Chemical Engineering Communications
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gcec20

UNSTEADY LAMINAR FREE CONVECTION FLOW PAST A NON-ISOTHERMAL VERTICAL CONE IN THE PRESENCE OF A MAGNETIC FIELD

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Available online: 19 Jan 2012

Chem. Eng. Comm., 199:354–367, 2012

ISSN: 0098-6445 print/1563-5201 online
DOI: 10.1080/00986445.2011.592443

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Unsteady Laminar Free Convection Flow past a Non-Isothermal Vertical Cone in the Presence of a Magnetic Field

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An analysis is performed to study the effects of unsteady incompressible flow past a vertical cone with variable surface temperature $T'_w(x) = T'_\infty + ax^n$ *varying as a power function of distance from the apex* ($x = 0$) *and magnetic field applied normal to the surface. The dimensionless coupled partial differential boundary layer equations are solved numerically using an efficient and unconditionally stable finite-difference scheme of the Crank-Nicolson type. The velocity and temperature fields have been studied for various combinations of physical parameters (Prandtl number, Pr, exponent in power law variation in surface temperature,* n, *and magnetic field parameter, M). The local as well as average skin friction and Nusselt number are also presented and analyzed graphically. The present results are compared with available results in the literature and are found to be in good agreement.*

Keywords Finite difference method; Free convection; MHD flow; Unsteady; Variable surface temperature; Vertical cone

Introduction

Natural convection flows under the influence of gravitational force have been investigated extensively because they occur frequently in nature as well as in science and engineering applications. When a heated surface is in contact with the fluid, the result of temperature difference causes a buoyancy force, which induces natural convection. From a technological point of view, the study of convection heat transfer from a cone is of special interest and has a wide range of practical applications. Mainly, these types of heat transfer problems deal with the design of spacecraft, nuclear reactors, solar power collectors, power transformers, steam generators, etc. Since 1953, many investigations (Merk and Prins, 1953, 1954; Hering and Grosh, 1962; Hering, 1965; Roy, 1974; Gorla and Startman, 1986; Alamgir, 1989; Pop and Takhar, 1991; Hossain and Paul, 2001a, 2001b; Pop et al., 2003; Takhar et al., 2004; Alam et al., 2007) have developed similarity/nonsimilarity solutions for axi-symmetrical problems for natural convection flows over a vertical cone in steady state. Pullepu and

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Ekambavanan (2006) have numerically studied the solutions of unsteady flows past plane/axi-symmetrical shape bodies. Also, Pullepu et al. (2007, 2008a, 2008b) numerically studied the problem of transient natural convection from a vertical cone with isothermal, non-isothermal surface temperature, or nonuniform surface heat flux using an implicit finite-difference method. All these investigations deal with the absence of the magnetohydrodynamic (MHD) field effect.

The MHD flow and heat transfer situation is of considerable interest because it can occur in many geothermal, geophysical, technological, and engineering applications such as nuclear reactors, migration of moisture through air contained in fibrous insulations, grain storage, nuclear waste disposal, dispersion of chemical pollutants through water-saturated soil, and others. Geothermal gases are electrically conducting and are affected by the presence of a magnetic field. Vajravelu and Nayfeh (1992) studied hydromagnetic convection from a cone and a wedge with variable surface temperature and internal heat generation or absorption. Chamkha (2001) considered the problem of steady-state, laminar heat, and mass transfer by natural convection boundary layer flow around a permeable truncated cone in the presence of a magnetic field and thermal radiation effects; nonsimilar solutions were obtained and solved numerically by an implicit finite-difference methodology, and the authors concluded that, in general, all of the local skin friction coefficients, local Nusselt number, and local Sherwood number reduced as the magnetic Hartmann number increased. Takhar et al. (2003) developed the problem of unsteady mixed convection flow over a vertical cone rotating in an ambient fluid with a time-dependent angular velocity in the presence of a magnetic field. The coupled nonlinear partial differential equations governing the flow were solved numerically using an implicit finite-difference scheme. Afify (2004) studied the effects of radiation and chemical reaction on steady free convective flow and mass transfer of an optically dense viscous, incompressible, and electrically conducting fluid past a vertical isothermal cone in the presence of a magnetic field. Similarity solutions were numerically solved by using a fourth-order Runge-Kutta scheme with the shooting method. Later, Chamkha and Al-Mudhaf (2005) focused on the study of unsteady heat and mass transfer by mixed convection flow over a vertical permeable cone rotating in an ambient fluid with time-dependent angular velocity in the presence of a magnetic field and heat generation or absorption effects with the cone surface maintained at variable temperature and concentration. Numerical solutions were obtained by solving the partial differential equations using an implicit, iterative, finite-difference scheme. El-Kabeir and Abdou (2007) studied chemical reaction and heat and mass transfer on MHD flow over a vertical isothermal cone surface in micropolar fluids with heat generation and absorption. Numerical solutions were obtained by using the fourth-order Runge-Kutta method with shooting technique.

MHD free convective flow through a porous medium has important applications in natural sciences, geophysics, and engineering and has received a great deal of attention in the past decades due to its wide applications. This type of flow is of great importance to the petroleum engineer concerned with the movement of oil, gas, and water through the reservoir of an oil or gas field, as well as for hydrologists in the study of migration of underground water and to chemical engineers for filtration processes. Beyond this, this type of flow is widely applicable in soil mechanics, water purification, ceramic engineering, and powder metallurgy. Examples of some applications include drying of porous solids, thermal insulation, enhanced oil recovery, packed-bed catalytic reactors, and many others. MHD free convective flow through a nonhomogeneous porous medium over an isothermal cone was reported by Kafoussias (1992). Chamkha (1996) studied the effects of non-Darcy hydromagnetic free convection from a cone and a wedge in porous medium. Later, Chamkha and Quadri (2002) solved the problem of combined heat and mass transfer by hydromagnetic natural convection over a cone embedded in a non-Darcian porous medium with heat generation/absorption effects. A nonsimilar form of the solution was solved numerically by an implicit, iterative, finite-difference method.

To our best knowledge, studies on unsteady laminar free convection flow past a non-isothermal vertical cone in the presence of a magnetic field have not received any attention in the literature. Hence, the present work is devoted to transient laminar free convection flow past a non-isothermal vertical cone in the presence of a magnetic field. The governing boundary layer equations are solved using an implicit finite-difference scheme of the Crank-Nicolson type for various values of Prandtl number, Pr, exponent in power law variation in surface temperature, n, and magnetic parameter, M. In order to check the accuracy of the numerical results, the present results are compared with the available results of Chamkha (1996) and Hossian and Paul (2001a), and they are found to be in excellent agreement.

Mathematical Analysis

A problem of an axi-symmetrical, unsteady, laminar free convection flow past a vertical cone of a viscous incompressible electrically conducting fluid with variable surface temperature under the influence of transversely applied magnetic field is formulated mathematically in this section. The following assumptions concerning the magnetic field are made: (i) the magnetic field is constant and is applied in a direction perpendicular to the cone surface; (ii) the magnetic Reynolds number is small so that the induced the magnetic field is neglected and, therefore, does not distort the magnetic field; (iii) the coefficient of electrical conductivity is a constant and throughout the fluid; (iv) the Joule heating of the fluid (magnetic dissipation) and viscous dissipation are neglected; (v) the Hall effect of magnetohydrodyanamics is neglected; (vi) the system is considered as axi-symmetrical; and (vii) the effect of pressure gradient is assumed negligible.

The coordinate system is chosen (as shown in Figure 1) such that x measures the distance along the surface of the cone from the apex ($x = 0$), and y measures the distance normally outward. Here, ϕ is the semi-vertical angle of the cone and $r(x)$ is the local radius of the cone. Initially ($t' \leq 0$); it is also assumed that the cone surface and the surrounding fluid, which is at rest, have the same temperature T'_∞. Then, at time $t' > 0$, the temperature of the cone surface is suddenly raised to $T'_w(x) = T'_\infty + ax^n$ and is maintained at this value, where a is a positive constant and n is the exponent in power law variation in surface temperature. The fluid properties are assumed constant except for density variations, which induce the buoyancy force term in the momentum equation. The governing boundary layer equations of continuity, momentum, and energy under Boussinesq approximation are as follows:

Equation of continuity:

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

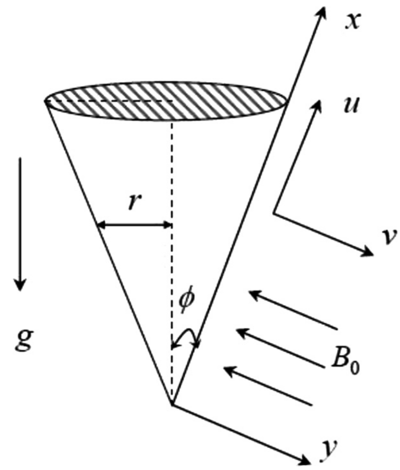

Figure 1. Physical model and coordinate system.

Equation of momentum:

$$\frac{\partial u}{\partial t'} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = g\,\beta\,(T' - T'_\infty)\cos\varphi + \upsilon\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2}{\rho}u \tag{2}$$

Equation of energy:

$$\frac{\partial T'}{\partial t'} + u\frac{\partial T'}{\partial x} + v\frac{\partial T'}{\partial y} = \alpha\frac{\partial^2 T'}{\partial y^2} \tag{3}$$

where u and v are the velocity components along the x- and y-axes, g is the acceleration due to gravity, α is the thermal diffusivity, β is the coefficient of thermal expansion, B_0 is the magnetic field strength, ρ is the density, and σ is the electrical conductivity of the fluid. The initial and boundary conditions are

$$\begin{aligned} &t' \le 0: \quad u = 0, \quad v = 0, \quad T' = T'_\infty \quad \text{for all } x \text{ and } y, \\ &t' > 0: \quad u = 0, \quad v = 0, \quad T'_w(x) = T'_\infty + a x^n \quad \text{at} \quad y = 0, \\ &\qquad u = 0, \quad T' = T'_\infty \quad \text{at} \quad x = 0, \\ &\qquad u \to 0, \quad T' \to T'_\infty \quad \text{as} \quad y \to \infty. \end{aligned} \tag{4}$$

Further, we introduce the following nondimensional variables:

$$\begin{aligned} &X = \frac{x}{L}, \quad Y = \frac{y}{L}Gr^{1/4}, \quad t = t'\left(\frac{\upsilon}{L^2}Gr_L^{1/2}\right) \quad R = \frac{r}{L}, \quad U = u\left(\frac{L}{\upsilon}Gr_L^{-1/2}\right), \\ &V = v\left(\frac{L}{\upsilon}Gr_L^{-1/4}\right), \quad T = \frac{(T' - T'_\infty)}{T'_w(L) - T'_\infty}, \quad M = \frac{\sigma B_0^2 L^2}{\mu}Gr_L^{-1/2} \end{aligned} \tag{5}$$

where M is the magnetic field parameter, L is the length of slant height, μ is the dynamic viscosity, υ is the kinematic viscosity, $Gr_L = g\beta(T'_w(L) - T'_\infty)L^3\cos\phi/\upsilon^2$

is the Grashof number based on L, and $r = x\sin\varphi$. Equations (1)–(3) can then be written in the following nondimensional form:

$$\frac{\partial}{\partial X}(RU) + \frac{\partial}{\partial Y}(RV) = 0, \quad or\left(\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} + \frac{U}{X} = 0\right) \tag{6}$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = T + \frac{\partial^2 U}{\partial Y^2} - MU, \tag{7}$$

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial X} + V\frac{\partial T}{\partial Y} = \frac{1}{\Pr}\frac{\partial^2 T}{\partial Y^2}. \tag{8}$$

where $\mathbf{Pr} = \boldsymbol{\upsilon}/\boldsymbol{\alpha}$ is the Prandtl number.

The corresponding nondimensional initial and boundary conditions are

$$\begin{aligned} &t \le 0: \quad U = 0, \quad V = 0, \quad T = 0 \quad \text{for all } X \text{ and } Y \\ &t > 0: \quad U = 0, \quad V = 0, \quad T = X^n \quad \text{at} \quad Y = 0 \\ &\qquad U = 0, \quad T = 0 \quad \text{at} \quad X = 0 \\ &\qquad U \to 0, \quad T \to 0 \quad \text{as} \quad Y \to \infty. \end{aligned} \tag{9}$$

Once the velocity and temperature profiles are known, it is of interest to study the local as well as the average skin friction and the rate of heat transfer in steady state and transient levels. Thus, the local nondimensional skin friction τ_X and the local Nusselt number Nu_X given by

$$\tau_X = Gr_L^{3/4}\left(\frac{\partial U}{\partial Y}\right)_{Y=0}, \quad Nu_X = \frac{X\,Gr_L^{1/4}}{T_w}\left(-\frac{\partial T}{\partial Y}\right)_{Y=0} \tag{10}$$

Also, the nondimensional average skin friction $\bar{\tau}$ and the average Nusselt number $\overline{Nu}$can be written as

Table I. Comparison of steady-state local skin friction and local Nusselt number values at X = 1.0 with those of Chamkha (2001) for full cone, when $n = 0$ and $M = 0$

$M = 0$	Local skin friction		Local Nusselt number	
$n = 0$	Chamkha (2001)	Present values	Chamkha (2001)	Present values
Pr	$f''(\infty, 0)$	$\tau_X/Gr_L^{3/4}$	$-\theta'(\infty, 0)$	$Nu_X/Gr_L^{1/4}$
0.001	1.5135	1.4149	0.0245	0.0294
0.01	1.3549	1.3356	0.0751	0.0797
0.1	1.0962	1.0911	0.2116	0.2115
1	0.7697	0.7668	0.5111	0.5125
10	0.4877	0.4856	1.0342	1.0356
100	0.2895	0.2879	1.9230	1.9316
1000	0.1661	0.1637	3.4700	3.5186

Table II. Comparison of steady-state local skin-friction and local Nusselt number values at X = 1.0 with those of Hossain and Paul (2001a) when $n = 0.5$ and $M = 0$

	Local skin friction		Local Nusselt number	
$M = 0$ $n = 0.5$	Hossain and Paul (2001a)	Present values	Hossain and Paul (2001a)	Present values
Pr	$f''(0)$	$\tau_X/Gr_L^{3/4}$	$-\theta'(0)$	$Nu_X/Gr_L^{1/4}$
0.01	1.23231	1.2240	0.08828	0.0914
0.05	1.09069	1.0922	0.18300	0.1829
0.1	1.01332	1.0150	0.24584	0.2466

$$\overline{\tau} = 2Gr_L^{3/4}\int_0^1 X\left(\frac{\partial U}{\partial Y}\right)_{Y=0} dX, \quad \overline{Nu} = 2Gr_L^{1/4}\int_0^1 \frac{X}{(T)_{Y=0}}\left(-\frac{\partial T}{\partial Y}\right)_{Y=0} dX. \quad (11)$$

Solution Procedure

The governing partial differential Equations (6)–(8) are unsteady, coupled, and nonlinear with initial and derivative boundary conditions (9). They are solved numerically by an implicit finite-difference method of the Crank-Nicolson type as

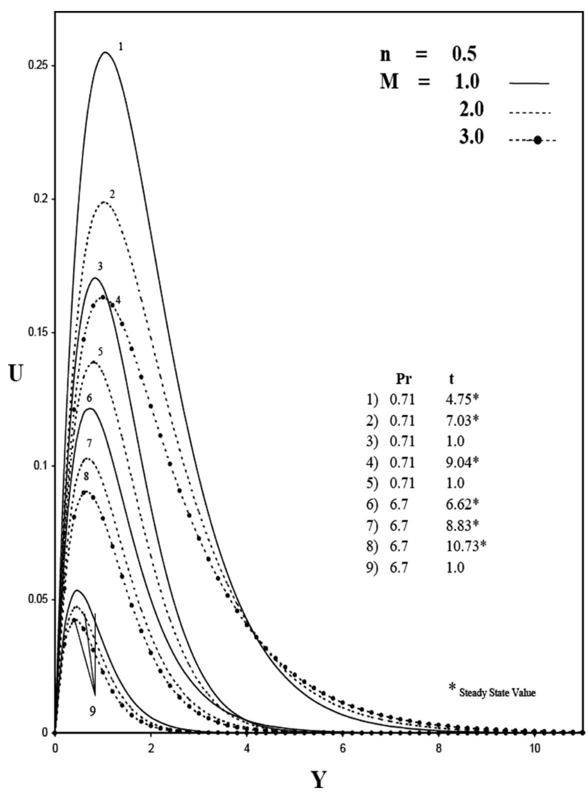

Figure 2. Transient velocity profiles at $X = 1.0$ for various values of Pr and M.

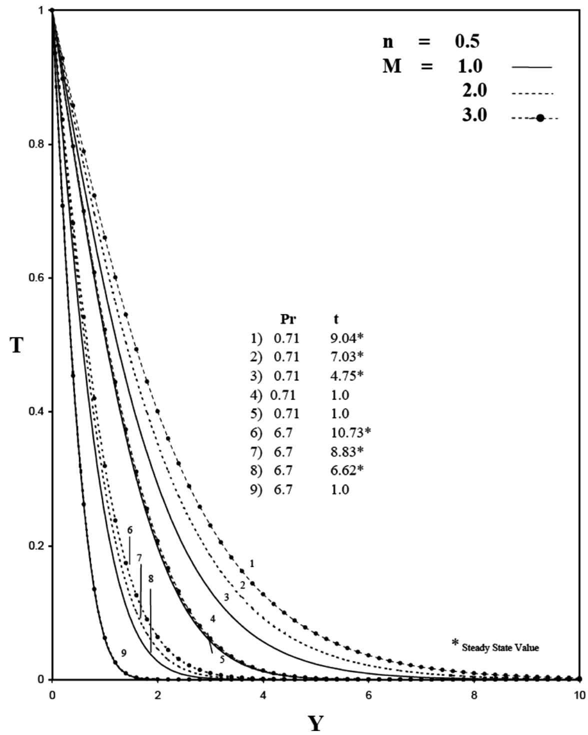

Figure 3. Transient temperature profiles at $X = 1.0$ for various values of Pr and M.

described in detail by Pullepu and coworkers (Pullepu and Ekambavanan, 2006; Pullepu et al., 2008a). The region of integration is considered as a rectangle with sides $X_{max}(=1.0)$ and $Y_{max}(=20)$, where Y_{max} corresponds to $Y = \infty$, which lies very well outside the momentum and thermal boundary layers. The derivatives involved in Equations (10) and (11) are obtained using a five-point approximation formula and then the integrals are evaluated using the Newton-Cotes closed integration formula. The finite-difference scheme is unconditionally stable as explained by Pullepu et al. (2008a). The stability and compatibility ensure the convergence.

Results and Discussion

In order to prove the accuracy of our numerical results, the present results for the steady-state flow at $X = 1.0$ are compared with available solutions from the open literature. The numerical values of the local skin friction τ_X and the local Nusselt number Nu_X for different values of the Prandtl number with $M = n = 0$ are compared with the results of Chamkha (2001) in Table I, where $f''(\infty, 0)$ and $-\theta'(\infty, 0)$ are the steady local skin friction and the local Nusselt number for a full cone obtained by Chamkha (2001). Also, the values of the local skin friction τ_X and local Nusselt number Nu_X for different values of Prandtl number with $n = 0.5$ and $M = 0$ are compared with the nonsimilarity solution of Hossain and Paul (2001a) in Table II, where $f''(0)$ and $-\theta'$ (0) are the steady local skin friction and the local Nusselt number for a full cone obtained by Hossain and Paul (2001a). It is observed that the results are in good agreement with each other.

Figures 2–5 present transient velocity and temperature profiles at $X = 1.0$, with various parameters Pr, n, and magnetic parameter M. The value of t with a star (*) symbol denotes the time taken to reach steady state. In Figures 2 and 3, transient velocity and temperature profiles are plotted for various values of Pr and M. Application of a magnetic field normal to the flow of an electrically conducting fluid gives rise to a resistive force that acts in the direction opposite to that of the flow. This force is called the Lorentz force. This resistive force tends to slow down the motion of the fluid along the cone and causes an increase in its temperature and decrease in velocity as M increases, which is clear from Figures 2 and 3. Also, it is observed from the figures that the momentum and thermal boundary layers become thick when Pr values decrease. The viscous force increases and thermal diffusivity reduces with increasing Pr, which causes a reduction in the velocity and temperature as expected. It is also noticed that the time taken to reach steady state increases with increasing Pr.

Transient velocity and temperature profiles for various values of $\boldsymbol{n}$ and $\boldsymbol{M}$ are depicted in Figures 4 and 5. It is noticed that as $\boldsymbol{n}$ increases, velocity and temperature reduce and the time taken to reach steady state increases. Momentum and thermal boundary layers become thin when the value of $\boldsymbol{n}$increases. Finally, it is concluded from Figures 2–5 that time to reach steady state, momentum, and thermal boundary layers thickness increase with increasing $\boldsymbol{M}$.

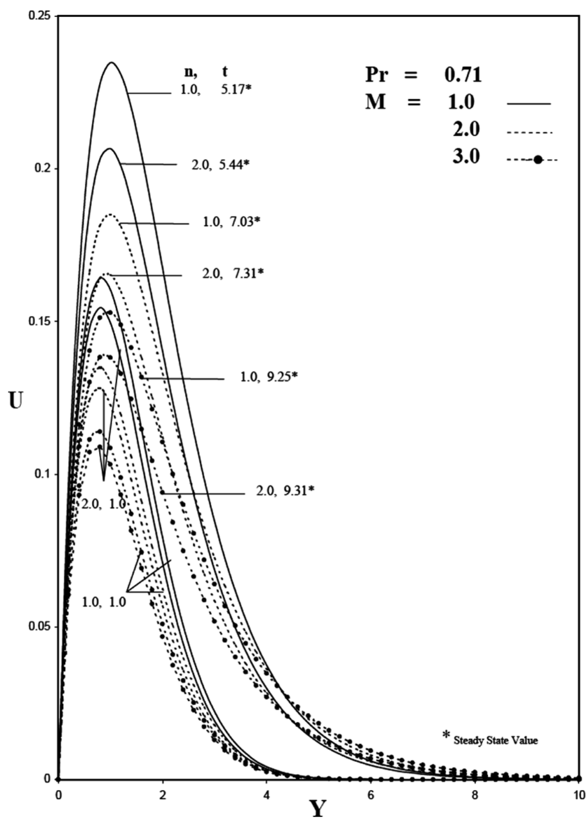

Figure 4. Transient velocity profiles at $X = 1.0$ for various values of n and M.

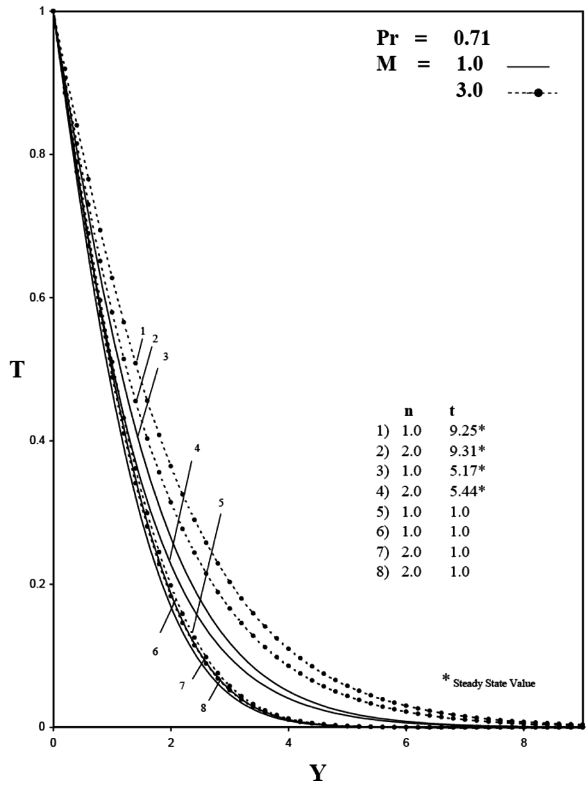

Figure 5. Transient temperature profiles at $X = 1.0$ for various values of n and M.

Figures 6 and 7 depict the variations of transient local skin friction τ_X and local Nusselt number Nu_X at various positions on the surface of the cone ($X = 0.25$ and 1.0) for controlling parameters n and M. It is observed from Figure 6 that the local skin friction decreases with increasing n or M and the effect of n over the local skin friction τ_X is less near the apex of the cone and increases gradually with increasing distance along the surface of the cone from the apex. From Figure 7, it is noticed that near the apex, the local Nusselt number Nu_X reduces with increasing n, but that trend is slowly changed and reversed as distance increases along the surface from the apex. It is observed from Figures 2–5 that the slope of velocity profile decreases while the slope of temperature profile increases as M increases. Due to this, local skin friction τ_X decreases and local Nusselt number Nu_X increases as M increases, which is clear from Figures 6 and 7. Also it was noticed that the effect of M on local skin friction is more than that of local Nusselt number.

Finally, Figures 8 and 9 illustrate the effects of n and M on the average skin friction $\bar{\tau}$ and average Nusselt number $\overline{Nu}$ in the transient period. Average skin friction $\overline{Nu}$ is greater for lower values of n. It is observed from Figures 8 and 9 that the values of average skin friction $\bar{\tau}$ and average Nusselt number $\overline{Nu}$ decrease with increasing the value of M. Also, it is clear from Figure 9 that the effect of n is almost negligible on average Nusselt number $\overline{Nu}$.

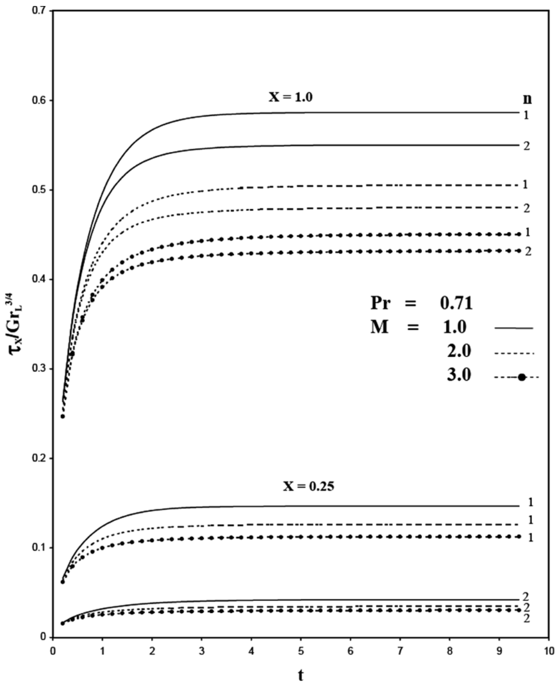

Figure 6. Local skin friction at $X = 0.25$ and 1.0 for various values of n and M in transient period.

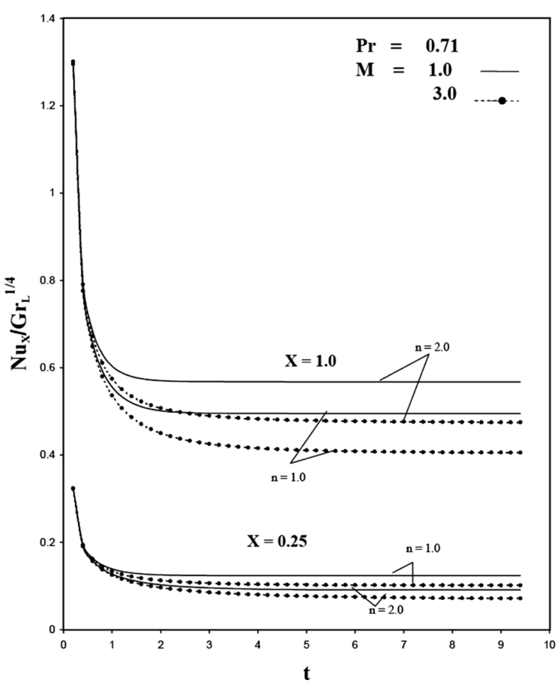

Figure 7. Local Nusselt number at $X = 0.25$ and 1.0 for various values of n and M in transient period.

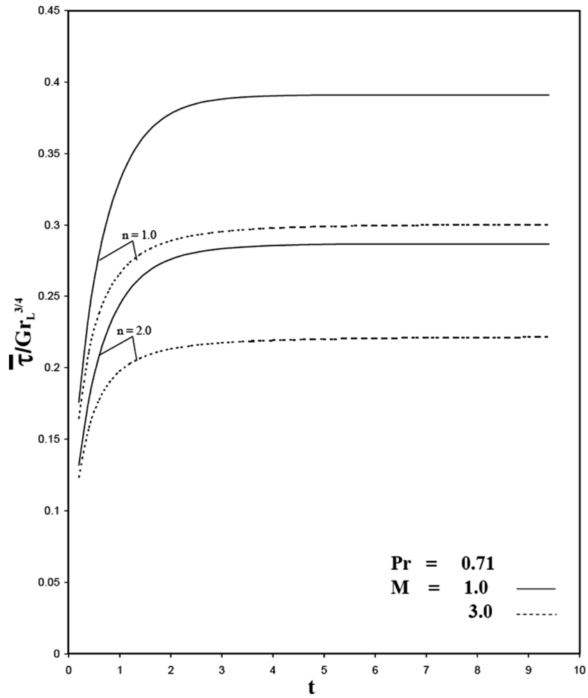

Figure 8. Average skin friction for various values of n and M.

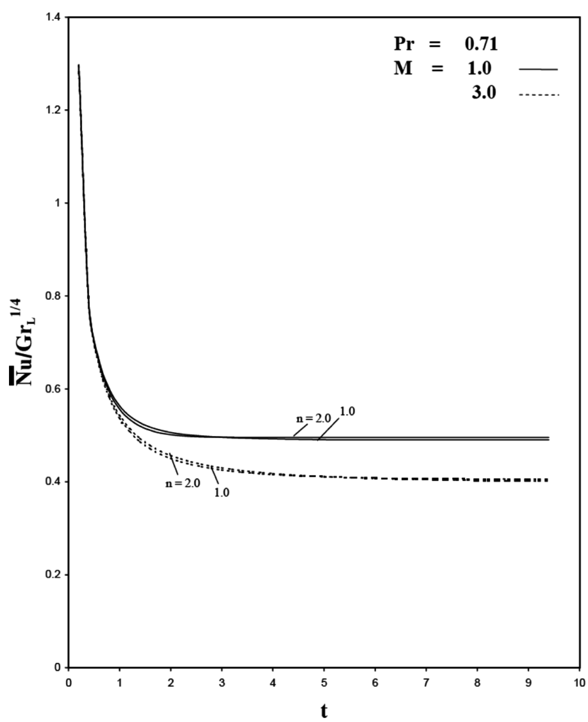

Figure 9. Average Nusselt number for various values of n and M.

Conclusions

This article deals with unsteady laminar free convection flow past a non-isothermal vertical cone in the presence of magnetic field. The dimensionless governing boundary layer equations are solved numerically using an implicit finite-difference method of the Crank-Nicolson type. Present results are compared with available results from the open literature and found to be in very good agreement. The following conclusions are drawn:

- Velocity U increases when the controlling parameters Pr, n, and M are reduced.
- Surface temperature T reduces for the lower values of M and the higher values of Pr, n.
- The time taken to reach steady state increases with increasing Pr, n, and M.
- Momentum boundary layers become thick when M is increased or values of Pr, n are reduced.
- The thermal boundary layer becomes thin when M is reduced or values of Pr, n are increased.
- Local skin friction τ_X and local Nusselt number Nu_X values reduce as Mincreases.

Nomenclature

a	Constant
B_0	magnetic field strength
$f''(0)$	local skin friction in Hossain and Paul (2001a)
$f''(\infty, 0)$	local skin friction in Chamkha (2001)
Gr_L	Grashof number
g	acceleration due to gravity
L	length of slant height
M	magnetic field parameter
Nu_x	local Nusselt number
$\overline{Nu}_L$	average Nusselt number
Nu_X	nondimensional local Nusselt number
$\overline{Nu}$	nondimensional average Nusselt number
n	exponent in power law variation in surface temperature
Pr	Prandtl number
R	dimensionless local radius of the cone
r	local radius of the cone
T'	Temperature
T	dimensionless temperature
t'	time
t	dimensionless time
U	dimensionless velocity in X-direction
u	velocity component in x-direction
V	dimensionless velocity in Y-direction
v	velocity component in y-direction
X	dimensionless spatial coordinate
x	spatial coordinate along cone generator
Y	dimensionless spatial coordinate along the normal to the cone generator
y	spatial coordinate along the normal to the cone generator

Greek Letters

α	thermal diffusivity
β	volumetric thermal expansion
$-\theta'$ (0)	local Nusselt number in Hossain and Paul (2001a)
$-\theta'$ (∞, 0)	local Nusselt number in Chamkha (2001)
μ	dynamic viscosity
υ	kinematic viscosity
ρ	density
σ	electrical conductivity of the fluid.
τ_x	local skin friction
τ_X	dimensionless local skin friction
$\bar{\tau}L$	average skin friction
$\bar{\tau}$	dimensionless average skin friction
φ	semi-vertical angle of the cone

Subscripts

w	condition on the wall
∞	free stream condition

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