, J/m^3K
σ	Conductivity of electricity, $\Omega^{-1}m^{-1}$
B_0	Magnetic field, $\Omega^{1/2}s^{-1/2}m^{-1}kg^{1/2}$
ϕ	Fraction volume of nanoparticle

Subscript

f	Base fluid
Nf	Nanofluid
s	Nanoparticles

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