THE UNSTEADY FLOW OF A NANOFLUID IN THE STAGNATION POINT REGION OF A TIME-DEPENDENT ROTATING SPHERE

by

Amir MALVANDI *

Young Researchers and Elite Club, Karaj Branch, Islamic Azad University, Karaj, Iran

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This paper deals with the unsteady boundary layer flow and heat transfer of nanofluid over a time-dependent rotating sphere where the free stream velocity varies continuously with time. The boundary layer equations were normalized via similarity variables and solved numerically. Best accuracy of the results has been obtained for regular fluid with previous studies. The nanofluid is treated as a two-component mixture (base fluid + nanoparticles) that incorporates the effects of Brownian diffusion and thermophoresis simultaneously as the two most important mechanisms of slip velocity in laminar flows. Results obtained indicate that the acceleration parameter and the dimensionless rotation parameter increase, surface shear stresses, heat transfer, and concentration rates, climb up. Also, increasing the thermophoresis is found to decrease heat transfer and concentration rates. This decrease suppresses for higher thermophoresis number. In addition, it was observed that unlike the heat transfer rate, a rise in Brownian motion, leads to an increase in concentration rate.

Key words: *nanofluid, rotating sphere, unsteady stagnation point, thermophoresis, similarity solution*

Introduction

Improving the technology, limit in enhancing the performance of conventional heat transfer is a main issue owing to low thermal conductivity of the most common fluids such as water, oil, and ethylene-glycol mixture. Since the thermal conductivity of solids is often higher than that of liquids, the idea of adding particles to a conventional fluid to enhance its heat transfer characteristics was emerged. Among all dimensions of particles such as macro, micro, and nano, due to some obstacles in the pressure drop through the system and keeping the mixture homogenous, nanoscaled particles have attracted more attention. These tiny particles are fairly close in size to the molecules of the base fluid and thus can realize extremely stable suspensions with slight gravitational settling over long periods of time. Very word "nanofluid" was proposed by Choi [1] to point out engineered colloids composed of nanoparticles dispersed in a base fluid. Following the seminal study of Masuda *et al.* [2], a considerable amount of research in this field has risen exponentially. Meanwhile, theoretical studies were emerged to model the nanofluids behaviors. Up to now, the proposed models are twofold; homogeneous flow models and dispersion models. Buongiorno [3] indicated that the homogeneous models tend to under predict the nanofluid heat transfer coefficient and due to nanoparticle size, dispersion effect is completely negligible. Hence, Buongiorno [3] developed an al-

* Corresponding author; e-mail: amirmalvandi@aut.ac.ir

ternative model to explain the abnormal convective heat transfer enhancement in nanofluids and eliminates the shortcomings of the homogenous and dispersion models. He considers seven slip mechanisms, including inertia, Brownian diffusion, thermophoresis, diffusiophoresis, Magnus, fluid drainage, gravity, and claimed. Of these seven, only Brownian diffusion and thermophoresis are important slip mechanisms in nanofluids. Moreover, Buongiorno [3] concluded that turbulence is not affected by nanoparticles. Based on this finding, he proposed a two-component four-equation non-homogeneous equilibrium model for convective transport in nanofluids. Above-mentioned model has recently been used by Kuznetsov and Nield [4] to study the influence of nanoparticles on natural convection boundary-layer flow past a vertical plate. Then, a comprehensive survey of convective transport of nanofluids in the boundary layer flow conducted by Khan and Pop [5], Bachok *et al.* [6-8], Khan and Aziz [9], Mustafa *et al.* [10], and Yacob *et al.* [11]. Some very recent review papers are performed by Daungthongsuk and Wongwises [12], Wang and Majumdar [13], and Shanthi *et al.* [14].

Stagnation point flow has a wide range of applications in engineering and several technical purposes. Hiemenz [15] developed the first investigation in this field. He applied similarity transformation to collapse 2-D Navier-Stokes equations to a non-linear ordinary differential one and then presented its exact solution. Extension of this study was carried out with a similarity solution by Homann and Angew [16] to the case of axisymmetric 3-D stagnation point flow. After these original studies, many researchers have put their attention on this subject [17-24]. Extension of the concept of rotating spheres due to its frequent applications in modern industry, especially in machinery design and fiber coating, has been involved many researchers until now [25-27]. Kumari and Nath [28], and Takhar *et al.* [29] considered a similar problem for unsteady flows. Popularity of the unsteady rotating sphere concepts can be gauged from the researches done by scientists for its frequent applications and can be found in literatures *e. g.* [30-32].

Owing to wide range of technological applications including electronic systems, hydrocyclone devices, quenching, and nuclear reactors flow over a sphere saturated in nanofluid has attracted so many attention [33-35]. To the best of the author's knowledge, despite the frequent mentioned literatures, there is no investigation on the unsteady flow and heat transfer of nanofluid in the stagnation point region of a time-dependent rotating sphere. In this paper, the basic boundary layer equations have been reduced to a two-point boundary value problem via similarity variables, and solved numerically. The employed model for nanofluid includes two-component four-equation non-homogeneous equilibrium model that incorporates the effects of Brownian diffusion and thermophoresis simultaneously. The numerical results of interest, such as the heat transfer and concentration rates, temperature and concentration profiles are obtained and demonstrated in both tabular and graphical form. It is hoped that the obtained results will not only present useful information for applications, but also serves as a complement to the previous studies.

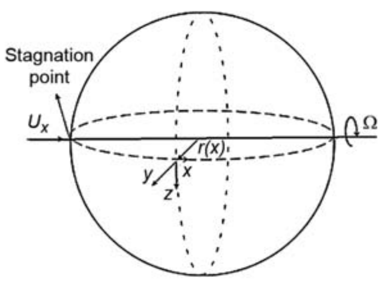

Figure 1. Physical model and co-ordinate system

Mathematical formulations

Consider the unsteady, incompressible boundary layer flow of nanofluids approaching to the stagnation point region of a constant temperature rotating sphere as in fig. 1. It is also assumed that the viscous dissipation terms are negligible and the free stream and angular velocities depend on time in the form of $U_e(x,t) = Ax/t$ and

$\Omega(t) = B/t$ where A and $B > 0$. Considering above assumptions, the basic unsteady incompressible conservation equations can be expressed [4, 32]:

$$(ru)_x + (rv)_y = 0 \tag{1}$$

$$u_t + uu_x + vu_y - \left(\frac{w^2}{r}\right) r_x = (u_e)_t + u_e(u_e)_x + \nu u_{yy} \tag{2}$$

$$w_t + uw_x + vw_y + \left(\frac{uw}{r}\right) r_x = \nu w_{yy} \tag{3}$$

$$T_t + uT_x + vT_y = \alpha T_{yy} + \tau \left(D_B C_y T_y + \frac{D_T}{T_\infty} T_y T_y \right) \tag{4}$$

$$C_t + uC_x + vC_y = D_B C_{yy} + \frac{D_T}{T_\infty} T_{yy} \tag{5}$$

Subject to the initial and boundary conditions:

$$\begin{gathered} u(0, x, y) = u_i(x, y), \qquad v(0, x, y) = v_i(x, y), \qquad w(0, x, y) = w_i(x, y), \\ T(0, x, y) = T_i(x, y), \qquad C(0, x, y) = C_i(x, y) \end{gathered} \tag{6}$$

$$\begin{gathered} u(t, x, 0) = 0, \qquad v(t, x, 0) = 0, \qquad w(t, x, 0) = \Omega(t) r, \qquad T(t, x, 0) = T_w, \qquad w(t, x, \infty) = 0, \\ u(t, x, w) = U_e(x, t) = Ax/t, \qquad T(t, x, \infty) = T_\infty = \text{const}, \qquad C(t, x, \infty) = C_\infty = \text{const} \end{gathered}$$

where x, y, and z are co-ordinates measured from the forward stagnation point along the surface, normal to the surface, and in the rotating directions, respectively, $r(x)$ – the radial distance from a surface element to the axis of symmetry $r(x) \simeq x$ in the vicinity of stagnation point region), u, v, and w – the velocity components along the x, y, and z co-ordinates, t – the time, i – the initial condition, α – the thermal diffusivity, ν – the kinematic viscosity, k – the thermal conductivity, D_B – the Brownian diffusion coefficient, D_T – the thermophoretic diffusion coefficient, $\tau = (\rho c_p)_p/(\rho c_p)_f$ – the ratio between the effective heat capacity of the nanoparticle material and heat capacity of the fluid, and c_p and T – the specific heat at constant temperature and local temperature, respectively. Introducing the following similarity parameters:

$$\begin{gathered} r \approx x, \qquad \frac{\mathrm{d}r}{\mathrm{d}x} = 1, \qquad \eta = (\nu t)^{-\frac{1}{2}} y, \qquad w = \left(\frac{Bx}{l}\right) S(\eta), \\ \psi = Ax\left(\frac{\nu}{t}\right)^{1/2} f(\eta), \qquad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \qquad \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty} \end{gathered} \tag{7}$$

equations (1)-(5) collapse into:

$$f''' + f''\left(Af + \frac{\eta}{2}\right) + f'(1 - Af') + A(\lambda s^2 + 1) - 1 = 0 \tag{8}$$

$$s'' + s'\left(Af + \frac{\eta}{2}\right) + s(1 - 2Af') = 0 \tag{9}$$

$$\frac{\theta''}{\Pr} + Nb\theta'\phi' + Nt\theta'^2 + Af\theta' + \frac{\eta}{2}\theta' = 0 \tag{10}$$

$$\phi'' + \mathrm{Le}\phi'\left(Af + \frac{\eta}{2}\right) + \frac{Nt}{Nb}\theta'' = 0 \tag{11}$$

The transformed boundary condition of (6) reduces to:

$$\begin{gathered} -\text{ at }\quad \eta = 0: \quad f = 0, \quad f' = 0, \quad \theta = 1, \quad \phi = 1, \quad s = 1 \\ -\text{ as }\quad \eta \to \infty: \quad f' = 1, \quad \theta = 0, \quad \phi = 0, \quad s = 0 \end{gathered} \tag{12}$$

where (') denotes differentiation with respect to η and the outcoming non-dimensional parameters are:

$$\Pr = \frac{\nu}{\alpha}, \qquad \mathrm{Le} = \frac{\nu}{D_B}, \qquad Nb = \frac{(\rho c_p)_p D_B (C_w - C_\infty)}{(\rho c_p)_f \nu}, \qquad Nt = \frac{(\rho c_p)_p D_T (T_w - T_\infty)}{(\rho c_p)_f \nu T_\infty} \tag{13}$$

where λ is the dimensionless rotation parameter, Pr, Le, Nb, and Nt denote the Prandtl number, Lewis number, Brownian motion, and thermophoresis, respectively. The skin friction coefficient in x- and z-directions can be defined:

$$\begin{gathered} C_{fx} = \frac{2\mu\left(\dfrac{\partial u}{\partial y}\right)_{y=0}}{\rho u_e^{\,2}} = \mathrm{Re}_x^{1/2}\ A^{-1/2} f''(0) \\ C_{fz} = \frac{2\mu\left(\dfrac{\partial w}{\partial y}\right)_{y=0}}{\rho u_e^{\,2}} = -\,\mathrm{Re}_x^{1/2}\ \lambda^{1/2} A^{-1/2} s'(0) \end{gathered} \tag{14}$$

where $\mathrm{Re}_x = u_e x/\nu = Ax^2/\nu t$, For the understudy boundary condition, Nusselt number can be expressed:

$$\mathrm{Nu} = \frac{-x\left(\dfrac{\partial T}{\partial y}\right)_{y=0}}{T_w - T_\infty} = -\,\mathrm{Re}_x^{1/2}\ A^{-1/2}\theta'(0) \tag{15}$$

Before goes farther in the results, it is worth advantageous to take more information on the physical aspects of governing parameters which appears in the nanofluid's model, *i. e.* Brownian motion and thermophoresis which were introduced in [36-38]. Brownian motion can be observed as random drifting of suspended nanoparticles, on the other hand, thermophoresis is nanoparticle migration due to imposed temperature gradient across the fluid. Mentioned phenomena is the two important slip mechanisms which emerges as a result of nanoparticles' slip velocity to the base fluid. For hot surfaces, due to repelling the sub-micron sized particles, the thermophoresis tends to blow nanoparticle volume fraction boundary layer away from the surface. Also, owing to size scale of particles, Brownian motion has significant influence on the surrounding liquids.

Result and discussion

The system of eqs. (8)-(11) with boundary conditions (12) have been solved numerically via shooting method based on 4th order Runge-Kutta. In view of comparing with earlier studies, it must be stated that there is no study on the nanofluid flow over a sphere which employs non-homogeneous equilibrium model. So, only the hydrodynamic and thermal parts of the problem, eqs. (8)-(10), in the absence of nanoparticle's effect can be compared with previous results. The best accuracy of results are obtained for surface shear stresses and temperature gradients namely, $f'(0)$, $s'(0)$, and $-\theta'(0)$, with the tabulated results of Anilkumar and Roy [32] in tab. 1, where in order to comparison, a free convection term has been added to eq. (8). In contrast to regular fluids, the present extension involves three more parameters namely Levis number, *Nb*, and *Nt*. Therefore we must be very selective to choose of the values of parameters. It should also be stated at the outset that one error is inevitable, because the physical domain is unbounded whereas the computational domain has to be finite. Here, for our bulk computations the far field boundary conditions denoted by $\eta_{\max}$ set to $\eta_{\max} = 10$ which was sufficient to achieve the far field boundary conditions asymptotically.

Table 1. Comparison of results for surface shear stresses and temperature gradients when $\lambda = 1$, $Nb = 0$, $Nt = 0$, Le = 0, and Pr = 0.7

	$f''(0)$		$-s'(0)$		$-\theta'(0)$	
A	Anilkumar and Roy [32]	Present study	Anilkumar and Roy [32]	Present study	Anilkumar and Roy [32]	Present study
0.5	0.79946	0.79913	0.30351	0.30339	0.46743	0.467648
1	1.28271	1.2828	0.64575	0.64579	0.58957	0.589527
2	1.91728	1.9172	1.05422	1.05415	0.77954	0.779526

Variations of surface shear stresses, reduced Nusselt and Sherwood numbers for different values of *A, λ, Nt, Nb,* Levis number, and Prandtl number are cited in tabs. 2-4. Considering tab. 2, we can see that increasing in thermophoresis, leads to decrease in the values of heat transfer rate $-\theta'(0)$ and concentration rate $-\phi'(0)$. It can be observed that a 0.1 increase in thermophoresis from $Nt = 0.1$ to $Nt = 0.2$, decreases heat transfer rate about 4% and concentration rate about 20%. This decrease suppresses (slightly) with increasing in thermophoresis, in other words, the effects of higher values of thermophoresis number on heat transfer and concentration rates are lower. In addition, as Brownian motion, *Nb* grows, $-\phi'(0)$ increases but $-\theta'(0)$ takes a decreasing trend. Clearly, increasing by 0.1 in Brownian motion parameter from $Nb = 0.1$ leads to (a) a 6% decrease in heat transfer rate which increases slightly in higher Brownian motion parameter (about 6.2% when $Nb = 0.5$) and (b) a 14% growth in concentration rate which is followed by a great decline in higher Brownian motion parameter (about 1% when $Nb = 0.5$). As Brownian motion increases, a larger extent of the fluid will be affected which leads to thicker thermal boundary layer and a drop in heat transfer rate. The ratio of thermal diffusivity to mass diffusivity, Lewis number, is another effective parameter which has been cited in tab. 3. We can observe that as Levis number intensifies, concentration rate increases, however, heat transfer

Table 2. Reduced Nusselt and Sherwood numbers when Le = 2 and $A = \lambda =$ Pr = 1

Nb	*Nt*	$-\theta'(0)$	$-\phi'(0)$
0.1	0.1	0.70306	0.83627
0.1	0.2	0.67534	0.66248
0.1	0.3	0.64885	0.52631
0.1	0.4	0.62354	0.42455
0.1	0.5	0.59937	0.35414
0.2	0.1	0.66110	0.96052
0.3	0.1	0.62108	1.00132
0.4	0.1	0.58296	1.02128
0.5	0.1	0.54669	1.03291

Table 3. Reduced Nusselt and Sherwood numbers when $Nt = Nb = 0.1$ and $A = \lambda = 1$

Pr	Le	$-\theta'(0)$	$-\phi'(0)$
1	1	0.71326	0.49287
1	2	0.70306	0.83627
1	5	0.69208	1.43176
1	10	0.68591	2.04036
2	2	0.88305	0.73490
5	2	1.11008	0.59892
10	2	1.20498	0.55832

Table 4. Surface shear stresses and heat transfer parameters when $Nt = Nb = 0.1$, Le = 2 and Pr = 1

λ	A	$-s'(0)$	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
1	1	0.67240	1.28493	0.70306	0.83627
1	2	1.19932	1.98443	0.87885	1.04488
1	3	1.56508	2.49736	1.02596	1.21952
3	1	0.77737	1.91755	0.73033	0.86848
3	2	1.31482	2.80147	0.91582	1.08861
3	3	1.69539	3.46915	1.07068	1.27245
5	1	0.85623	2.47946	0.75182	0.89386
5	2	1.40650	3.54450	0.94597	1.12428
5	3	1.80054	4.35909	1.10755	1.31608
10	1	0.99961	3.71620	0.79292	0.94242
10	2	1.58080	5.20997	1.00511	1.19421
10	3	2.00335	6.36546	1.18045	1.40233

rate decreases; furthermore, it is observed that unlike $-\phi'(0)$ a rise in the Prandtl number leads to increase $-\theta'(0)$. The results in tab. 4 indicate that as A and λ increase, surface shear stresses $-s'(0)$, $f''(0)$, heat transfer rate $-\theta'(0)$, and concentration rate $-\phi'(0)$ climb up all. To provide an additional insight about the effects of A and λ into the understudied problem, the graphical results will be discussed hereinafter.

Graphical results

Effects of acceleration parameter on velocity profiles in x- and y-directions (f', s), temperature and concentration profiles are shown in figs. 2 and 3, respectively. At the edge of the boundary layer, as A grows, U_e climbs up; hence, increasing in acceleration parameter leads to decrease in the value of velocity in x- and y-directions (thinner boundary layer) which adds more momentum in the longitude direction inside the boundary layer. Obviously the flow accelerates in this direction which leads to increase in the temperature and mass transfer both, on the other hand, the thickness of the thermal and concentration boundary layers decrease, see fig. 3. Another noteworthy conclusion of fig. 3 is that increasing in A suppresses the fluid motion in the rotating direction so the velocity and temperature increase everywhere and the boundary layer in the rotating direction became thinner.

Figure 4 shows the effects of rotation parameter on x- and y- directions on velocity profiles. Clearly, as λ increases, the boundary layer thickness in x- and y-directions decrease; this is because of a rise in λ which injects an additional momentum into the boundary layer and accelerates the fluid. This additional momentum leads to more heat and mass transfer through the boundary layer; hence thicknesses of the thermal and concentration boundary layers decrease (fig. 5). It is worth mentioning that since λ affects the velocity profile in y-direction, temperature profile and concentration profile indirectly, its effects are small.

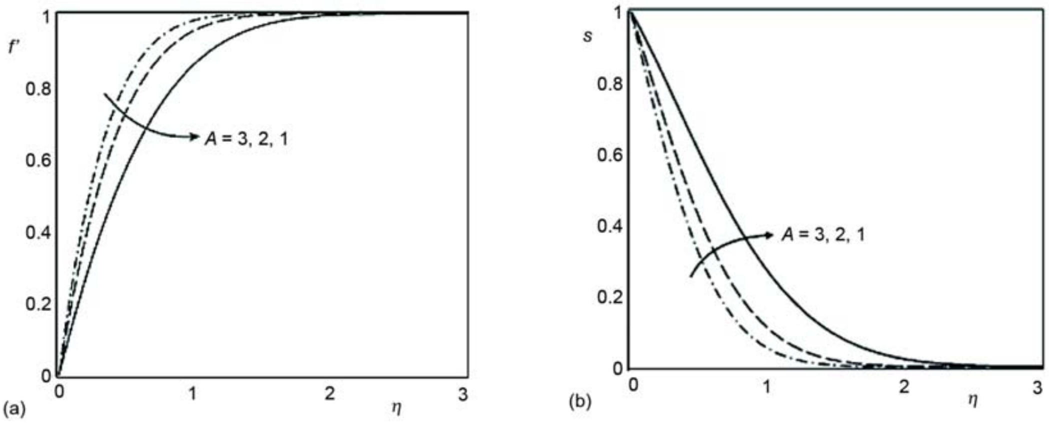

Figure 2. Effects of acceleration parameter on hydrodynamic boundary layers along x- and z-directions when $Nt = Nb = 0.1$, Le = 2, and λ = Pr = 1

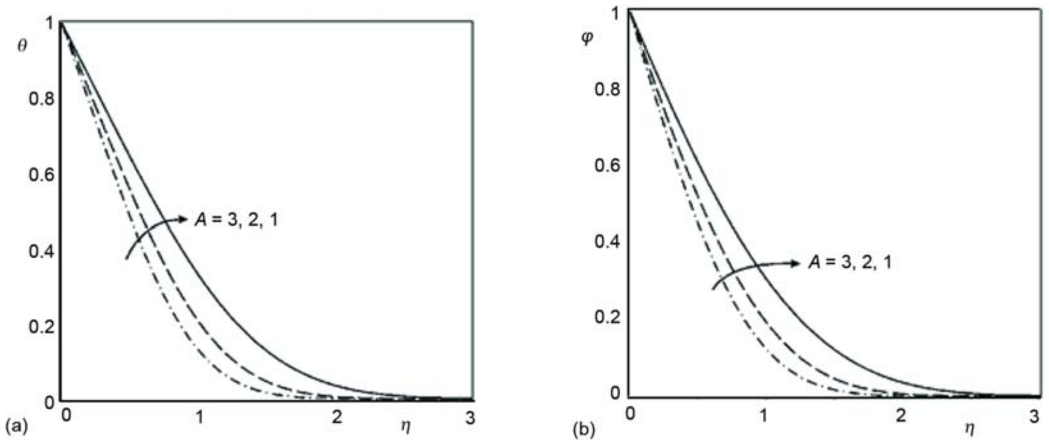

Figure 3. Effects of acceleration parameter on temperature and concentration profiles when $Nt = Nb = 0.1$, Le = 2, and λ = Pr = 1

Conclusions

A numerical study on the unsteady boundary layer flow and heat transfer of nanofluid in the stagnation point region over a time-dependent rotating sphere has been performed. The employed model for nanofluid includes two-component four-equation non-homogeneous equilibrium model that incorporates the effects of Brownian diffusion and thermophoresis simultaneously. Governing PDE including continuity, momentum and heat transport in nanofluids have been transformed into ODE ones via similarity variable. The bold outcomes of this paper can be summarized as follows:

- As acceleration parameter A and rotation parameter λ increase, surface shear stresses, reduced Nusselt and Sherwood numbers climb up.

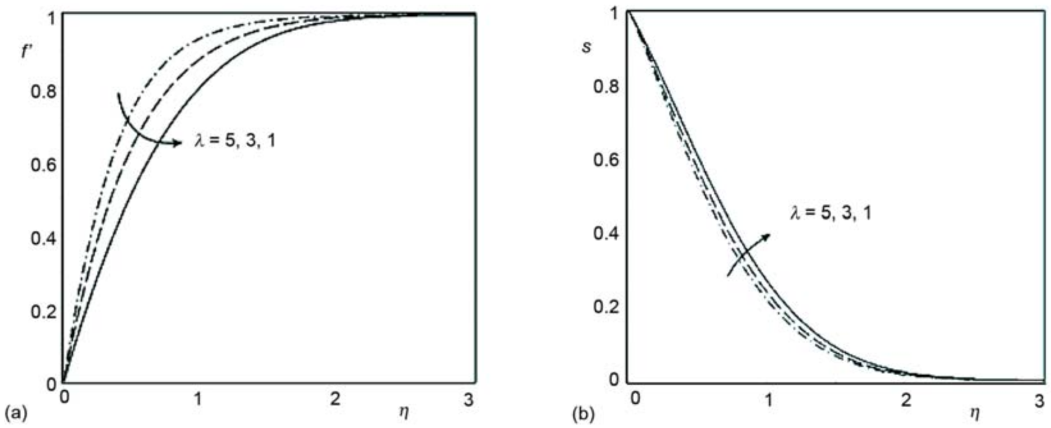

Figure 4. Effects of dimensionless rotation parameter on hydrodynamic boundary layers along x- and z-directions when *Nt* = *Nb* = 0.1, Le = 2, and A = Pr = 1

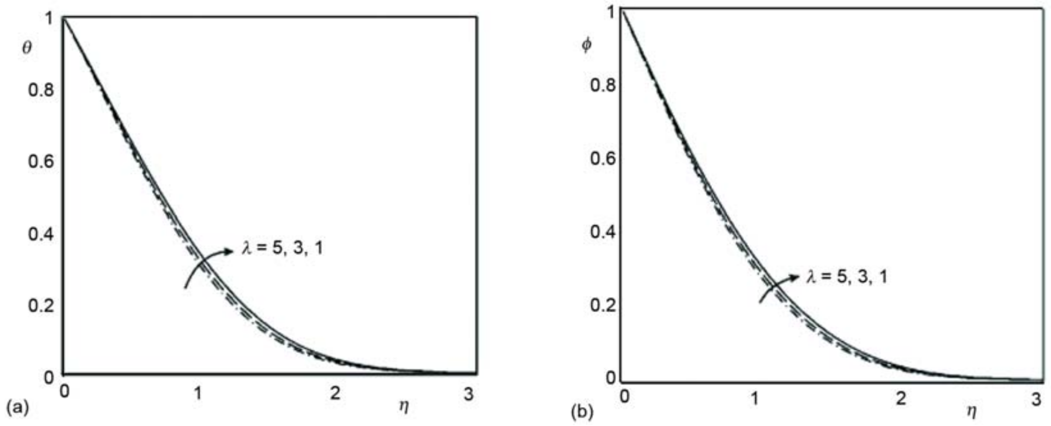

Figure 5. Effects of dimensionless rotation parameter on temperature and concentration profiles when *Nt* = *Nb* = 0.1, Le = 2, and *A* = Pr = 1

- It is observed that unlike concentration rate, a rise in Prandtl number increases reduced Nusselt number.
- Increasing in thermophoresis, leads to decrease in the values of reduced Nusselt and Sherwood numbers. In addition, as Brownian motion grows, unlike reduced Sherwood number, reduced Nusselt number takes a decreasing trend.
- Observed that as Lewis number intensifies, concentration rate increases, however, heat transfer rate decreases.

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