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Review

MHD flow and heat transfer of Cu–water nanofluid in a semi porous channel with stretching walls

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ABSTRACT

This paper deals with heat transfer analysis on MHD nanofluids in a porous channel with stretching walls. An incompressible Copper (Cu)–water nanofluid is filled in the porous channel. The governing partial differential equations are first transformed into ordinary differential equations by using suitable similarity transformation. The resulting nonlinear ordinary differential equations are then solved numerically by using shooting method. It is found that the different values of nanoparticle volume fraction, Reynolds number, magnetic field and Prandtl number affects the profiles of velocity, temperature, skin friction and heat transfer.

Contents

1. Introduction

Fluid heating and cooling are essential in numerous mechanical fields, for example, force plant operations, assembling and transportation. In need of cooling high energy devices, effective cooling techniques are entirely needed. Engine oil, water and ethylene glycol are some of the common fluids used for heat transfer. Heat transfer abilities in these fluids are very limited because of low properties for heat transfer. On the other hand, as compared to fluids, thermal conductivities of metal are almost three times higher. In desire of developing a fluid medium having thermal conductivity equivalent to metal, these two substances are combined and called nanofluid. Characterization of steady fluid motions in the porous channels can be followed back to 1953 when some of the works were carried out by Berman [1] to examine the laminar two dimensional flow of an incompressible fluid determined by uniform injection inside a rectangular channel with porous walls. Numerous studies are considered previously with various conditions [2–6]. Nanofluids are prepared for increasing thermophysical properties, for instance, thermal conductivity, thermal diffusivity, thickness, and convective heat transfer coefficients diverged from those of the base fluids like water, ethylene or triethylene-glucose and diverse coolants, biofluids, and polymer game plans, as clarified by Choi [7] and Wong and Leon [8].

On the other hand, magnetic nanofluids have much more significance in the various engineering fields. These fluids react to applied magnetic fields and heat transfer and hydrodynamic characteristics. Often magnetite and aluminum oxide nanoparticles are exploited in the architecture of such fluids. Parekh and Lee [9] escorted experimental studies of magnetic nanofluids. The tribological performance, thermal enhancement features and biomedical insinuations of magnetic nanofluids were studied by Andablo-Reyes et al. [10], Chiang et al. [11] and Patel [12]. Uddin et al. [13] investigated theoretically the features of magnetohydrodynamics

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viscous incompressible boundary layer flow of nanofluid from a convectively heated permeable vertical surface.

Sheikholeslami et al. [14] has analytically investigated flow of laminar nanofluid in a semi-porous channel. This analysis was done during the presence of transverse magnetic field. Soleimani et al. [15] have used finite element method to study the natural convection for transfer of heat by using semi-annulus enclosure having nanofluid. A steady magneto–hydrodynamic free convection boundary layer flow past a vertical semi-infinite flat plate embedded in water filled with a nanofluid has been theoretically studied by Hamad et al. [16]. In this case cooling performance of copper and silver nanoparticles is the highest. Sheikholeslami and Ganji [17], used a homotopy perturbation method (HPM), studied the heat transfer of a nano fluid flow, squeezed between parallel plates. Sheikholeslami et al. [18] studied the effect of MHD, in enclosure having nanofluid, on natural convection heat transfer. Sheikholeslami and Ganji [19] have also investigated three dimensional mass and heat transfer using a nanofluid in a rotating system. Studies in the presence of magnetic field, using a concentric annulus, among heated elliptic and cold square cylinders, free convection heat transfer was done by Sheikholeslami et al. [20]. Heat transfer has direct relation with Hartmann number but inverse relation with Rayleigh number. Recently, Chen et al. [21] investigated the problem of mixed convection MHD nanofluid in a channel. The mentioned studies revealed that enhancement in heat transfer increases with an increasing nanoparticles concentration.

In this study, we consider a MHD flow and heat transfer of Cu–water nanofluid in a semi porous channel with stretching walls which has not been studied before. It is hoped that the results will contribute towards better understanding of nanofluid problems in channel.

2. Problem formulation

We consider two dimensional steady laminar incompressible flow of electrically conductive nanofluid in a semi porous channel $(-a \leqslant y \leqslant a)$ by Nouri et al. [22]. The Cartesian coordinate system with x-axis is taken in the direction of the flow and y-axis is perpendicular to the channel. The upper wall is assumed located at $y = a$, which is static and non-permeable, and the lower wall is located at $y = -a$, which is permeable as well as stretching in the direction of x-axis as shown in Fig. 1. Flow is subjected to a constant applied magnetic field B° in the direction of y-axis. Governing equations of the following fluid model is given below:

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

$$\rho_{nf}\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu_{nf}\frac{\partial^2 u}{\partial y^2} - \sigma_{nf}B^{\circ 2}u \tag{2}$$

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \mu_{nf}\frac{\partial^2 v}{\partial x^2} \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k_{nf}}{(\rho C_p)_{nf}}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

where u and v are the velocity component along x and y axes respectively, σ_{nf} is effective electrical conductivity of nanofluid, ρ_{nf} is effective density, μ_{nf} is the effective dynamic viscosity, $(\rho C_p)_{nf}$ is heat capacitance andk_{nf} thermal conductivity of the nanofluid. These physical quantities described mathematically given by Brinkman [23]:

$$\rho_{nf} = \rho_f(1-\varphi) + \rho_s \tag{5}$$

$$\mu_{nf} = \frac{\mu_f}{(1-\varphi)^{2.5}} \tag{6}$$

$$(\rho C_p)_{nf} = (\rho C_p)_f(1-\varphi) + (\rho C_p)_s\varphi \tag{7}$$

$$\frac{k_{nf}}{k_f} = \frac{k_s + 2k_f - 2\varphi(k_f - k_s)}{k_s + 2k_f + 2\varphi(k_f - k_s)} \tag{8}$$

$$\frac{\sigma_{nf}}{\sigma_f} = 1 + \frac{3\left(\frac{\sigma_s}{\sigma_f} - 1\right)\varphi}{\left(\frac{\sigma_s}{\sigma_f} + 2\right) - \left(\frac{\sigma_s}{\sigma_f} - 1\right)\varphi} \tag{9}$$

Here φ is the solid volume fraction, φ_s is for nanosolid-particles, φ_f is for base fluid. Our preference is to solve Eqs. (1)-(4) through Eqs. (5)-(9), with boundary conditions:

$$u = bx,\ \ v = -v^{\circ}\ T = T_1\ at\ y = -a\,(Lower\ Wall) \tag{10}$$

$$u = 0,\ \ v = 0,\ \ T = T_2 \text{ at } y = a\,(Upper\ Wall) \tag{11}$$

where $b < 0$ for shrinking walls channel and $b > 0$ for stretching walls. Introducing similarity transformation to convert governing equations (1)-(4) into ordinary differential equations by Misra et al. [24].

$$\eta = \frac{y}{a},\quad u = bxf'(\eta),\quad v = -abf(\eta)$$

$$\theta(\eta) = \frac{T - T_2}{T_1 - T_2}$$

Put this similarity transformation into Eqs. (1)-(4) and utilize the Eqs. (5)-(9) then we get,

$$f'''' - M^2B^{\circ}(1-\varphi)^{2.5}f'' - A_1R(1-\varphi)^{2.5}(f'f'' - ff''') = 0 \tag{12}$$

$$\frac{1}{Pr}\theta'' + \frac{A_2}{A_3}f\theta' = 0 \tag{13}$$

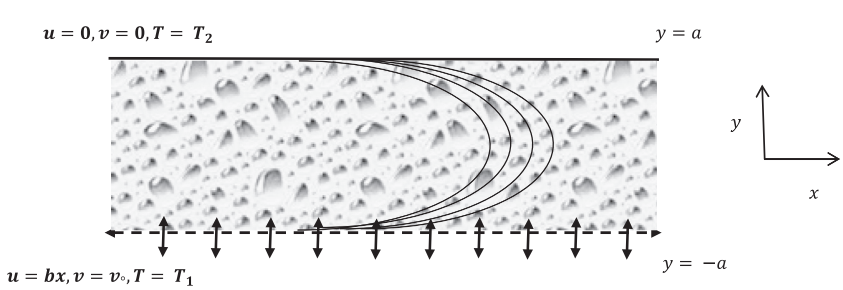

Fig. 1. Physical model of the proposed problem.

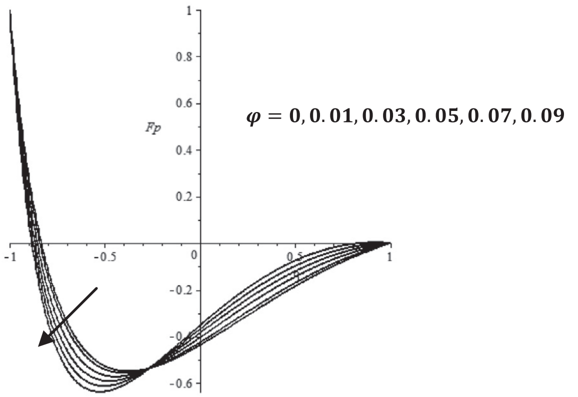

Fig. 2. Effect of φ on velocity profile for $M = 0.4, R = 10, \lambda = 0.5$.

where $R = \frac{a^2 b}{\upsilon_f}$ is stretching Reynolds number, $M^2 = \frac{\sigma B_0^2 a^2}{\mu_f}$ is Hartman number, $Pr = \frac{a^2 b(\rho C_p)_f}{\kappa_f}$ is the Prandtl number, λ is suction parameter and the values of A_1, A_2, A_3 are:

$$A_1 = \frac{\rho_{nf}}{\rho_f} = (1-\varphi) + \frac{\rho_s}{\rho_f}\varphi \tag{14}$$

$$A_2 = \frac{(\rho C_p)_{nf}}{(\rho C_p)_f} = (1-\varphi) + \frac{(\rho C_p)_s}{(\rho C_p)_f}\varphi \tag{15}$$

$$A_3 = \frac{\kappa_{nf}}{\kappa_f} = \frac{\kappa_s + 2\kappa_f - 2\varphi(\kappa_f - \kappa_s)}{\kappa_s + 2\kappa_f + 2\varphi(\kappa_f - \kappa_s)} \tag{16}$$

Moreover, boundary conditions becomes

$$\left.\begin{array}{l} f'(-1) = 1, f'(1) = 0,\ \theta(-1) = 1 \\ f(-1) = \lambda, f(1) = 0,\ \theta(1) = 0 \end{array}\right\} \tag{17}$$

3. Numerical method for solution

Eqs. (12) and (13) subject to the boundary condition (17) are solved numerically by using shooting technique. A standard methodology is to compose the nonlinear ODEs in the form of a first order initial value problem as follows:

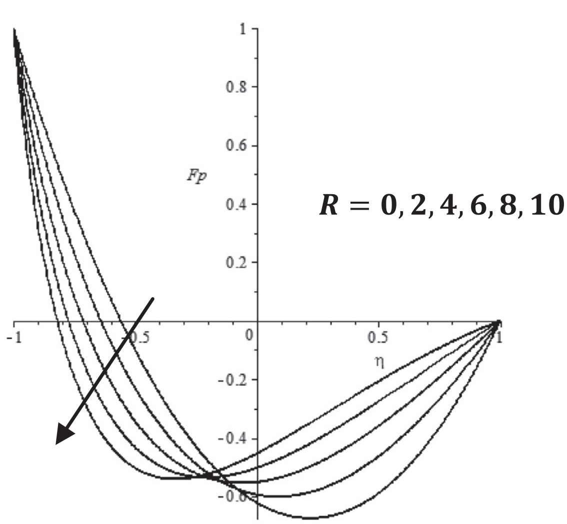

Fig. 3. Effect of Reynolds number on velocity profile for $\varphi = 0.03, M = 0.4, \lambda = 0.5$.

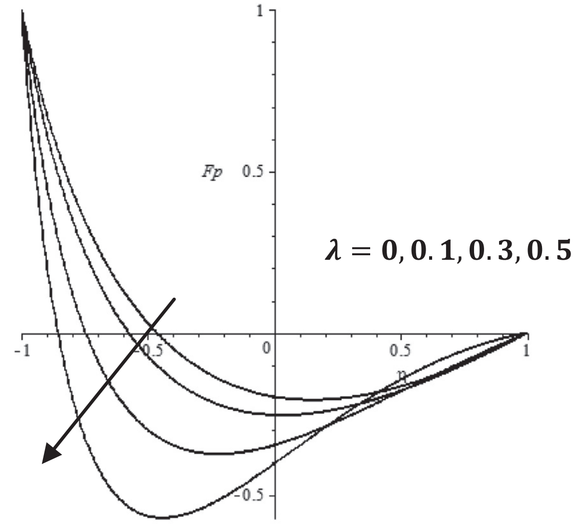

Fig. 4. Effect of suction on velocity profile for $\varphi = 0.03, R = 10, M = 0.4$.

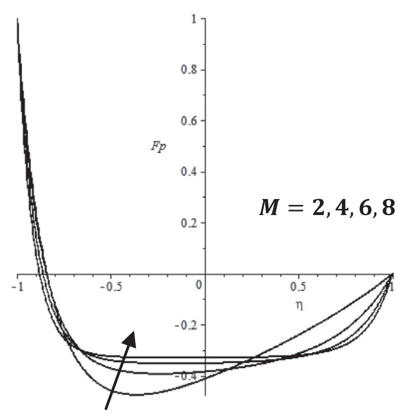

Fig. 5. Effect of magnetic field on velocity profile for $\varphi = 0.03, R = 10, \lambda = 0.5$.

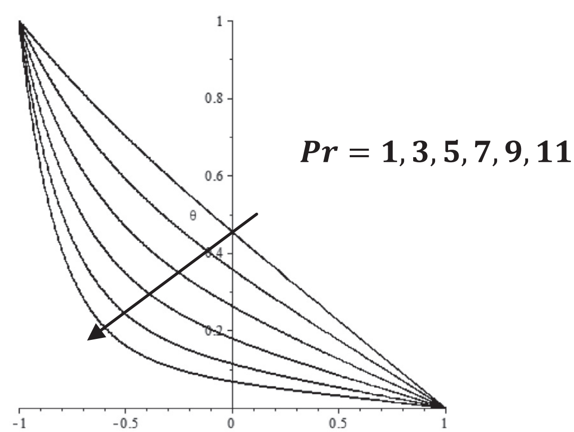

Fig. 6. Effect of Prandtl number on $\theta(\eta)$ for $M = 0.4, R = 10, \lambda = 0.5, \varphi = 0.03$.

Table 1
Thermophysical properties of water and copper nanoparticle.

	ρ/kg m^{-3}	C_p/j kg^{-1} k	k/W m^{-1} k	$\beta \times 10^5$/K^{-1}
Pure water	991.1	4179	0.613	21
Copper (Cu)	8933	385	401	1.67

Table 2
Effect of different parameters on skin friction and heat transfer rate for Cu–water nanofluid.

Reynolds number	Magnetic field	Prandtl number	Suction parameter	Solid volume fraction	$f''(-1)$	$\theta'(-1)$
10	0.4	1.0	1.0	0	−9.384752739	−0.709290125
				0.01	−9.846596801	−0.694623691
				0.03	−10.71745956	−0.668955131
				0.05	−11.51701997	−0.647222635
				0.07	−12.24689148	−0.628538897
				0.09	−12.91298929	−0.612199712
0	0.4	1.0	1.0	0.03	−2.800909116	−0.787739677
2					−3.910754184	−0.759006092
4					−5.299500304	−0.732485523
6					−6.901388546	−0.709232644
8					−8.695953803	−0.688577949
10					−10.71745956	−0.668955131
10	0.4	1.0	0.0	0.03	−3.742085886	−0.562724070
			0.1		−4.543897119	−0.587615101
			0.3		−6.877754916	−0.633277452
			0.5		−10.71745956	−0.668955131
10	0	1.0	1.0	0.03	−10.75677730	−0.667396680
	2				−10.48398313	−0.687931523
	4				−11.49142634	−0.698915350
	6				−13.38986618	−0.698123028
	8				−15.57744388	−0.694903830
10	0.4	1	1.0	0.03	–	−0.668955132
		3				−1.142279804
		5				−1.816013339
		7				−2.676178601
		9				−3.669210781

By putting:

$$f' = p \tag{18}$$

$$p' = q \tag{19}$$

$$q' = s \tag{20}$$

$$s' = M^2 B^{\circ}(1-\varphi)^{2.5} q + A_1 R(1-\varphi)^{2.5}(pq - fs) \tag{21}$$

$$\theta' = z \tag{22}$$

$$z' = -Pr\frac{A_2}{A_3} fz \tag{23}$$

Subject to the boundary conditions

$$\left.\begin{array}{l} p(-1) = 1, p(1) = 0, \theta(-1) = 1 \\ f(-1) = \lambda, f(1) = 0, \theta(1) = 0 \\ q(-1) = \alpha, s(-1) = \beta, z(-1) = \gamma \end{array}\right\} \tag{24}$$

where α, β, γ are unknown initial conditions. It is important to know that we have to shoot the values of missing initial values so called α, β, γ such that solution satisfies the boundary conditions $f(1) = 0$, $p(1) = 0$ and $\theta(1) = 0$ of the original boundary value. This computation is done with the aid of *shootlib* function in Maple software [25].

4. Results and discussions

The performance of solid volume fraction on velocity profile can be depicted by Fig. 2 for the fixed value of $M = 0.4, R = 10, \lambda = 0.5$. It is observed that prior to the center of the channel, solid volume fraction velocity profile increases. Afterwards, reversed phenomena can be observed. In Fig. 3, reversible flow occurs for the variation of stretching Reynolds number for fixed values of the other parameters, $\varphi = 0.03, M = 0.4, \lambda = 0.5$. This is in accordance with the variation of stretching Reynolds number. Fig. 4 is the representation of consequences of suction parameter on velocity profile. Apart from the upper wall of the channel, velocity profile enhances speedily. The effect of magnetic field on velocity profile is observed in Fig. 5 for fixed values of $\varphi = 0.03, R = 10, \lambda = 0.5$. Due to variation of magnetic field velocity increases near the walls of the channel and decreases at the rest of the channel. Effect of Prandtl number on $\theta(\eta)$ for fixed values of $M = 0.4, R = 10, \lambda = 0.5, \varphi = 0.03$ is represented in Fig. 6. It is observed that an increase values in Prandtl number decreases in the profile of $\theta(\eta)$. So it is concluded from Fig. 6 that thermal diffusivity decreases by increasing Prandtl number. Therefore, away from heated surface heat diffuses slowly.

Table 1 represents some thermophyscial properties of water and copper nanoparticle. Numerical values of the effect of Reynolds number, magnetic field, suction parameter and solid volume fraction on skin friction and heat transfer are shown in Table 2. The magnitude values of skin friction and heat transfer increases and decreases respectively by increasing in the values of solid volume fraction from 0 to 0.09. Skin friction increases numerically as stretching Reynolds number increases, however heat transfer rate decreases for the fixed values of other parameters. Trend of the numerical values of skin friction and heat transfer rate increase as suction parameter increases from 0 to 0.5. An increase values in magnetic field leads skin friction and heat transfer rate decreases. It is worthy to notice that magnetic field applied perpendicular to the channel which oppose the fluid motion, therefore, heat is produced as can be seen in Table 2. In fact, in real life application, magnetic nanoparticles are more strengthen to tumor cells therefore it absorb much more power than microparticles in alternating current magnetic fields endurable in humans as reported by Hayat et al. [26]. Heat transfer rate increases by increase the values of Prandtl number by setting $M = 0.4, R = 10$, $\lambda = 0.5, \varphi = 0.03$.

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