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RESEARCH ARTICLE

EFFECT OF NEWTONIAN HEATING ON PERMEABLE STRETCHING SHEET IN A COPPER-WATER NANOFLUID IN A POROUS MEDIUM

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ABSTRACT

The steady, two dimensional flow of a copper (Cu) - water nanofluid over a permeable a stretching sheet in the presence of porous medium and Newtonian heating. Using the similarity transformations, the governing equations have been transformed into a system of ordinary differential equations. These differential equations are highly nonlinear which cannot be solved analytically. Therefore, fourth order Runge-Kutta Gill procedure together with shooting technique has been used for solving it. Numerical results are obtained for the skin-friction coefficient and the local Nusselt number as well as the velocity and temperature profiles for different values of the governing parameters, namely, permeability parameter, volume fraction of nanoparticles, conjugate parameter for Newtonian heating, and Prandtl number.

INTRODUCTION

In recent years, a great deal of interest has been evinced in the study of mixed convective heat and mass transfer in nanofluids as it has many industrial importance, specially, in nanotechnology. Nanofluid is a suspension of solid nano particles or fibers of diameter 1-100 nm in basic fluids such as water, oil and ethylene glycol. Nanoparticles are made from various materials, such as Cu; Ag; Au; Fe; Hg; Ti etc. metals and non metallic Al_2O_3, CuO, TiO_2, SiO_2 etc. (Choi *et al*. (2001)). Khan and Pop (2010) investigated the boundary-layer flow of a nanofluid past a stretching sheet. Sheikholeslami *et al*. (2012) investigated the flow and heat transfer of Cu-water nanofluid between a stretching sheet and a porous surface in a rotating system. Sharma and Ishak (2014) studied the boundary layer flow of Cu-water based nanofluid with heat transfer over a stretching sheet and second order velocity slip flow model is considered instead of no-slip at the boundary. Lin and Zheng (2015) investigated the marangoni boundary layer flow and heat transfer of copper-water nanofluid over a porous medium disk. Sulochana and Sandeep (2015) investigated the stagnation point flow and heat transfer behavior of Cu–water nanofluid towards horizontal and exponentially permeable stretching or shrinking cylinders in presence of suction or injection, heat source and shape of nanoparticles.

In all these studies mentioned above, the Newtonian heating condition was neglected at the boundary. The situation where the heat is transported to the convective fluid via a bounding surface having finite heat capacity is known as Newtonian heating (or conjugate convective flows). This configuration occurs in convection flows set up when the bounding surfaces absorb heat by solar radiation. Merkin (1994) in his pioneering work studied the free convection boundary layer flow past a vertical plate with Newtonian heating. He found the asymptotic solution near the leading edge analytically and the full solutions along the whole plate for free convection boundary layer over vertical surfaces numerically. On the other hand, the Newtonian heating situation occurs in many important engineering devices, such as heat exchanger and conjugate heat transfer around fins. Makinde (2013) investigated the combined effects of viscous dissipation and Newtonian heating on boundary-layer flow over a flat plate for three types of water-based nanofluids containing metallic or nonmetallic nanoparticles such as copper (Cu), alumina (Al2O3), and titania (TiO2) for a range of nanoparticle volume fractions. Arpita Jain (2014) studied the chemically reactive boundary layer flow past an accelerated plate with radiation and Newtonian heating. Hussanan *et al*. (2014) investigated the unsteady boundary layer flow and heat transfer of a Casson fluid past an oscillating vertical plate with Newtonian heating.

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Afify *et al*. (2014) studied the slip flow effects, Newtonian heating, and thermal radiation, two-dimensional magnetohydrodynamic (MHD) flows and heat transfer past a permeable stretching sheet. Shehzad *et al*. (2015) investigated the two-dimensional boundary layer flow of an incompressible third grade nanofluid over a stretching surface. Influence of thermophoresis and Brownian motion is considered in the presence of Newtonian heating and viscous dissipation. They concluded that the temperature and thermal boundary layer thickness are increasing functions of Newtonian heating parameter and an increase in thermophoresis and Brownian motion parameters tends to an enhancement in the temperature. Ramzan and Yousaf (2015) investigated the boundary layer flow of three-dimensional viscoelastic nanofluid past a bi-directional stretching sheet with Newtonian heating.

In the present paper, the steady, two dimensional flow of a copper (Cu)- water nanofluid over a permeable a stretching sheet in the presence of porous medium and Newtonian heating is investigated. Using the similarity transformations, the governing equations have been transformed into a set of ordinary differential equations, which are nonlinear and cannot be solved analytically, therefore, bvp4c MATLAB solver has been used for solving it. The results for velocity and temperature functions are carried out for the wide range of important parameters namely; namely, permeability parameter, solid volume fraction of nanoparticles, conjugate parameter for Newtonian heating and Prandtl number. The skin friction and the rate of heat transfer have also been computed.

Mathematical Formulation

Consider the steady, laminar boundary layer flow and heat transfer of a viscous and incompressible Cu-water nanofluid over a stretching sheet. In this two-dimensional model, rectangular Cartesian coordinates (x, y) are used, in which the x- and y-axes are taken as the coordinates parallel to the plate and normal to it, respectively, and the fluid occupies the region y≥0. Further, u and v are the velocity components along the x- and y- directions, respectively. The thermo-physical properties of the nanofluid are given in table-1.

Table 1 Thermo Physical properties of water and nanoparticles [Oztop & Abu-Nada (2008)]

Physical properties	Water/base fluid	Cu (copper)
ρ (kg/m^3)	997.1	8933
c_p (J/kg K)	4179	385
k (W/m K)	0.613	401
Φ	0.0	0.05

The physical model and coordinate system of this problem is shown in Fig. A. We assume that the wall is subjected to a Newtonian heating of the form proposed by Merkin (1994).

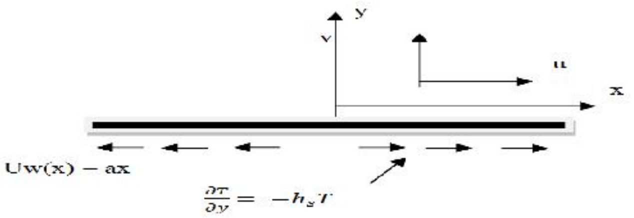

Figure A Schematic diagram of the physical problem

Under the above assumptions, the Partial differential equations and the corresponding boundary conditions govern the problem are given by:

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

Momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{\mu_{nf}}{\rho_{nf}}\frac{\partial^2 u}{\partial y^2}-\frac{\nu}{k'}u \qquad (2)$$

Energy equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\frac{\partial^2 T}{\partial y^2} \qquad (3)$$

The boundary conditions are

$$u=u_w=ax, v=0, \frac{\partial T}{\partial y}=-h_s T \quad \text{at} \quad y=0$$

$$u\to 0, T\to T_\infty \quad \text{as} \quad y\to\infty \qquad (4)$$

where *u* and *v* are the velocity components along the *x*- and *y*-axes, respectively, h_s is the convective heat transfer coefficient, *T* is the temperature of the nanofluid, T_∞ is the ambient temperature, μ_{nf} is the viscosity of the nanofluid, α_{nf} is the thermal diffusivity of the nanofluid and ρ_{nf} is the density of the nanofluid, which are given by (Oztop and Abu-Nada (2008))

$$\alpha_{nf}=\frac{k_{nf}}{(\rho C_p)_{nf}}, \rho_{nf}=(1-\phi)\rho_f+\phi\rho_s, \mu_{nf}=\frac{\mu_f}{(1-\phi)^{2.5}}$$

$$(\rho C_p)_{nf}=(1-\phi)(\rho C_p)_f+\phi(\rho C_p)_s, \frac{k_{nf}}{k_f}=\frac{(k_s+2k_f)-2\phi(k_f-k_s)}{(k_s+2k_f)+\phi(k_f-k_s)} \qquad (5)$$

Here, ϕ is the nanoparticle volume fraction, $(\rho C_p)_{nf}$ is the heat capacity of the nanofluid, k_{nf} is the thermal conductivity of the nanofluid, k_f and k_s are the thermal conductivities of the fluid and of the solid fractions, respectively, and ρ_f and ρ_s are the densities of the fluid and of the solid fractions, respectively. It should be mentioned that the use of the above expression for k_{nf} is restricted to spherical nanoparticles where it does not account for other shapes of nanoparticles (Abu-Nada (2008)). Also, the viscosity of the nanofluid μ_{nf} has been approximated by Brinkman (1952) as viscosity of a base fluid μ_f containing dilute suspension of fine spherical particles.

The governing Eqs. (2) - (3) subject to the boundary conditions (4) can be expressed in a simpler form by introducing the following transformation:

$$\eta = \left(\frac{a}{\nu_f}\right)^{1/2} y, \psi = \left(\nu_f a\right)^{1/2} f(\eta), \theta(\eta) = \frac{T - T_\infty}{T_\infty} \qquad (6)$$

where η is the similarity variable and ψ is the stream function defined as $u = \frac{\partial \psi}{\partial y}$ and $v = -\frac{\partial \psi}{\partial x}$, which identically satisfies Eq. (1). Employing the similarity variables (6), Eqs. (2) and (3) reduce to the following ordinary differential equations:

$$\frac{1}{(1-\phi)^{2.5}\left(1-\phi+\phi\rho_s/\rho_f\right)} f'''(\eta)+f(\eta)f''(\eta)-f'(\eta)^2-\frac{1}{Kp}f'(\eta)=0 \qquad (7)$$

$$\frac{1}{\Pr}\frac{k_{nf}/k_f}{\left[1-\phi+\phi\left(\rho C_p\right)_s/\left(\rho C_p\right)_f\right]}\theta''(\eta)+f(\eta)\theta'(\eta)=0 \qquad (8)$$

The boundary conditions become,

$$f(0)=0, f'(0)=1, \theta'(0)=-\gamma\left(1+\theta(0)\right)$$

$$f'(\eta)\to 0, \theta(\eta)\to 0 \quad as \ \eta\to\infty \qquad (9)$$

Here primes denote differentiation with respect to η.

Pr is the Prandtl number, and γ is the convective parameter defined respectively as

$$\Pr = \frac{\nu_f}{\alpha_f}, Kp = \frac{k'a}{\nu}, \gamma = h_s\left(\frac{\nu_f}{a}\right)^{1/2} \qquad (10)$$

The physical quantities of interest are the skin friction coefficient C_f and the local Nusselt number Nu_x, which are defined as

$$C_f = \frac{\tau_w}{\rho_f U_\infty^2}, Nu_x = \frac{x q_w}{k_f\left(T_w - T_\infty\right)} \qquad (11)$$

where the surface shear stress τ_w and the surface heat flux q_w are given by

$$\tau_w = \mu_{nf}\left(\frac{\partial u}{\partial y}\right)_{y=0}, q_w = -k_{nf}\left(\frac{\partial T}{\partial y}\right)_{y=0} \qquad (12)$$

with μ_{nf} and k_{nf} being the dynamic viscosity and thermal conductivity of the nanofluids, respectively. Using the similarity variables (6), we obtain

$$C_f \operatorname{Re}_x^{1/2} = \frac{1}{(1-\phi)^{2.5}} f''(0), \frac{Nu_x}{\operatorname{Re}_x^{1/2}} = -\frac{k_{nf}}{k_f}\theta'(0) \qquad (13)$$

where $\operatorname{Re}_x = \frac{U_\infty x}{\nu_f}$ is the local Reynolds number.

Solution of The Problem

For solving Eqs. 7 – 9, a step by step integration method i.e. Runge–Kutta method has been applied. For carrying in the numerical integration, the equations are reduced to a set of first order differential equation. For performing this we make the following substitutions:

$$y_1 = f, y_2 = f', y_3 = f'', y_4 = \theta, y_5 = \theta'$$

$$y_3' = (1-\phi)^{2.5}\left(1-\phi+\phi\rho_s/\rho_f\right)\left[y_2^2 + \frac{1}{Kp} y_2\right]$$

$$y_5' = -\Pr\left(\frac{1-\phi+\phi\left(\rho C_p\right)_s/\left(\rho C_p\right)_f}{k_{nf}/k_f}\right)\left[y_1 y_5\right]$$

$$y_1(0)=0, y_2(0)=1, y_5(0)=-\gamma\left(1+y_4(0)\right)$$

$$y_2(\infty)=0, y_4(\infty)=0$$

In order to carry out the step by step integration of Eqs. Refspseqn 7-9, Gills procedures as given in Ralston and Wilf (1960) have been used. To start the integration it is necessary to provide all the values of y_1, y_2, y_3, y_4 at $\eta = 0$ from which point, the forward integration has been carried out but from the boundary conditions it is seen that the values of y_3, y_5 are not known. So we are to provide such values of y_3, y_5 along with the known values of the other function at $\eta = 0$ as would satisfy the boundary conditions as $\eta \to \infty (\eta = 10)$ to a prescribed accuracy after step by step integrations are performed. Since the values of y_3, y_5 which are supplied are merely rough values, some corrections have to be made in these values in order that the boundary conditions to $\eta \to \infty$ are satisfied. These corrections in the values of y_3, y_5 are taken care of by a self-iterative procedure which can for convenience be called ‘‘Corrective procedure’’. This procedure has been taken care of by the software which has been used to implement R–K method with shooting technique.

As regards the error, local error for the 4th order R–K method is $O\left(h^5\right)$; the global error would be $O\left(h^4\right)$. The method is computationally more efficient than the other methods. In our work, the step size $h = 0.01$. Therefore, the accuracy of computation and the convergence criteria are evident. By reducing the step size better result is not expected due to more computational steps vis-a` -vis accumulation of error.

RESULTS AND DISCUSSION

The governing equations (7) - (8) subject to the boundary conditions (9) are integrated as described in section 3. In order to get a clear insight of the physical problem, the velocity and temperature have been discussed by assigning numerical values to the parameters encountered in the problem.

Figures 1 & 2 establishes the different values of permeability of the porous medium parameter (Kp) on velocity and temperature profiles, respectively. The values of K is taken to be Kp = 0.5, 1, 1.5, 2 and the other parameters are fixed as ϕ = 0.2, γ = 0.3 and Pr = 6.2. It is noticed that, with the hype in the values of K from 0.5 to 2.0 then the velocity increases consequently increases the thickness of momentum boundary layer but the temperature distribution of the fluid decreases. The reason for this, the porous medium obstructs the fluid to move freely through the boundary layer. This leads to reduce in the thickness of thermal boundary layer.

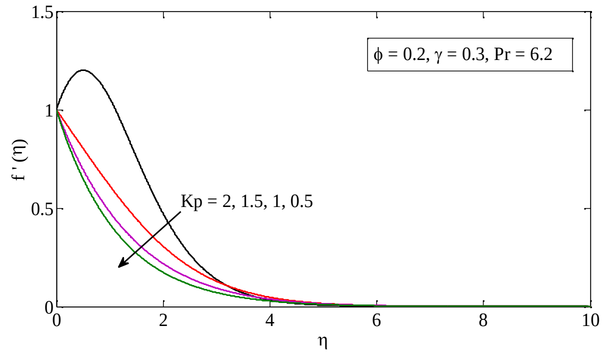

Fig.1 Velocity for various values of *Kp*

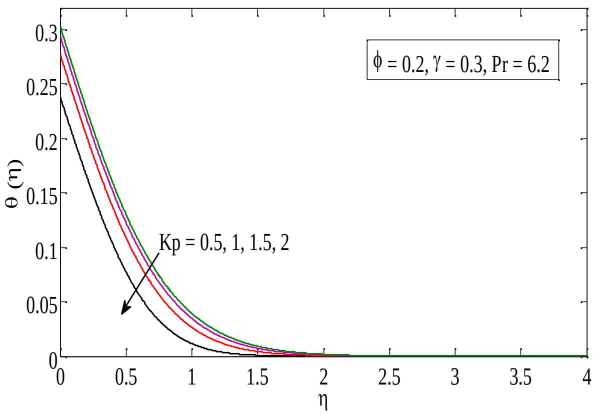

Fig.2 Temperature for various values of *Kp*

Figure 3 & 4 show the effect of the solid volume fraction of nanoparticles (ϕ) on velocity and temperature profiles and the other parameters are fixed as Kp = 2, γ = 0.3 and Pr = 6.2. We observe that the velocity decreases whereas temperature increases with the increases the values of solid volume fraction of nanoparticles (ϕ). The variation of the temperature profiles with conjugate parameter for Newtonian heating (γ) is shown in Figures 5 respectively and the other parameters are fixed as ϕ = 0.2, Kp = 2 and Pr = 6.2. It is observed that the temperature distribution increases with an increasing the values conjugate parameter for Newtonian heating (γ).

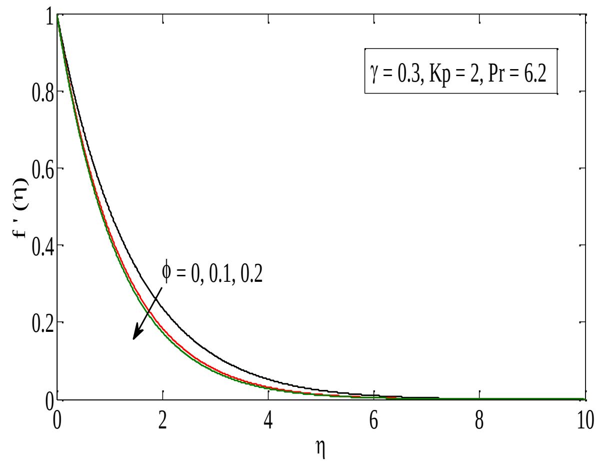

Fig.3 Velocity for various values of ϕ

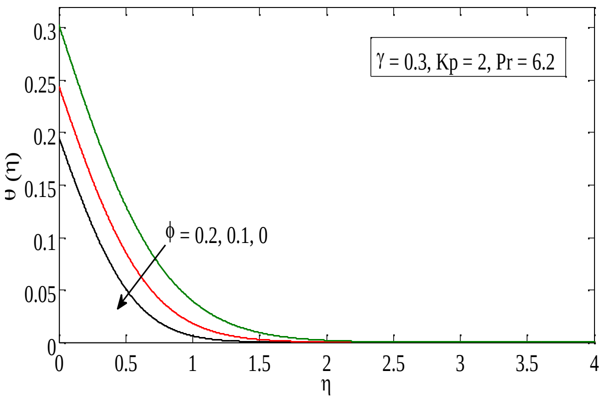

Fig.4 Temperature for various values of ϕ

Figure 6 displays the temperature profiles θ(η) for all values of Pr = 2, 3, 4 and 5 and the other parameters are fixed as ϕ = 0.2, γ = 0.3 and Kp = 2. It is found that as Pr increases, the temperature profiles decrease. It is also shown from these figures that the thermal boundary layer thickness increases sharply with a decrease in Pr. This is because for small values of the Prandtl number Pr($\ll$1), the fluid is highly conductive. Physically, if Pr increases, the thermal diffusivity decreases and this phenomenon leads to the decreasing of energy transfer ability that reduces the thermal boundary layer.

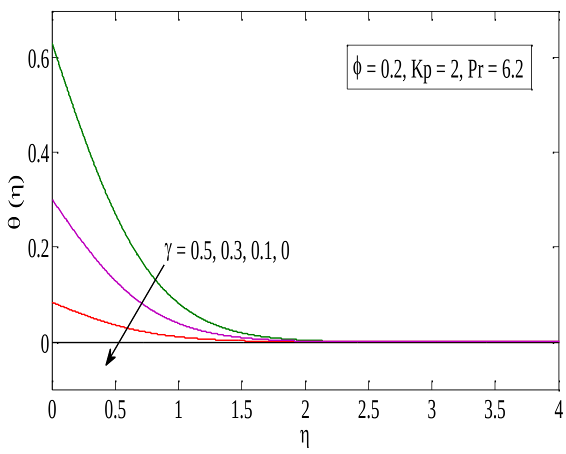

Fig.5 Temperature for various values of γ

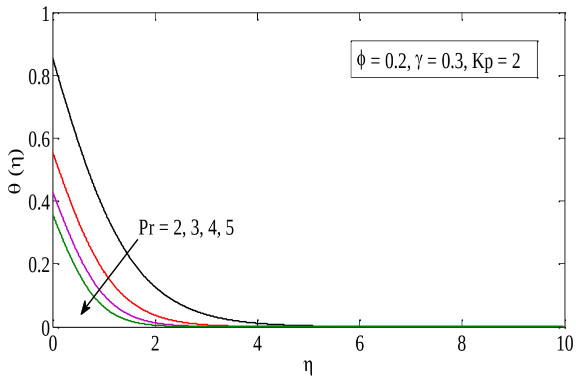

Fig.6 Temperature for various values of *Pr*

Figure 7 illustrates the variation of the wall temperature θ(0) for various values of γ when Pr = 1 and 7. Also, to get a physically acceptable solution, γ must be less than some critical value, say γ_c, depending on Pr. From our numerical solution, it is found that the surface temperature becoming unbounded when $\gamma = \gamma_c$. It can be seen from this table that θ(0) becomes large as γ approaches the critical values γ_c = 0.40801 and 1.381 when Pr = 1 and 7, respectively. On the other hand, Figure 8 illustrates the variation of wall temperature θ(0) with Prandtl number Pr when γ = 1. To get a physically acceptable solution, Pr must be greater than some critical value, say Pr_c, depending on γ. It can be seen from this figure that θ(0) becomes large as Pr approaches the critical value Pr_c = 4.131 when γ = 1.

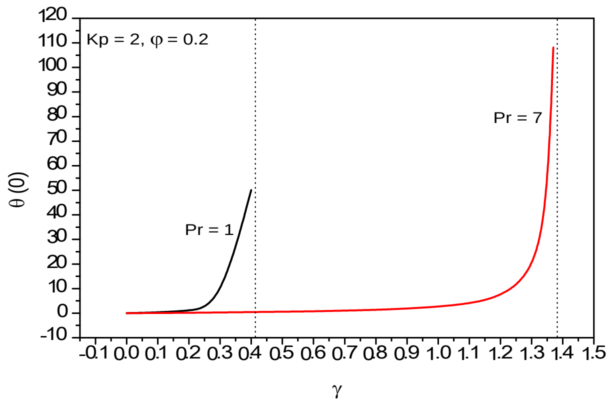

Fig.7 Wall temperature for different values of γ and Pr

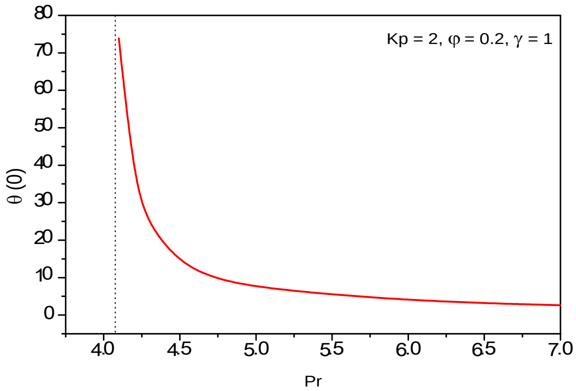

Fig.8 wall Temperature for various values of *Pr*

Figure 9 shows the effects of permeability parameter (Kp) and solid volume fraction of nanoparticles (ϕ) on skin friction coefficient. From Figure 9 it is seen that the skin friction decreases with an increasing permeability parameter (Kp) and solid volume fraction of nanoparticles (ϕ).

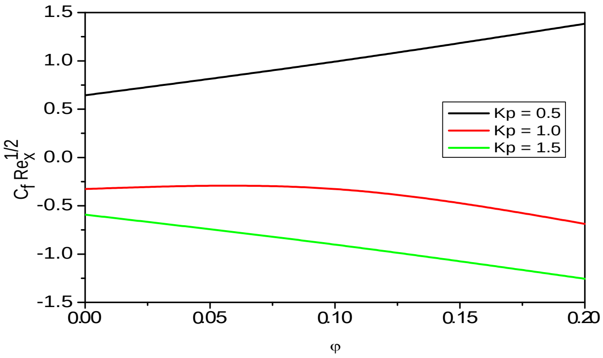

Fig.9 skin-friction for different values of Kp and ϕ when Pr = 6.2 and γ = 0.3

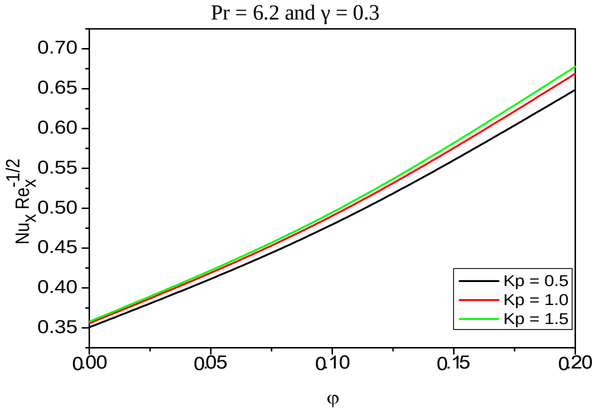

Fig.10 Nusselt number for different values of *Kp* and ϕ when Pr = 6.2 and γ = 0.3

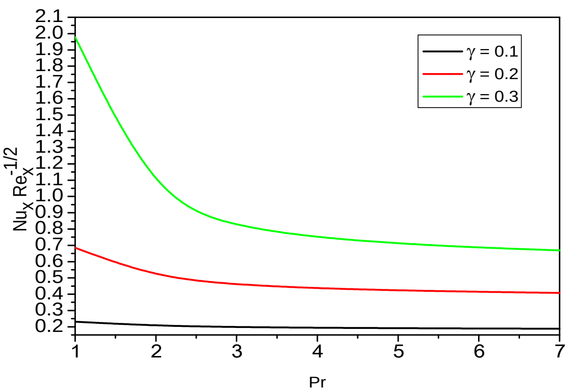

Fig.11 Local Nusselt number for different values of *Pr* and γ when Kp = 2 and ϕ = 0.2

Table 1 Comparison for viscous case –¯ '(0) with Pr for ϕ = Kp = 0.

Pr	–¯ '(0) Present results	Khan and Pop (2010)	Wang (1989)
0.07	0.066000	0.066	0.066
0.2	0.169522	0.169	0.169
0.7	0.453916	0.454	0.454
2.0	0.911358	0.911	0.911

The effect of permeability parameter (Kp) and solid volume fraction of nanoparticles (ϕ) on local Nusselt number is shown in figure10. It is found that the local Nusselt number enhances with an increasing the values of permeability parameter (Kp) and solid volume fraction of nanoparticles (ϕ). The effect of

Prandtl number (Pr) and conjugate parameter for Newtonian heating (γ) on local Nusselt number is shown in figure 11. It is found that the local Nusselt number reduces with an increasing the values of Pr but it increases with an increasing the values of conjugate parameter for Newtonian heating (γ). Tables.1, 2 & 3 shows that the present results perfect agreement to the previously published data.

CONCLUSIONS

In the present paper, the steady, two dimensional flow of a copper (Cu) - water nanofluid over a permeable a stretching sheet in the presence of porous medium and Newtonian heating. The governing equations are approximated to a system of non-linear ordinary differential equations by similarity transformation. Numerical calculations are carried out for various values of the dimensionless parameters of the problem. It has been found that

1. The velocity increases whereas temperature decreases with an increase in the permeability parameter.
2. The velocity decreases whereas temperature increases with an increase in the solid volume fraction of nanoparticles.
3. The fluid temperature increases in the presence of Newtonian heating.
4. The skin friction decreases with an increase the permeability parameter or the solid volume fraction of nanoparticles.
5. The local Nusselt number enhances with an increase in the permeability parameter or the solid volume fraction of nanoparticles or conjugate parameter for Newtonian heating whereas local Nusselt number reduces with increase the Prandtl number.

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