Columbia International Publishing
American Journal of Heat and Mass Transfer
(2017) Vol. 4 No. 1 pp. 53-63
doi:10.7726/ajhmt.2017.1004
Research Article

Effects of Soret, Dufour, Variable Viscosity and Variable Thermal Conductivity on Unsteady Free Convective Flow Past a Vertical Cone

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Received: 18 September 2016; Published online: 4 February 2017

Abstract

In this paper investigation have been carried out on Soret and Dufour effects, variable viscosity and variable thermal conductivity effects on unsteady free convective flow past a vertical cone. Here a mathematical model is considered on unsteady free convective flow over an incompressible fluid past a vertical cone with nonuniform surface temperature and concentration. The governing partial differential equations are altered into dimensionless form, and then solved numerically by an iterative technique based on finite difference scheme. The velocity, the temperature and the concentration profile have been drawn for various values of Soret number, Dufour number, time, viscosity parameter and thermal conductivity parameter. The local skin friction is also studied for various parameters.

Keywords: Soret effect; Dufour effect; Variable viscosity; Variable thermal conductivity; Vertical cone; Finite difference method

1. Introduction

Free convection flow occurs frequently in nature because of temperature difference and also concentration difference. Natural convection is important in industrialized process for the design of reliable equipment, for power plant, space vehicles, combustion turbines and various propulsion devices for aircrafts. Prasad et. al. (2011) analyzed numerically unsteady free convection heat and mass transfer over a walters- B viscoelastic flow past a semi infinite vertical plate. Mohiddin et. al. (2012) carried out the numerical study of free convection flow past a vertical cone with variable heat and mass flux. Pullepu et. al. (2014) discussed the chemical reactions effects on unsteady free convective and mass transfer flow on a vertical cone by heat generation/absorption in presence of variable wall temperature or variable wall concentration. Reddy et. al. (2015) discussed the effects

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of chemical reaction and radiation on MHD free convection flow with viscous dissipation on spontaneously started infinite vertical plate. Sivaraj et. al. (2015) studied the variable electric conductivity and chemical reaction effects on free convection flow over a vertical cone. Pullepu et. al. (2016) studied the effects of chemical reaction and heat generation/absorption on free convective flow from a vertical cone in presence of uniform wall temperature / uniform wall concentration.

The Soret and Dufour effects are important in higher temperature and concentration gradients. Cheng (2010) discussed the Soret and Dufour effects by natural convection from a vertical truncated cone saturated in porous medium with variable wall temperature or variable wall concentration. The effects of Soret and Dufour on natural convection flow on a vertical cone in a porous medium by constant wall heat and mass fluxes has been studied by Cheng (2011). Moorthy and Vadivu (2012) considered the variable viscosity to study Soret and Dufour effects on natural convection flow through a vertical surface inside a porous medium. Mahdy et. al. (2014) considered the Soret and Dufour effects on non Darcian natural convection flow from a vertical wavy surface surrounded by a porous medium. Babu et. al. (2015) considered chemical reaction to study Soret and Dufour effects on hydromagnetic free convective flow past an infinite vertical permeable plate. Arthur et. al. (2015) analyzed analytically Soret and Dufour effects on hydromagnetic flow past a vertical plate surrounded by porous medium. Herwig and Gersten (1990) recognized that when the viscosity and the thermal conductivity of a running fluid are sensitive to the variation of temperature then these properties may change with temperature. Chiam (1998) discussed the variable thermal conductivity effect over a linearly stretching sheet. Pantokratoras (2004) investigated further results of the variable viscosity on a continuous moving flat plate. Salem (2007) discussed variable viscosity and thermal conductivity effects on MHD flow with viscoelastic fluid on a stretching sheet. Manjunatha and Gireesha (2016) studied the variable viscosity and the thermal conductivity effects on MHD flow and heat transfer of a dusty fluid.

Pullepu et. al. (2014) in their study has not taken account of Soret and Dufour effects which are considered in the present study.

2. Mathematical Formulation of the Problem

Consider an incompressible unsteady laminar free convection flow past a vertical cone, where the x' axis is considered along the surface of the cone, y' axis is considered along the normal to the cone and the radius of the cone is r' as shown in Fig. 1. It is also considered that the surface of the cone and the adjacent fluid are at the same temperature $T_\infty{}'$ and concentration $C_\infty{}'$. When $t' > 0$, the temperature of the cone surface is raised to $T_w{}'(x) = T_\infty{}' + ax'^n$ and concentration near the surface is also raised to $C_w{}'(x) = C_\infty{}' + bx'^m$ where, n is surface temperature power law exponent and m is surface concentration power law exponent. Let, u' and v' be the velocity components in x' and y' directions. The viscosity and thermal conductivity are taken as inverse linear function of temperature,

$$\left.\begin{aligned} \frac{1}{\mu} = \frac{1}{\mu_\infty}[1+\gamma(T' - T_\infty')] \text{ or } \mu = \frac{\mu_\infty}{[1+\gamma(T'-T_\infty')]} = \frac{\mu_\infty}{[1+\gamma\theta(T_w'-T_\infty')]} = \frac{\mu_\infty}{(1+\epsilon\theta)} \\ \frac{1}{k} = \frac{1}{k_\infty}[1+\beta(T' - T_\infty')] \text{ or } k = \frac{k_\infty}{[1+\beta(T'-T_\infty')]} = \frac{k_\infty}{[1+\beta\theta(T_w'-T_\infty')]} = \frac{k_\infty}{(1+\omega\theta)} \end{aligned}\right\} \quad (1)$$

where $\epsilon = \gamma(T_w' - T_\infty')$, $\omega = \beta(T_w' - T_\infty')$, μ is the coefficient of viscosity, μ_∞ is the reference viscosity, k is the thermal conductivity , k_∞ is the reference thermal conductivity, γ and β are the constants.

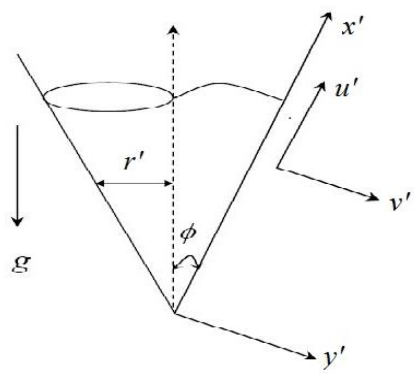


Fig. 1. Physical configuration and coordinate system

The governing equations are

$$\frac{\partial(r'u')}{\partial x'} + \frac{\partial(r'v')}{\partial y'} = 0 \quad (2)$$

$$\frac{\partial u'}{\partial t'} + u'\frac{\partial u'}{\partial x'} + v'\frac{\partial u'}{\partial y'} = g\beta_T(T' - T_\infty')cos\varphi + \frac{1}{\rho}\frac{\partial}{\partial y'}\left(\mu\frac{\partial u'}{\partial y'}\right) + g\beta_C(C' - C_\infty')cos\varphi - \frac{\sigma {B_0}^2 u'}{\rho} \quad (3)$$

$$\frac{\partial T'}{\partial t'} + u'\frac{\partial T'}{\partial x'} + v'\frac{\partial T'}{\partial y'} = \frac{1}{\rho C_P}\frac{\partial}{\partial y'}\left(k\frac{\partial T'}{\partial y'}\right) + \frac{D_m k_t}{C_S C_p}\frac{\partial^2 C'}{\partial y'^2} \quad (4)$$

$$\frac{\partial C'}{\partial t'} + u'\frac{\partial C'}{\partial x'} + v'\frac{\partial C'}{\partial y'} = D_m\frac{\partial^2 C'}{\partial y'^2} + \frac{D_m k_t}{T_m}\frac{\partial^2 T'}{\partial y'^2} \quad (5)$$

where g is acceleration due to gravity, β_T , β_C are the coefficient of thermal expansion and concentration expansion, T_m is the mean fluid temperature, C_p is the specific heat at constant pressure, C_S is the concentration susceptibility, D_m is the molecular diffusivity, k_t is thermal diffusion ratio.

The corresponding initial and boundary conditions are

$$\left.\begin{array}{ll} t' \le 0: u'=0, v'=0, T'=T_\infty', C'=C_\infty' & \forall\, x', y' \\ t' > 0: u'=0, v'=0, T'=T_\infty'+ax'^n, \quad C'=C_\infty'+bx'^m & \text{at } y'=0 \\ \quad u'=0, T'=T_\infty', C'=C_\infty' & \text{at } x'=0 \\ \quad u'\to 0, \; T'\to T_\infty', C'\to C_\infty' & \text{as } y'\to\infty \end{array}\right\} \quad (6)$$

The local skin friction τ is defined as $\tau = \mu(\frac{\partial u'}{\partial y'})_{\,y=0}$

Introducing the non dimensional quantities

$$\left.\begin{array}{l} x'=xL,\ y'=yL(Gr)^{\frac{-1}{4}},\ r'=rL,\ v'=\frac{v\nu_\infty(Gr)^{\frac{1}{4}}}{L},\ u'=\frac{u\nu_\infty(Gr)^{\frac{1}{2}}}{L},\ t'=\frac{tL^2(Gr)^{\frac{-1}{2}}}{\nu_\infty},\ \theta=\frac{T'-T_\infty'}{T_w'-T_\infty'}, \\ \varphi=\frac{C'-C_\infty'}{C_w'-C_\infty'},\ M=\frac{\sigma B_0^2L^2(Gr)^{\frac{-1}{2}}}{\rho\nu_\infty},\ Gr=\frac{g\beta_T(T_w'-T_\infty')L^3\cos\varphi}{\nu_\infty^2},\ Sc=\frac{\nu_\infty}{D_m},\ Pr=\frac{\nu_\infty}{\alpha_\infty},\ N=\frac{Gm}{Gr}, \\ Gm=\frac{g\beta_C(C_w'-C_\infty')L^3\cos\varphi}{\nu_\infty^2},\ Sr=\frac{D_mk_t(T_w'-T_\infty')}{T_m\nu_\infty(C_w'-C_\infty')},\quad Du=\frac{D_mk_t(C_w'-C_\infty')}{C_SC_P\nu_\infty(T_w'-T_\infty')} \end{array}\right\} \quad (7)$$

and using eqs.(1) and (7) in eqs. (2) – (6), we get

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \quad (8)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\theta+\left(\frac{1}{1+\epsilon\theta}\right)\frac{\partial^2 u}{\partial y^2}-\frac{\epsilon}{(1+\epsilon\theta)^2}\frac{\partial u}{\partial y}\frac{\partial\theta}{\partial y}+N\varphi-Mu, \quad (9)$$

$$\frac{\partial\theta}{\partial t}+u\frac{\partial\theta}{\partial x}+v\frac{\partial\theta}{\partial y}=\frac{1}{Pr}\left(\frac{1}{1+\omega\theta}\right)\frac{\partial^2\theta}{\partial y^2}-\frac{1}{Pr}\frac{\omega}{(1+\omega\theta)^2}\left(\frac{\partial\theta}{\partial y}\right)^2+Du\frac{\partial^2\varphi}{\partial y^2} \quad (10)$$

and

$$\frac{\partial\varphi}{\partial t}+u\frac{\partial\varphi}{\partial x}+v\frac{\partial\varphi}{\partial y}=\frac{1}{Sc}\frac{\partial^2\varphi}{\partial y^2}+Sr\frac{\partial^2\theta}{\partial y^2}. \quad (11)$$

The initial and boundary conditions becomes

$$\left.\begin{array}{lll} t\le 0: & u=0, v=0, \theta=0, \varphi=0 & \forall\ x, y; \\ t>0: & u=0, v=0, \theta=1, \varphi=1 & \text{at } y=0, \\ & u=0, \theta=0, \varphi=0 & \text{at } x=0 \\ \text{and} & u\to 0, \theta\to 0, \varphi\to 0 & \text{as } y\to\infty. \end{array}\right\} \quad (12)$$

Using the non dimensional quantities, the local skin friction becomes $\tau = (Gr)^{\frac{3}{4}}(\frac{\partial u}{\partial y})_{y=0}$

3. Method of Solution

Equations (8) - (11) are dimensionless partial differenential equations subject to the initial and boundary conditions (12) are reduced to a system of difference equations using this finite difference scheme $\frac{\partial u}{\partial y} = \frac{u^{i+1}{}_{j,n} - u^{i}{}_{j,n}}{\Delta y}$, $\frac{\partial^2 u}{\partial y^2} = \frac{u^{i+1}{}_{j,n} + u^{i-1}{}_{j,n} - 2u^{i}{}_{j,n}}{(\Delta y)^2}$ and then the system of difference equations is solved numerically by an iterative method.

The finite difference scheme of equations (8)- (11) as follows

$$\frac{u(i+1,j,n) - u(i,j,n)}{dx} + \frac{v(i,j+1,n) - v(i,j,n)}{dy} = 0, \tag{13}$$

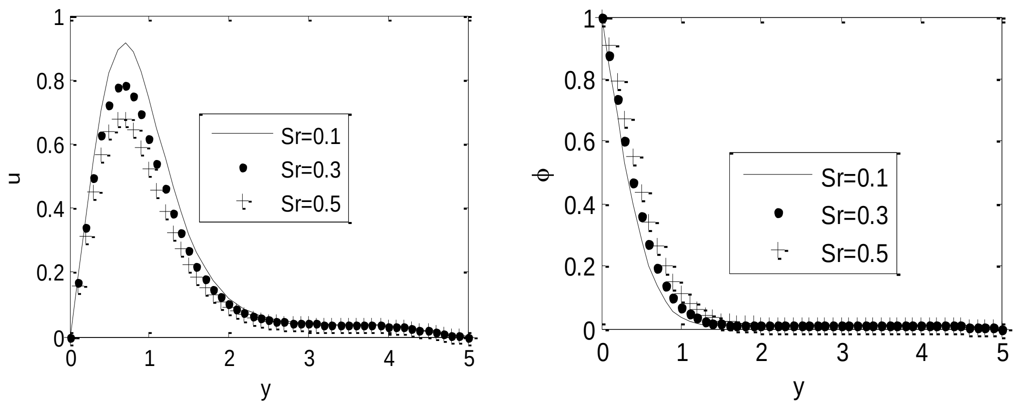
$$\frac{u(i,j,n+1) - u(i,j,n)}{dt} + u(i,j,n)\frac{u(i+1,j,n) - u(i,j,n)}{dx} + v(i,j,n)\frac{u(i,j+1,n) - u(i,j,n)}{dy} = \theta(i,j,n) + \frac{1}{(1+\epsilon\theta(i,j,n))}\left(\frac{u(i,j+1,n) - 2u(i,j,n) + u(i,j-1,n)}{(dy)^2}\right) - \frac{\epsilon}{(1+\epsilon\theta(i,j,n))^2}\frac{\left(u(i,j+1,n) - u(i,j,n)\right)\left(\theta(i,j+1,n) - \theta(i,j,n)\right)}{(dy)^2} + N\varphi(i,j,n) - M\,u(i,j,n), \tag{14}$$

$$\frac{\theta(i,j,n+1) - \theta(i,j,n)}{dt} + u(i,j,n)\frac{\theta(i+1,j,n) - \theta(i,j,n)}{dx} + v(i,j,n)\frac{\theta(i,j+1,n) - \theta(i,j,n)}{dy} = \frac{1}{Pr}\frac{1}{(1+\omega\theta(i,j,n))}\left(\frac{\theta(i,j+1,n) - 2\theta(i,j,n) + \theta(i,j-1,n)}{(dy)^2}\right) - \frac{1}{Pr}\frac{\omega}{(1+\omega\theta(i,j,n))^2}\frac{\theta(i,j+1,n) - \theta(i,j,n)}{dy} + Du\left(\frac{\varphi(i,j+1,n) - 2\varphi(i,j,n) + \varphi(i,j-1,n)}{(dy)^2}\right), \tag{15}$$

$$\frac{\varphi(i,j,n+1) - \varphi(i,j,n)}{dt} + u(i,j,n)\frac{\varphi(i+1,j,n) - \varphi(i,j,n)}{dx} + v(i,j,n)\frac{\varphi(i,j+1,n) - \varphi(i,j,n)}{dy} = \frac{1}{Sc}\left(\frac{\varphi(i,j+1,n) - 2\varphi(i,j,n) + \varphi(i,j-1,n)}{(dy)^2}\right) + \left(\frac{\theta(i,j+1,n) - 2\theta(i,j,n) + \theta(i,j-1,n)}{(dy)^2}\right). \tag{16}$$

4. Results and Discussion

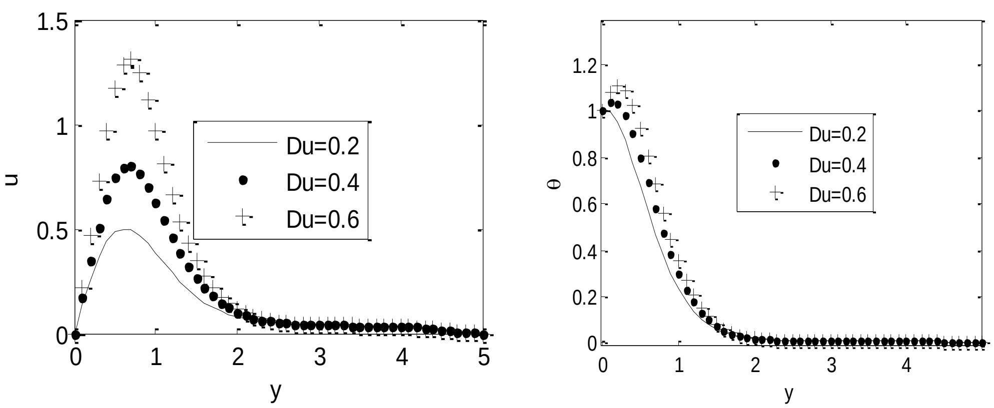
Figs. 2 (a)–(b) exhibit the velocity and concentration profiles for various values of *Sr*=(0.1, 0.3, 0.5), by taking *Du*=0.4, *Pr*= 0.71, *Sc*=0.6, *M*=1, $\omega = 0.1$, *N*=1, *t*=0.2, ϵ=0.1. From Fig. 2 (a) it is observed that velocity decreases with increase in *Sr* and also noticed that velocity increases for *y* less than 1, attains the maximum value at about *y*=1 and then decreases exponentially towards the end of the boundary layer. From Fig. 2 (b) it is clear that concentration decreases exponentially from the maximum value at the surface to the minimum value at the end of boundary layer and also noticed that concentration increases with increase in *Sr.* Increase in *Sr* leads to increase in concentration as a result of greater mass diffusivity. Higher mass diffusivity represents greater probability of molecular collision which is the result of large difference in concentration. Higher the concentration gradient increases the difference in concentration of molecules. It can be inferred that increase in mass diffusivity increases concentration gradient resulting in increased concentration.



(a) (b)

Fig. 2. Effects of Soret number on (a) velocity profile (b) concentration profile

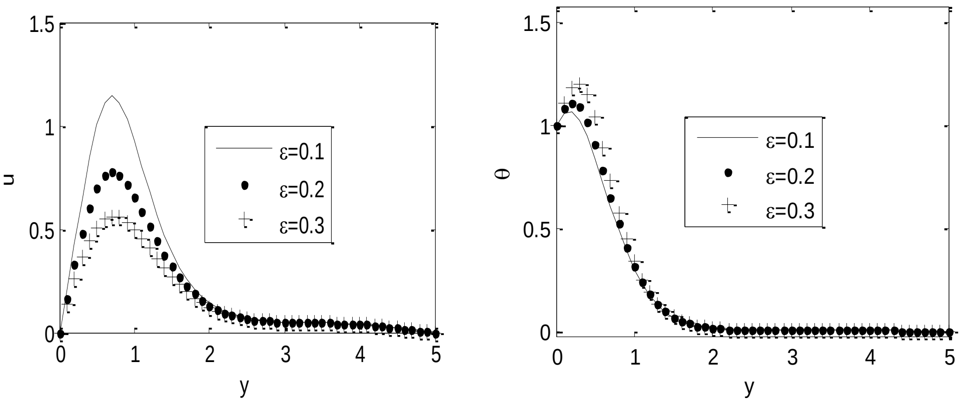
Figs. 3 (a) – (b) exhibit the velocity and temperature profiles for various values of *Du*=(0.2, 0.4, 0.6), by taking *Sr*=0.5, *Pr*= 0.71, *Sc*=0.6, *M*=1, *t*=0.2, $\omega = 0.1$, *N*=1, ϵ=0.1. From Fig. 3 (a) It is noticed that velocity increases with increase in *Du*. From Fig. 3 (b) it is observed that temperature increases with increase in *Du*. Increase in *Du* leads to enhance the temperature as a result of greater thermal diffusivity. As thermal diffusivity increases, thermal conductivity rises which leads to increase in molecular vibrations as a result temperature increases. This result was co-incide in case of air only.



(a) (b)

Fig. 3. Effects of Dufour number on (a) velocity profile (b) temperature profile

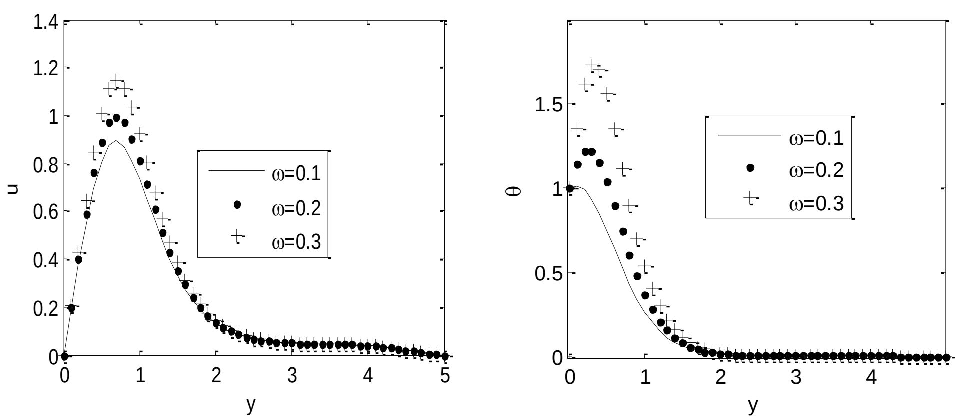
Figs. 4 (a) – (b) exhibit that the velocity and temperature profiles for various values of ϵ = (0.1, 0.2, 0.3), by taking *Sr*=0.5, *Pr*= 0.71, *Sc*=0.6, *M*=1, $\omega = 0.1$, *N*=1, *t*=0.2, *Du*=0.4. It is observed that velocity decreases and temperature increases as ϵ increases. Increase in the values of ϵ causes fall in velocity as a result of greater viscosity. Increase in the values of ϵ also causes rise in temperature because in case of air, when viscosity increases the cohesive forces between the molecules are less, whereas the molecular momentum transfer is high, resulting in increase in temperature.



(a) (b)

Fig. 4. Effects of viscosity parameter on (a) velocity profile (b) temperature profile

Figs. 5 (a) – (b) exhibit the velocity and temperature profiles for various values of ω = (0.1, 0.2, 0.3), by taking Sr=0.5, Pr= 0.71, Sc=0.6, M=1, N=1, t=0.2, Du=0.4, ϵ=0.1. It is observed that velocity and temperature both increases as ω increases. When thermal conductivity increases the heat transfer increases hence temperature increases.



(a) (b)

Fig. 5. Effects of thermal conductivity parameter on (a) velocity profile (b) temperature profile

Fig. 6 exhibits the temperature profile for various values of t = (0.5, 0.6, 0.7), by taking Sr=0.5, Pr= 0.71, Sc=0.6, M=1, N=1, Du=0.4, ϵ=0.1, $\omega = 0.1$. It is observed that temperature increases as t increases. Fig. 7 exhibits the velocity profile for various value of M= (1, 2, 3), by taking Sr=0.5, Pr= 0.71, Sc=0.6, t=0.2, N=1, Du=0.4, ϵ=0.1, $\omega = 0.1$. It is noticed that velocity decreases as M increases.

Application of magnetic field to the flow direction gives rise a Lorentz force which produces more reduction in velocity field.

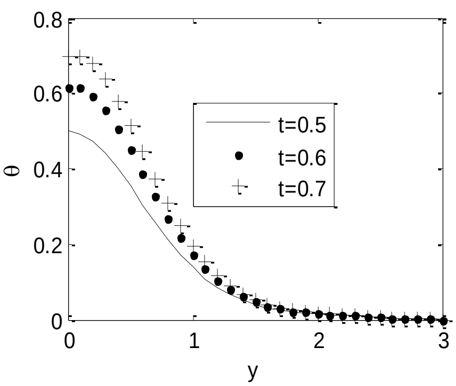


Fig. 6. Effects of time on temperature profile

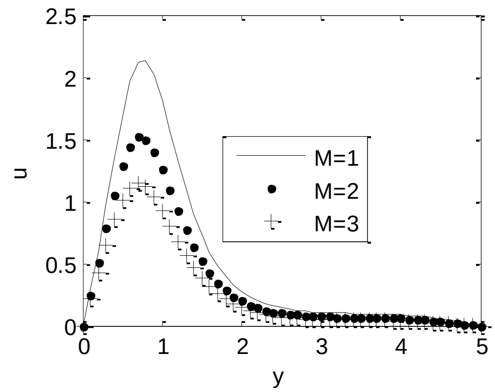


Fig. 7. Effects of magnetic parameter on velocity profile

From Fig. 8 it can be seen that local skin friction decreases by decreasing Soret number and increasing Schmidt number. From Fig. 9 it can be seen that local skin friction decreases by increasing Dufour number and Prandtl number.

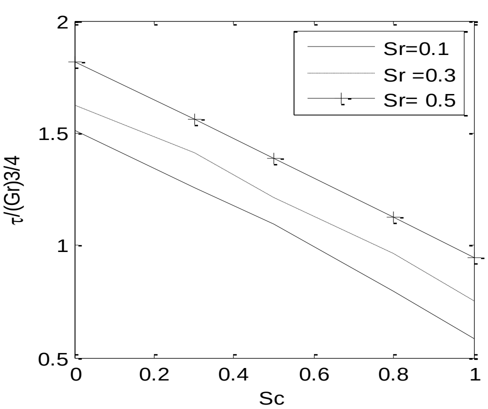


Fig. 8. Effects of *Sr* on Skin friction with various value of *Sc*

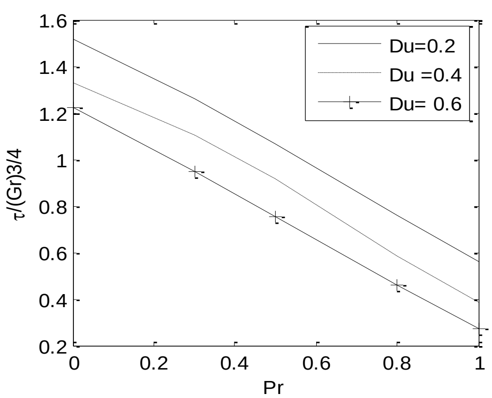


Fig. 9. Effects of *Du* on Skin friction with various value of *Pr*

From Fig. 10 it can be seen that local skin friction increases by increasing viscosity parameter and increasing Magnetic parameter. From Fig. 11 it can be seen that local skin friction decreases with the decreasing thermal conductivity parameter and increasing Prandtl number.

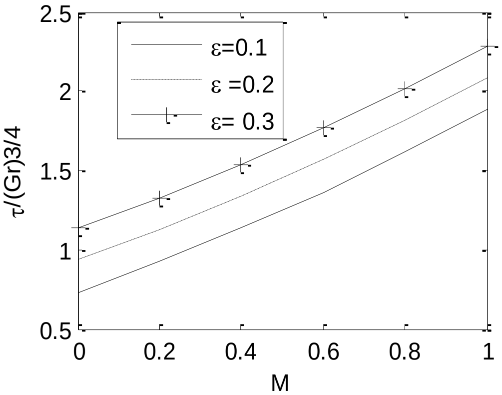


Fig. 10. Effects of ϵ on skin friction with various value of M

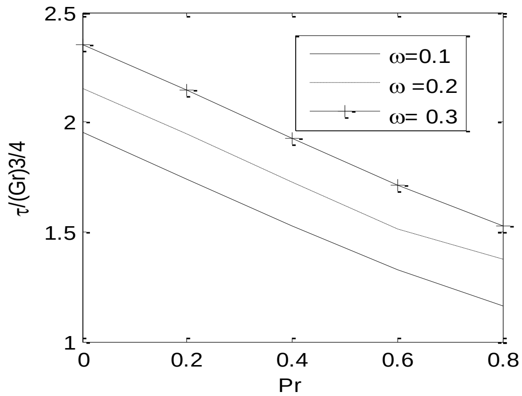


Fig. 11. Effects of ω on Skin friction with various value of *Pr*

Comparison of values of steady – state local skin friction with those of Pullepu (2014) for vertical cone, for various values of *Pr*, when $Sr=0$, $Du=0$, $\epsilon=0$, $\omega=0$ and M =0 is given below :

Pr	Pullepu (2014)	Present result
0.001	1.4149	1.4321
0.01	1.3356	1.3537
0.1	1.0911	1.0936
1	0.7688	0.7691
10	0.4856	0.4873
100	0.2879	0.2883
1000	0.1637	0.1649

5. Conclusion

- The velocity decreases and concentration increases with the increase of Soret number.
- The velocity and tempearture increases with the increase of Dufour number.
- The velocity decreases and tempearture increases with the increase of viscosity parameter.
- The velocity and temperature increases with the increase of thermal conductivity parameter.
- The velocity decreases with the increase of magnetic parameter and temperature increases with increase of time.
- The local skin friction decreases with the decrease of Soret number and increase of Schmidt number.
- The local skin friction decreases with the increase of Dufour number and Prandtl number.

- The local skin friction increases with the increase of viscosity parameter and increase of Magnetic parameter.
- The local skin friction decreases with the decrease of thermal conductivity parameter and increasing Prandtl number.

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