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ORIGINAL RESEARCH PAPER

Investigation of two phase unsteady nanofluid flow and heat transfer between moving parallel plates in the presence of the magnetic field using GM

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ABSTRACT: In this paper, unsteady two phase simulation of nanofluid flow and heat transfer between moving parallel plates, in presence of the magnetic field is studied. The significant effects of thermophoresis and Brownian motion have been contained in the model of nanofluid flow. The three governing equations are solved simultaneously via Galerkin method (GM). Comparison with other works indicates that this method is very applicable to solve these problems. The semi analytical analysis is accomplished for different governing parameters in the equations e.g. the squeeze number, Eckert number and Hartmann number. The results showed that skin friction coefficient value increases with increasing Hartmann number and squeeze number in a constant Reynolds number. Also, it is shown that the Nusselt number is an incrementing function of Hartmann number while Eckert number is a reducing function of squeeze number .This type of results can help the engineers to make better and researchers to investigate faster and easier.

KEYWORDS: *Brownian; Eckert number; Galerkin method (GM); Hartmann number; Nanofluid; Thermophoresis*

INTRODUCTION

One of most important engineering problems, peculiarly heat transfer equations are nonlinear problems, so some them are solved using numerical methods and some are solved using different analytical methods. One of the known analytical simulation methods is the galerkin method, which is based on guessing the base functions with polynomial equations.

Sheikholeslami et al. [1] Investigated rotating magnetic hydrodynamic (MHD) viscous flow and heat transfer between stretching and porous surfaces. The three dimensional analysis of steady deposition of fluid on an inclined rotating disk is also investigated by Sheikholeslami et al. [2] .They showed that by increasing normalized thickness, Nusselt number increase however this trend is more significant in bigger Prandtl numbers . In new years several researchers used different methods to solve these sort of problems [3–5]. Studying heat transfer enhancement in various energy systems is essential due to the increment in energy prices. In the last decade, nanofluids technology was propounded and examined by various researchers numerically or experimentally to control heat transfer in different applications. The nanofluid can be employed in different engineering applications, such as chemical processes, cooling of electronic equipment and heat exchangers. Most of the researchers supposed that nanofluids treat as standard pure fluids .Khanafer et al. [6] numerically investigated the heat transfer increment due to adding nano-particles in a variously heated enclosure.

Abu-Nada et al. [7] studied free convection heat transfer increment in a horizontal concentric annuli. They showed that for some Rayleigh numbers, nanoparticles with higher thermal conductivities lead more increment in heat transfer. Rashidi et al. [8] performed the second law of thermodynamics analysis on an electrically conducting incompressible nanofluid flowing over a porous rotating disk.

Heat transfer and nanofluid flow specifications between two parallel plates in a rotating system were studied by Sheikholeslami et al. [9]. They demonstrated that Nusselt number increases with increment of nanoparticle Reynolds number and volume fraction and decreases with increasing magnetic, rotation parameters and Eckert number. Sheikholeslami et al. [10] investigated the MHD free convection in an eccentric semi annulus filled with nanofluid. They founded that the Nusselt number reduces with an increment in the position of internal cylinder at higher Rayleigh numbers. Recently, several researchers studied about heat transfer and nanofluid flow [11–14]. Whole of the above investigations supposed that there are not whatsoever slip velocities between nanoparticles and fluid molecules and supposed that the concentration of nanoparticles is uniform. It is believed that in natural convection of nanofluids, the nanoparticles could not attend fluid molecules due to some slip mechanisms such as thermophoresis and Brownian motion, so the volume fraction of nanofluids may not be uniform and different concentration of nanoparticles will exist in a mixture. Nield and Kuznetsov [15] investigated the natural convection in a horizontal layer of a porous medium. Khan and Pop

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Nomenclature			
		k	thermal conductivity
c_p	specific heat at constant pressure	Nb	Brownian motion parameter
B	magnetic field	Nu	Nusselt number
D_T	thermophoretic diffusion coefficient	Pr	Prandtl number
Ha	Hartmann number	Sc	Lewis number
l	distance of plate		**Greek Symbols**
Nt	thermophoretic parameter	α	thermal diffusivity
p	Pressure	θ	dimensionless temperature
S	squeeze number	ρ	density (kgm^{-3})
T	fluid temperature	Φ	dimensionless concentration
C	nanofluid concentration	μ	dynamic viscosity of nanofluid
D_B	Browniandiffusion coefficient	γ	rate of squeezing
E_C	Eckert number	σ	electrical conductivity of nanofluid

[16]studied on boundary-layer flow of a nanofluid past a stretching sheet. Free convection heat transfer in an enclosure filled with nanofluid was studied by Sheikholeslami et al. [17]. They studied two phase modeling of nanofluid in a rotating system with permeable sheet. They showed that Nusselt number is a direct function of injection parameter and Reynolds number but it is a reverse function of Schmidt number, rotation parameter, Brownian parameter and thermophoretic parameter .The investigate of unsteady squeezing viscous flow between two parallel plates has vast spectrum of scientific and engineering applications such as polymer processing ,hydrodynamic machines, chemical processing equipment, lubrication system, food processing and cooling towers formation and dispersion of fog. Mahmood et al. [18] studied the heat transfer characteristics in the squeezed flow over a porous surface. MHD squeezing flow of a viscous fluid between parallel disks was studied by Domairry and Aziz [19].

Governing Equations

Heat and mass transfer analysis in the unsteady two-dimensional squeezing flow of nanofluid between the infinite parallel plates is carried out (Figure 1).

Fig. 1. Schematic geometry of problem

The two plates are placed at $l(1-\gamma t)^{1/2} = h(t)$. When $\gamma>0$ the two plates are squeezed until they touch $t=1/\gamma$ and for $\gamma<0$ the two plates are separated. The viscous dissipation effect, the generation of heat due to friction caused by shear in the flow, is retained. Also, it is also assumed that the uniform magnetic field ($\vec{B} = B\vec{e}_y$)) is applied, where $\vec{e}_y$ is a unit vector in the Cartesian coordinate system. The electric current J and the electromagnetic force F are defined by $J=\sigma(\vec{V}\times\vec{B})$ and $F=\sigma(\vec{V}\times\vec{B})\times\vec{B}$, respectively. The governing equations for mass, momentum, energy and species transfer in unsteady two dimensional flow of nanofluid are [20]:

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

$$\rho_f\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial v}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2})-\sigma B^2 u, \tag{2}$$

$$\rho_f\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}), \tag{3}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2})+\frac{\mu}{\left(\rho c_p\right)_f}(4(\frac{\partial u}{\partial x})^2) + \frac{(\rho c_P)_p}{(\rho c_P)_f}\left[\begin{array}{l} D_B\left\{\frac{\partial C}{\partial x}.\frac{\partial T}{\partial x}+\frac{\partial C}{\partial y}.\frac{\partial T}{\partial y}\right\} \\ +(D_T/T_c)\left\{\left(\frac{\partial T}{\partial x}\right)^2+\left(\frac{\partial T}{\partial y}\right)^2\right\}\end{array}\right], \tag{4}$$

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2})+\left(\frac{D_T}{T_c}\right)\left\{\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right\} \tag{5}$$

Here u and v are the velocities in the x and y directions respectively, T is the temperature, C is the Concentration, P is the pressure, ρ_f is the base fluid's density, μ is the dynamic viscosity, k is the thermal conductivity, C_p is the specific heat of nanofluid, D_B is the diffusion coefficient of the diffusing species.

The relevant boundary conditions are:

$$\begin{array}{l} C=0,\quad v=v_w=dh/dt,\quad T=T_H, \\ C=C_H \quad at\ y=h(t), \\ v=\partial u/\partial y=\partial T/\partial y= \\ \partial C/\partial y=0 \quad at\ y=0. \end{array} \tag{6}$$

The reduced governing equations will be obtained by introducing new dimensionless parameters:

$$\eta = \frac{y}{[\ell(1-\gamma t)^{1/2}]}, \qquad u = \frac{\gamma x}{[2(1-\gamma t)]} f'(\eta),$$
$$v = -\frac{\gamma \ell}{[2(1-\gamma t)^{1/2}]} f(\eta), \quad \theta = \frac{T}{T_H}, \tag{7}$$
$$\phi = \frac{C}{C_h}.$$

Substituting the above parameters into equations 2 and 3 and then eliminating the pressure gradient from the resulting equations will give:

$$f^{iv} - S\left(\eta f''' + 3f'' + f'f'' - ff'''\right) - Ha^2 f'' = 0, \tag{8}$$

Also substituting equation 7 into equations 4 and 5 will lead to the following differential equations:

$$\theta'' + \Pr S\left(f\theta' - \eta\theta'\right) + \Pr Ec\left(f''^2\right) + Nb\,\phi'\theta' + Nt\,\theta'^2 = 0, \tag{9}$$

$$\phi'' + S.Sc\left(f\phi' - \eta\phi'\right) + \frac{Nt}{Nb}\theta'' = 0, \tag{10}$$

With these boundary conditions:

$$f(0)=0, \quad f''(0)=0, \quad \theta'(0)=0,$$
$$\phi'(0)=0, \quad f(1)=1, \quad f'(1)=0, \tag{11}$$
$$\theta(1)=\phi(1)=1,$$

Where S is the squeeze number, Pr is the Prandtl number, Ec is the Eckert number, Sc is the Schmidt number, Ha is Hartman number of nanofluid, Nb is the Brownian motion parameter and Nt is the thermophoretic parameter, defined as:

$$S = \frac{\gamma l^2}{2\mu}\rho_f, \quad \Pr = \frac{\mu}{\rho_f \alpha}, \quad Ec = \frac{1}{c_p}\left(\frac{\gamma x}{2(1-\gamma t)}\right)^2$$
$$Sc = \frac{\mu}{\rho_f D}, \quad Ha = \ell B\sqrt{\frac{\sigma}{\mu}(1-\gamma t)}, \tag{12}$$
$$Nb = (\rho c)_p D_B (C_h) / \left((\rho c)_f \alpha\right),$$
$$Nt = (\rho c)_p D_T (T_H) / [(\rho c)_f \alpha T_c].$$

Nusselt number is defined as:

$$Nu = \frac{-\ell k \left(\frac{\partial T}{\partial y}\right)_{y=h(t)}}{T_H} \tag{13}$$

In terms of dimensionless parameters of equation 7, it will change to:

$$Nu^* = \sqrt{1-\alpha t}\,Nu = -\theta'(1)$$
$$C_f{}^* = l^2 / x^2 (1-\alpha t)\,\mathrm{Re}_x\, C_f = f''(1) \tag{14}$$

The Galerkin method

The method is used as a weighted residual method. It is an approximation technique for solving differential equations .The method is perfectly universal; it can be applied to elliptic, hyperbolic and parabolic equations, nonlinear problems, as well as complicated boundary conditions.

Principles of the method

In this method an approximate trial solution containing a finite number of undetermined coefficients can be constructed by the superposition of some basic functions such as polynomial functions written bellow

$$\tilde{T}(t) = 1 + c_1 t + c_2 t^2 + \ldots \tag{15}$$

The method requires that the weighted averages of the residual should vanish over the interval considered. The residual vanishes only with the exact solution for the problem. When are known, the trial solution given by equation 15 becomes a approximate solution for the problem .The weighting functions are taken as the same basis functions used to construct the trial solution . In this method weight functions can be interpreted as:

$$w_i = \frac{\partial \tilde{T}}{\partial c_i} \qquad i = 1, 2, \ldots, n \tag{16}$$

The weight functions are used for the integration of the residual (Re) over the interval 0<t<1. Thus, the Galerkin method becomes

$$\int_{t=0}^{1} w_i\, \mathrm{Re}(c_1, c_2, \ldots, c_n, t)\, dt = 0 \tag{17}$$

Equation 17 provide several algebraic equations for the determination of the unknown coefficients $C_1, C_2, \ldots, C_n$.

Applying the GM to the problem

For this problem, we wish to obtain an approximate solution in the specific interval 0<η<1. To construct a trial solution f(η), θ(η), Φ(η), the basis functions are chosen to be polynomials in η and create a trial solution of the form:

$$f(\eta)=c0+c_1\eta+\ c_2\eta^2+c_3\eta^3+c_4\eta^4+c_5\eta^5+c_6\eta^6$$
$$\theta(\eta)=c_7+c_8\eta+\ c_9\eta^2+c_{10}\eta^3+c_{11}\eta^4+c_{12}\eta^5+$$
$$c_{13}\eta^6+c_{14}\eta^7+c_{15}\eta^8+c_{16}\eta^9+c_{17}\eta^{10} \qquad (18)$$
$$\phi(\eta)=c_{19}+c_{20}\eta+\ c_{21}\eta^2+c_{22}\eta^3+c_{23}\eta^4+c_{24}\eta^5+$$
$$c_{25}\eta^6+c_{26}\eta^7+c_{27}\eta^8+c_{28}\eta^9+c_{29}\eta^{10}$$

K is the Boltzmann constant (K=1.3807×10^{-23} *J/K*). In model of Li-Kleinstreuer $K_{Brownian}$ is [20]:

$$\int_{R=0}^{1}\eta\,\mathrm{Re}(c_0,c_1,\ c_2,c_3\ ,c_4,c_5,c_6,\eta)\,dR=0 \qquad (19a)$$

$$\int_{R=0}^{1}\eta\ \mathrm{Re}(c_7,c_8,c_9\ ,c_{10},c_{11},c_{12},c_{13},c_{14},c_{15},c_{16},c_{17},\eta)\,dR=0 \qquad (19b)$$

$$\int_{R=0}^{1}\eta\ \mathrm{Re}(c_{18},\ c_{19},c_{20}\ ,c_{21},c_{22},c_{23},c_{24},c_{25},c_{26},c_{29},\eta)\,dR=0 \qquad (19c)$$

Including another equation from boundary condition equation 11 we have thirty algebraic equations that provide the unknown coefficients C_0,C_1…C_{29}. By introducing these coefficients into equation (8,9,10), temperature ,concentration and base fluid distribution equations will be determined. For (Ha=2, Sc=0.5, Ec=0.1, S=0.5, Pr=10, Nt=0.1, Nb=0.1) The base fluid, temperature andconcentrationfunctions are respectively:

$$f(\eta)=1.388557\eta-0.277852\eta^3-0.113178\eta^4+$$
$$0.0419559\eta^5-0.066505\eta^6 \qquad (20a)$$

$$\theta(\eta)=1.50396+0.05907\eta^2-0.51627\eta^3+$$
$$2.16618\eta^4-6.37084\eta^5+9.66760\eta^6 \qquad (20b)$$
$$-8.60040\eta^7+3.55484\eta^8-0.12826\eta^9-0.33633\eta^{10}$$

$$\phi(\eta)=0.49858-0.05887\eta^2+0.50616\eta^3-$$
$$2.04233\eta^4+5.73434\eta^5-7.93510\eta^6+5.86772\eta^7 \qquad (20c)$$
$$-1.05467\eta^8-1.11192\eta^9+0.59609\eta^{10}$$

RESULTS AND DISCUSSION

In this paper, nanofluid flow and heat transfer among moving parallel plates is studied. The effects of important parameters on heat and mass specifications are investigated. The present GM code is validated by comparing the obtained results with Mustafa et al. [20]. As it is shown in Table 1, the results are in a very good agreement.

Table 1
Comparison between the present work and Mustafa et al [20].

S	Mustafa et al. [20]	present work	Mustafa et al. [20]	present work
	-f″(1)	- f″(1)	- θ′(1)	- θ′(1)
1.0	2.170090	2.17009125	3.319899	3.31987581
−0.5	2.614038	2.61412563	3.129491	– 3.12939564
0.01	3.007134	3.00713256	3.047092	3.04702323
0.5	3.336449	3.33645265	3.026324	3.02636583
2.0	4.167389	4.16738421	3.118551	3.11857344

Effect of the Hartmann number and squeeze number on the velocity profiles and skin friction coefficient is shown in Figure 2.

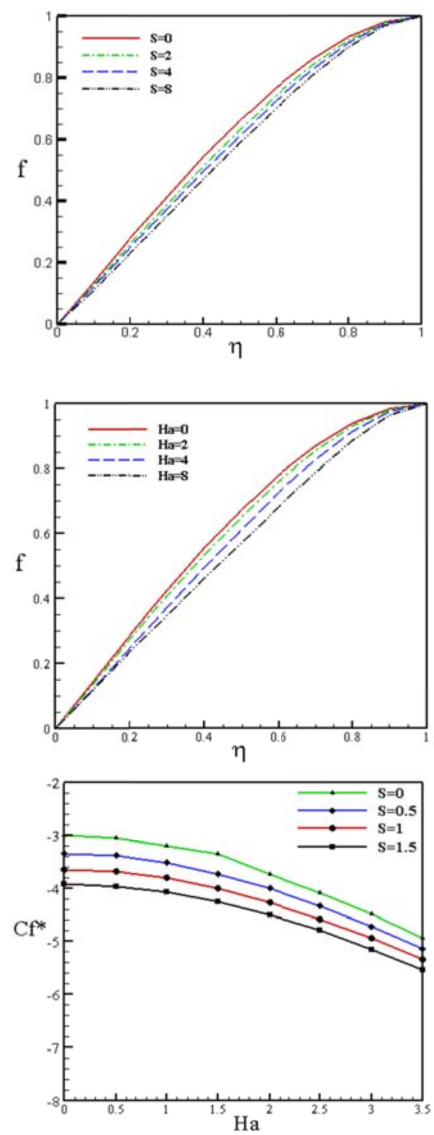

Fig. 2. Effect of the squeeze number and Hartmann number on the velocity profiles and skin friction coefficient in a constant Reynolds Numberand Ha = 2, S=0.5

It is important to mention that the squeeze number S characterizes the motion of the plates. S > 0 is related to the plates moving separate, and S < 0 is related to the plates moving together (that called squeezing flow). In this paper positive values of squeeze number are attended. As squeeze number increases, horizontal velocity reduces slightly. It is valuable noting that the effect of magnetic field is reducing the value of the velocity all over the enclosure because the presence of magnetic field defines a force that is called the Lorentz force and acts against the flow if the magnetic field is applied in the normal direction. This is a resisting force that slows down the fluid velocity and consequently reduces the skin friction coefficient. At a constant Reynolds number, by increasing the Hartmann number , the fluid momentum force is collated with a resisting Force ineffective on velocity value so skin friction coefficient value increases. Figure 3 shows the effect of the squeeze number and Hartmann number on the temperature profile and Nusselt number.

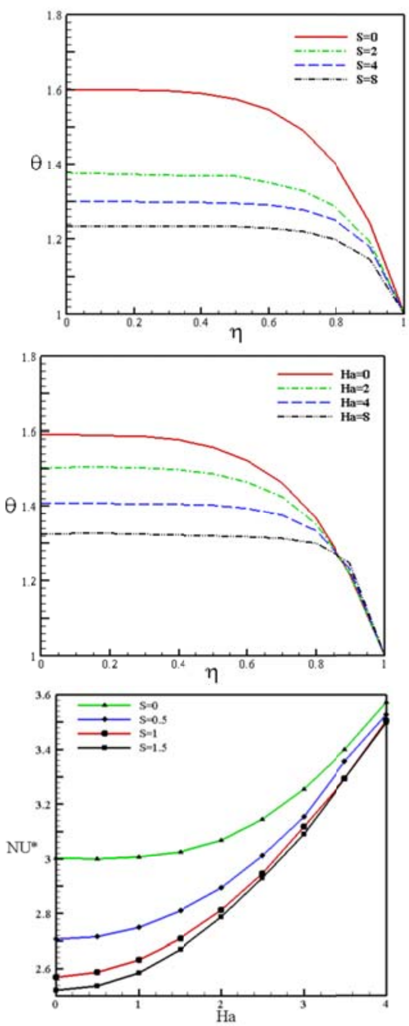

Fig. 3. Effect of the squeeze number and Hartmann number on the temperature profile and Nusselt number for Ec = 0.1, Nt = 0.1, Nb = 0.1, Sc = 0.5 and Pr = 10

An increment in the squeeze number ψ can be relevant to the reduction in the kinematic viscosity, an increment in the distance of plates or an increment in the speed at which the plates move. Temperature grows as the squeeze number and Hartmann number increase. Thus Nusselt number increases with an increment in Hartmann number and squeeze number. Effect of the squeeze number and Hartmann number on the concentration profile is shown in Figure 4. The concentration profile increases with an increment in squeeze number and Hartmann number when $\eta < 0.5$ while it conversely decreases with increasing of these parameters for $\eta > 0.5$.

Effect of Eckert number on the Nusselt number and temperature profile is depicted in Figure 5. considering viscous dissipation effects significantly increases the temperature. Nusselt number increases with an increment in the Eckert number because of the reduction in thermal boundary layer thickness near the upper plate.

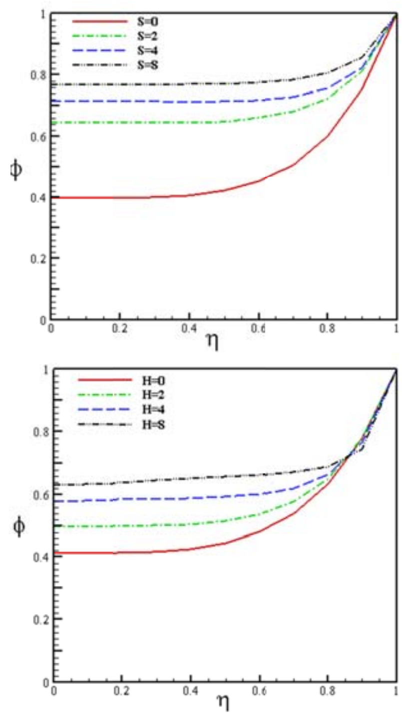

Fig. 4. Effect of the squeeze number and Hartmann number on the concentration profile when Nt = Nb = 0.1, Ha = 2, S = 0.5, Sc = 0.5 and Pr = 10

CONCLUSIONS

Unsteady two phase heat transfer and flow of nanofluid in the presence of MHD is analytically investigated in this paper .The significant effect of thermophoresis and Brownian motion have been contained in the model. GM is used to solve the governing equations. The effects of the Hartmann number, squeeze number, Brownian motion, Schmidt number, thermophoretic parameter and Eckert number on the temperature and concentration profiles are studied. The results indicated that skin friction coefficient reduces with increasing squeeze number and Hartmann number. Also it can be found that the Nusselt number enhances with an increment in the Schmidt number Eckert number and Hartmann number, but it reduces with increasing squeeze number.

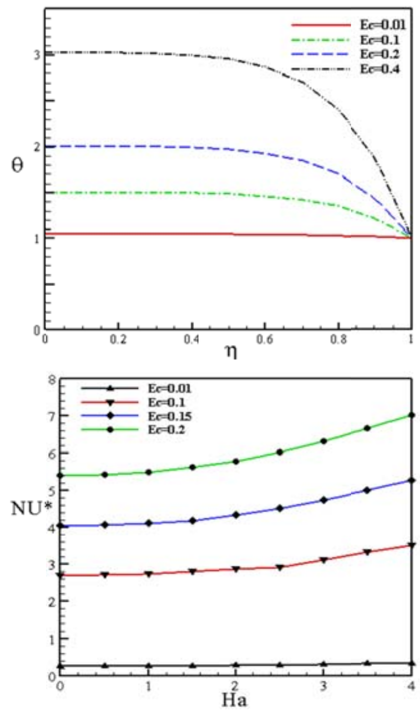

Fig. 5. Effect of Eckert number on the temperature profile and Nusselt number when Nt = Nb = 0.1, Ha = 2, S = 0.5, Sc = 0.5 and Pr = 10

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