MELTING HEAT TRANSFER IN A NANOFLUID BOUNDARY LAYER ON A STRETCHING CIRCULAR CYLINDER

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Abstract:

A boundary layer analysis is presented for the warm, laminar nanoliquidfluid flow to a melting cylindrical surface moving parallel to a uform stream. The resulting system of non-linear ordinary differential equations is solved numerically using Runge-Kutta method with shooting techniques. Numerical results are obtained for the velocity, temperature and concentration distributions, as well as the friction factor, local Nusselt number and local Sherwood number for several values of the parameters, namely, the Reynolds number, Prandtl number and nanofluid parameters. The obtained results are presented graphically and in tabular form and the physical aspects of the problem are discussed.

NOMENCLATURE

C	specific heat	T_∞	ambient temperature
D_B	Brownian diffusion coefficient	u, w	Darcy velocity components
D_T	thermophoretic diffusion coefficient	(r,z)	Cartesian coordinates
		Greek Symbols:	
f	reduced stream function	α_m	thermal diffusivity
g	gravitational acceleration	η	dimensionless distance
k_m	effective thermal conductivity	θ	dimensionless temperature
K	permeability of porous medium	$\emptyset$	dimensionless concentration
Le	Lewis number	μ	viscosity of fluid
M	melting parameter	ρ_f	fluid density
n	concentration	ρ_p	nano-particle mass density
N_b	Brownian motion parameters	$(\rho C)_f$	heat capacity of the fluid
N_t	thermophoresis parameters	$(\rho C)_m$	effective heat capacity
Nu	Nusselt number	$(\rho C)_p$	effective heat capacity of nano-particle material
p	pressure		
q	wall heat flux	τ	heat capacity ratio
Re	Reynolds number	**Subscripts**	
T	temperature	w	Refers to condition at wall
T_m	melting surface temperature	∞	Refers to condition far from the wal
T_0	solid surface temperature		

1. Introduction

The study of convective heat transfer in nanofluids is gaining a lot of attention. The nanofluids have many applications in the industries since materials of nanometer size have unique physical and chemical properties. Nanofluids are solid-liquid composite materials consisting of solid nanoparticles or nanofibers with sizes typically of 1-100 nm suspended in liquid. Nanofluids have attracted great interest recently because of reports of greatly enhanced thermal properties. For example, a small amount (< 1% volume fraction) of Cu nanoparticles or carbon nanotubes dispersed in ethylene glycol or oil is reported to increase the inherently poor thermal conductivity of the liquid by 40% and 150% respectively (Eastman et al, 2001, Choi et al, 2001). Conventional particle-liquid suspensions require high concentration (>10%) of particles to achieve such enhancement. However, problems of rheology and stability are amplified at high concentration, precluding the widespread use of conventional slurries as heat transfer fluids. In some cases, the observed enhancement in thermal conductivity of nanofluids is orders of magnitude larger than predicted by well-established theories. Other perplexing results in this rapidly evolving field include a surprisingly strong temperature dependence of the thermal conductivity (Patel et al, 2003) and a three-fold higher critical heat flux compared with the base fluids (You et al, 2003, Sakiadis, 1961). These enhanced thermal properties are not merely of academic interest. If confirmed and found consistent, they would make nanofluids promising for application in thermal management. Furthermore, suspensions of metal nanoparticles are also being developed for other purposes, such as medical applications including cancer therapy. The interdisciplinary nature of nanofluid research presents a great opportunity for exploration and discovery at the frontiers of nanotechnology.

The characteristics of flow and heat transfer of a viscous and incompressible fluid over flexed or continuously moving flat surfaces in a moving or a quiescent fluid are well understood. These flows occur in many manufacturing processes in modern industry, such as hot rolling, hot extrusion, wire drawing and continuous casting. For example, in many metallurgical processes such as drawing of continuous filaments through quiescent fluids and annealing and tinning of copper wires, the properties of the end product depends greatly on the rare of cooling involved in these processes. Sakiadis (1961) was the first one to analyze the boundary layer flow on continuous surfaces. Crane (1970) obtained an exact solution the boundary layer flow of Newtonian fluid caused by the stretching of an elastic sheet moving in its own plane linearly. Tsou et al. (1967) extended the research to the heat transfer phenomenon of the boundary layer flow on a continuous moving surface.Gorla and Sidawi (1994) studied the characteristics of flow and heat transfer from a continuous surface with suction and blowing. Wang (1988) analyzed the flow due to a stretching circular cylinder in a stagnant ambient viscous, incompressible, Newtonian fluid. Chamkha et. al. (2010) studied the heat transfer to the stretching cylinder moving in a stagnant incompressible, Newtonian fluid. Ishak (2010) presented a similarity solution for the flow and heat transfer to a permeable surface with convective boundary conditions. Ishat et al. (2008) considered surface mass transfer effects on heat transfer from a stretching cylinder.

Phase change heat transfer finds applications in magma solidification, permafrost melting, preparation of semiconductor materials etc. The analogy between melting and diffusion mass transfer or transpiration cooling was noted by Huang and Shih (1975). Pedroso and Domoto (1973) developed a method for calculating melting rates based on the diffusion/melting analogy. Epstein (1975) considered the effect of melting on heat transfer to submerged bodies. Epstein and Cho (1976) analyzed melting heat transfer from a flat plate. Ishak et al. (2010) considered melting heat transfer from a moving flat plate. Bachok et al. (2010) investigated melting heat transfer at a stagnation point on a stretching sheet.

We present here a similarity analysis for the problem of steady boundary-layer flow and heat transfer from a warm, laminar liquid flow to a melting cylinder moving parallel to a constant free stream of a nanofluid. It is assumed that the melting of the plate takes place at a steady state. The development of the velocity, temperature and concentration distributions have been illustrated for several values of nanofluid parameters, Lewis number and melting parameter.

2. Analysis

Consider a stretching circular tube of radius a moving at a velocity w = 2cz in a stagnant free stream nanofluid. The physical properties of the fluid are assumed to be constant. Under such condition, the governing equations of the steady, laminar boundary-layer flow on the moving surface are given by:

$$\frac{\partial(rw)}{\partial z} + \frac{\partial(ru)}{\partial r} = 0 \tag{1}$$

$$w\frac{\partial w}{\partial z} + u\frac{\partial w}{\partial r} = v\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r}\right) \tag{2}$$

$$w\frac{\partial u}{\partial z} + u\frac{\partial u}{\partial r} = -\frac{1}{\rho_f}\frac{\partial p}{\partial r} + v\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} - \frac{u}{r^2}\right) \tag{3}$$

$$w\frac{\partial T}{\partial z} + u\frac{\partial T}{\partial r} = \frac{\alpha}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \tau\left\{D_B\left(\frac{\partial n}{\partial z}\frac{\partial T}{\partial z} + \frac{\partial n}{\partial r}\frac{\partial T}{\partial r}\right) + \left(\frac{D_T}{T_\infty}\right)\left[\left(\frac{\partial T}{\partial z}\right)^2 + \left(\frac{\partial T}{\partial r}\right)^2\right]\right\} \tag{4}$$

$$w\frac{\partial n}{\partial z} + u\frac{\partial n}{\partial r} = \frac{D_B}{r}\frac{\partial}{\partial r}\left(r\frac{\partial n}{\partial r}\right) + \left(\frac{D_T}{T_\infty}\right)\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) \tag{5}$$

The boundary conditions are given by,

$$r = a: u = 0, w = 2cz, k\frac{\partial T}{\partial y} = \rho[\lambda + C_s(T_m - T_0)]v_w, n = n_w$$

$$r \rightarrow \infty: w = 0, T = T_\infty, n = n_\infty \tag{6}$$

The boundary layer flows in nano fluids have been analyzed recently by Nield and Kuznetsov (2009.a) and Nield and Kuznetsov (2009.b). Our model used for nanofluid is similar to these authors.
Proceeding with the analysis, we define the following transformations:

$$\eta = \left(\frac{r}{a}\right)^2$$

$$u = -c\,a\left(\frac{f(\eta)}{\sqrt{\eta}}\right)$$

$$w = 2cz\,f'(\eta)$$

$$\theta = \frac{T - T_\infty}{T_w - T_\infty}$$

$$\phi = \frac{n - n_\infty}{n_w - n_\infty} \tag{7}$$

Using the transformation variables defined in Equation (7), the governing transformed equations may be written as:

$$\eta\,f''' + f'' + Re_a\,(ff''' - f'^2) = 0 \tag{8}$$

$$\frac{\theta''}{P_r} + \frac{\theta'}{P_r\eta} + N_b\theta'\phi' + N_t(\theta')^2 + \frac{Re_a}{2\eta}f\theta' = 0 \tag{9}$$

$$\phi'' + \phi'\left(\frac{1}{2}L_eRe_a\,f + \frac{1}{\eta}\right) + \frac{N_t}{N_b}\frac{1}{\eta}\theta' + \frac{N_t}{N_b}\theta'' = 0 \tag{10}$$

The transformed boundary conditions are given by

$$\eta = 1: Pr.Re_a.f + 2M\theta' = 0, f = 0, f' = 1, \theta = 1, \phi = 1$$

$$\eta \rightarrow \infty: f' = 0, \theta = 0, \phi = 0 \tag{11}$$

where prime denote differentiation with respect to η and the four parameters are defined by

$$M = \frac{C_f(T_\infty - T_m)}{\lambda + C_s(T_m - T_0)};$$

$$N_t = \frac{\varepsilon(\rho C)_p D_T(T_w - T_\infty)}{(\rho C)_f T_\infty\,\alpha_m}$$

$$N_b = \frac{\varepsilon(\rho C)_p D_B(T_w - T_\infty)}{(\rho C)_f\,\alpha_m}; \; Re = \frac{c\,a^2}{2v}; L_e = \frac{v}{D_B}; P_r = \frac{v}{\alpha}$$

$$\tau = \frac{\varepsilon(\rho C)_p}{(\rho C)_f} \tag{12}$$

Here, *Pr, Le, N_b* and *N_t* denote the Prandtl number, the Lewis number, the Brownian motion parameter and the thermophoresis parameter, respectively. It is important to note that this boundary value problem reduces to the classical problem of flow and heat and mass transfer due to a stretching cylinder in a viscous fluid when Nb and Nt are zero.

The quantities of practical interest, in this study, are the friction factor C_f, Nusselt number *Nu* and the Sherwood number *Sh* which are defined as:

The wall shear stress is given by

$$\tau_w = \mu \frac{\partial w}{\partial r})_{r=a} = \frac{4\mu cz}{a} \mu f''(1) \tag{13}$$

The friction factor C_f is give by

$$C_f = \frac{\tau_w}{\frac{\rho W^2}{2}} = 4\frac{z}{a}\frac{1}{Re_z} f''(1) \tag{14}$$

where $Re_z = \frac{cz^2}{2\upsilon}$

The local heat transfer rate (Local Nusselt number) is given by

$$Nu_x = \frac{q_w x}{k(T_w - T_\infty)} = -2\sqrt{\frac{Re_z}{Re_a}}\,\theta'(1) \tag{15}$$

Similarly the local Sherwood number is given by

$$Sh_x = \frac{q_m x}{D_B(n_w - n_\infty)} = -2\sqrt{\frac{Re_z}{Re_a}}\,\phi'(1) \tag{16}$$

where q_w and q_m are wall heat and mass flux rates, respectively.

3. Results and Discussion

The nonlinear ordinary differential equations (8)-(10), satisfying the boundary conditions (11) were integrated numerically by using the fourth-order Runge-Kutta scheme along with the shooting method for several values of the governing parameters, namely, melting parameter M, Prandtl number (Pr), Lewis number (Le), Brownian motion parameter (N_b) and thermophoresis parameter (N_t). As per Pantokratoras (2009), the value of the edge of the boundary layer distance η_∞ was set to be 35. This was found to give accurate results. In order to assess the accuracy of the present results, we obtained results for the reduced friction factor -f''(1) and Nusselt number $-\theta'(1)$ by ignoring the effects of M, N_b and N_t. These results are shown in Tables 1-3. A comparison of our results with literature values indicates excellent agreement and therefore our results are highly accurate.

Table 1: Comparison of results for -f''(1)

Re_a	Present results	Wang (1988)	Chamkha et al (2010)	Ishak et al (2008)
0.5	0.88700	0.88220	0.88700	0.8827
1.0	1.17923	1.17776	1.17953	1.1781
2.0	1.59448	1.59390	1.59444	1.5941
5.0	2.41755	2.41745	2.41798	2.4175
10.0	3.34467	-	-	3.3445

Table 2: Comparison of results for $-\theta'(1)$ ($N_t = N_b = 0$, $Re_a = 3$)

Pr	Present results	Chamkha et al (2008)
0.70	1.15053	1.15053
2.00	2.10654	2.10655
7.00	4.23743	4.23743

Table 3: Comparison of results for $-\theta'(1)$ ($N_t = N_b = 0$, $Re_a = 10$)

Pr	Present results	Ishak et al (2008)
0.70	1.15683	1.15683
2.00	3.03604	3.0360
7.00	6. 15919	6.1592
10.00	7.46678	7.4668

Table 4: Effects of M on -f''(1), -θ'(1) and -φ'(1) for N_b=0.3, N_t=0.1, Le=10, Pr=0.007 and Re=5.0

M	-f''(1)	-θ'(1)	-φ'(1)
0	1.465554	2.885982E-01	4.332448
0.5	1.225042	2.894680E-01	6.351898
1.0	1.079356	2.913474E-01	8.526056
2.0	9.033523E-01	2.939987E-01	13.126320
3.0	7.967334E-01	2.962927E-01	17.872870
5.0	6.672747E-01	3.004993E-01	27.423650

Table 5: Effects of Re on -f''(1), -θ'(0) and -φ'(0) for M=1.0, N_b=0.3, N_t=0.1, Le=10 and Pr=1.0

Re	-f''(1)	-θ'(1)	-φ'(1)
0.5	8.856947E-01	3.130347E-01	1.664970
1.0	1.179914	3.768276E-01	2.143076
2.0	1.595489	4.730244E-01	2.808954
5.0	2.418254	6.765498E-01	4.110941
10	3.346068	9.134587E-01	5.565769

Table 6: Effects of Le on -f''(1), -θ'(1) and -φ'(1) for M=1.0, N_b=0.3, N_t=0.1, Pr=1.0 and Re=5.0

Le	-f''(1)	-θ'(1)	-φ'(1)
1	2.418453	7.238915E-01	1.320297
10	2.418254	6.765498E-01	4.110941
10^2	2.418129	6.578494E-01	12.78660
10^3	2.418007	6.524682E-01	40.21021

Table 7: Effects of N_t on -f''(1), -θ'(1) and -φ'(1) for M=0.5, N_b=0.3, Le=10, Pr=1.0 and Re=5.0

N_t	-f''(1)	-θ'(1)	-φ' 1)
0.1	1.465142	9.067177E-01	4.340492
0.2	1.465078	8.648823E-01	4.359981
0.3	1.465281	8.250847E-01	4.389859
0.4	1.465446	7.873235E-01	4.428391
0.5	1.465281	7.520800E-01	4.474232

Table 8: Effects of N_b on -f''(1), -θ'(1) and -φ'(1) for M=0.5, N_t=0.3, Le=10, Pr=1.0 and Re=5.0

N_b	-f''(1)	-θ'(1)	-φ'(1)
0.1	1.465203	9.769198E-01	4.191690
0.2	1.465203	8.978819E-01	4.344063
0.3	1.465281	8.250847E-01	4.389859
0.4	1.465399	7.565706E-01	4.410043
0.5	1.465446	6.942467E-01	4.419178

Tables 4-8 display the resulting values of velocity gradient -f''(1), the surface heat transfer rate –θ'(1) and the mass transfer rate – φ'(1), which are proportional to the friction factor, Nusselt number and Sherwood number respectively. The results in Table 3 indicate that effect of increasing the melting parameter M is to increase the heat and mass transfer rates from the surface and decrease the friction factor. Table 4 indicates that as Re increases, friction factor as well as the heat and mass transfer rates increase. Table 5 indicates that as the Lewis number, Le increases, mass transfer rates get augmented. Tables 6 and 7 indicate that as N_t and N_b increase, heat transfer rates decrease whereas the mass transfer rates increase.

Figures 1-3 display results for the variation of velocity, temperature and concentration within the boundary layer. As M increases, the velocity within the boundary layer increases and the concentration decreases. The concentration boundary layer thickness decreases as M increases. This enhances the mass transfer rates.

Figures 4-6 and show the velocity, temperature and concentration distributions within the boundary layer as the Reynolds number, Re increases. The velocity, temperature and concentration within the boundary layer decrease as Re increases.
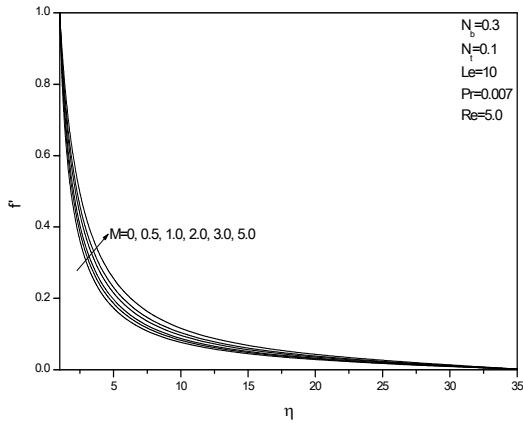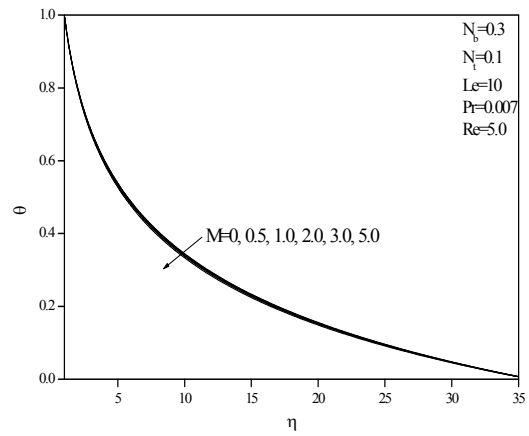
Fig. 1: Effects of M on velocity profiles

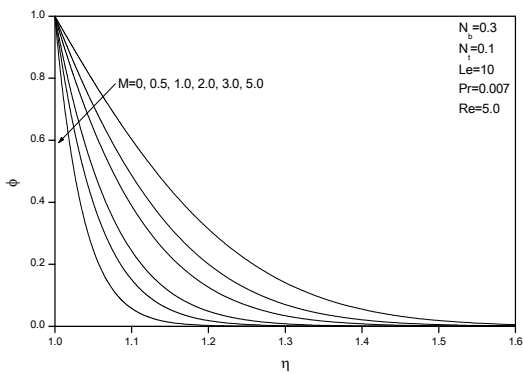Fig. 2: Effects of M on temperature profiles

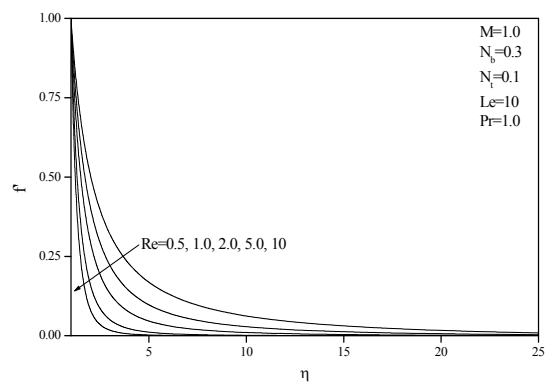Fig.3: Effects of M on solid volume fraction profiles
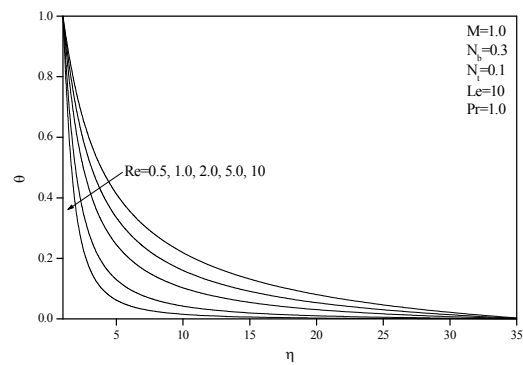

Fig. 4: Effects of Re on velocity profiles

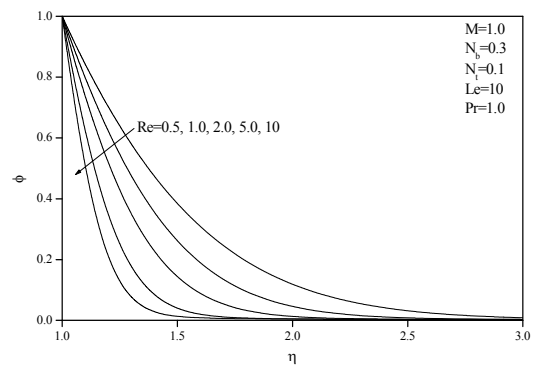Fig. 5: Effects of Re on temperature profiles
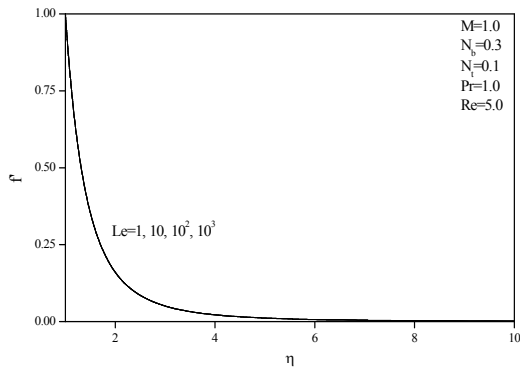

Fig. 6: Effects of Re on solid volume fraction profiles
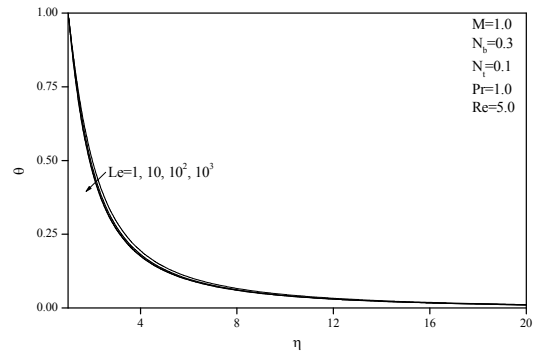
Fig. 7: Effects of Le on velocity profiles
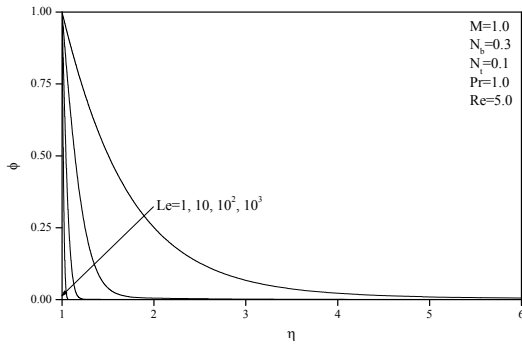

Fig. 8: Effects of Le on temperature profiles
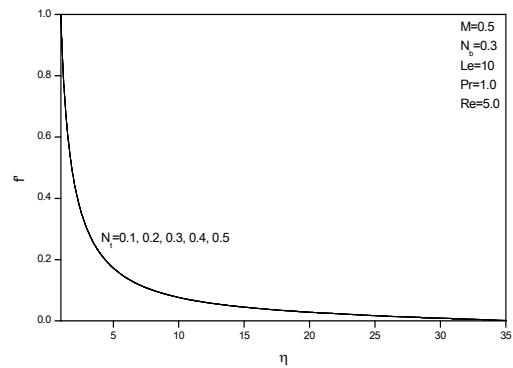

Fig. 9: Effects of Le on solid volume fraction profiles
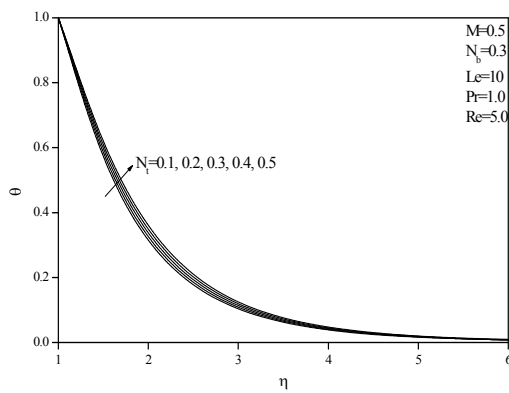

Fig. 10: Effects of N_t on velocity profiles
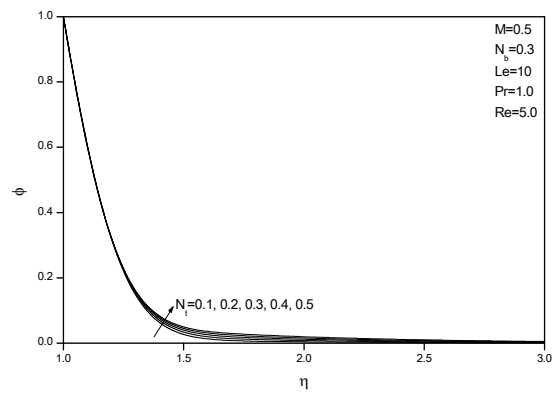

Fig. 11: Effects of N_t on temperature profiles

Fig. 12: Effects of N_t on solid volume fraction profiles

Figures 7 and 8 indicate that Le has no significant effect on the velocity and temperature distributions. Figure 9 shows the concentration distribution as the Lewis number increases. As Le increases, we observe that the concentration decreases and the concentration boundary layer thickness decreases. This in turn increases the

surface mass transfer rates as Le increases. From Figures 10-15, we observe that as N_t increases, the temperature and concentration increase. As N_b increases, the temperature increases whereas the concentration decreases. The thickness of the boundary layer for concentration is smaller than the thermal boundary layer thickness.
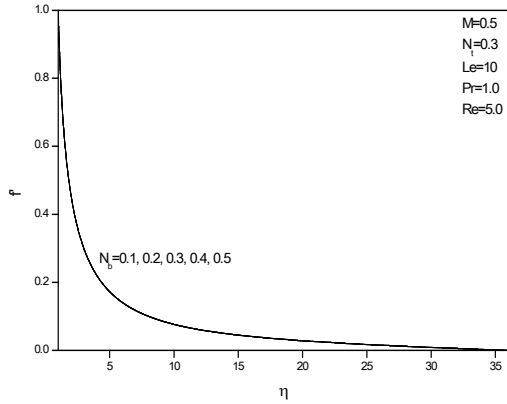

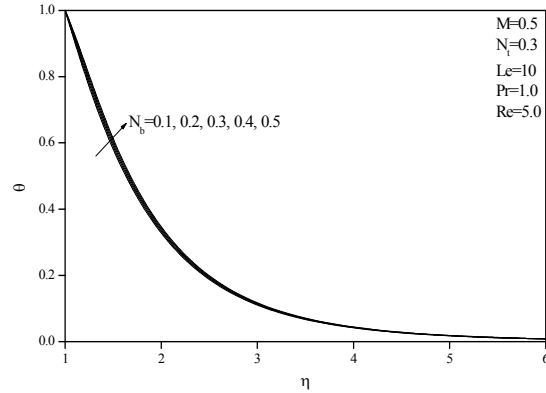Fig. 13: Effects of N_b on velocity profiles
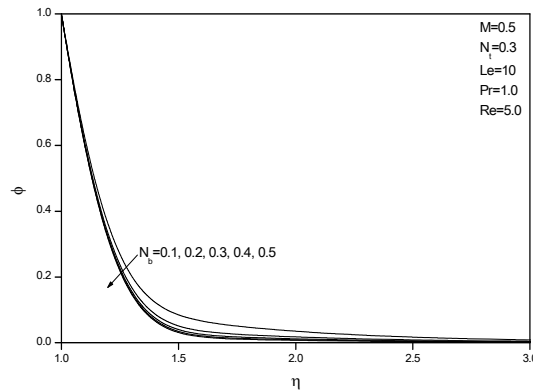

Fig. 14: Effects of N_b on temperature profiles

Fig. 15: Effects of N_b on solid volume fraction profiles

4. Concluding Remarks

In this work, we have studied the problem of the steady boundary layer flow of a warm, laminar nanoliquid over a melting cylinder moving parallel to a uniform free stream of the same material. The governing boundary layer equations are solved numerically using the fourth-order Runge-Kutta scheme along with the shooting method. The development of the Nusselt number and Sherwood number as well as the temperature, concentration and velocity distributions for various values of the velocity ratio, melting and nanofluid parameters has been discussed and illustrated in tabular forms and graphs. The results indicate that the melting phenomenon increases the heat transfer rate, (Nusselt number) at the solid/fluid interface. The nanofluid parameters display a considerable effect on the rates of heat transfer and mass transfer.

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