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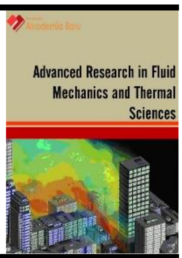

Numerical Solution of Boundary Layer Flow over a Moving Plate in a Nanofluid with Viscous Dissipation: A Revised Model

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ABSTRACT

Model of boundary layer flow over a moving plate in nanofluid with viscous dissipation effect is revisited. A new boundary condition is applied with the assumption that there is no nanoparticle flux at the surface. The nanoparticle volume fraction on the boundary is passively control rather than active control and this makes the model more realistic. A similarity transformation is introduced to reduce the governing non-linear partial differential equation into ordinary differential equation. The ordinary differential equations are computed numerically through numerical method namely Runge-Kutta Felhberg (RKF) technique. Validations of the result has been made by comparing the present results with results from the previous studies. In this study, it is found that the presence of viscous dissipation contributes to an increase in temperature profile. In addition, it is observed that an increment in Brownian motion parameter produce negligible effect on temperature profile. Furthermore, both nanoparticle concentration and temperature profile intensify with an increase of thermophoresis parameter.

1. Introduction

During the past few decades, the study of heat transfer of nanofluid is in the limelight due to its potential in increasing the rate of heat transfer and wide application in industry ranging from electronic devices, engine cooling system as well as biomedical and biotechnology field. The term nanofluid was first coined by Choi [1] and it is a liquid suspensions that contain nanometer sizes particles (nanoparticles) with diameter less than 50nm [2]. Nanofluid has been investigated widely for the enhancement of thermophysical properties specifically in thermal conductivity, thermal diffusivity, convective heat transfer coefficients and viscosity. In fact, a few study has been conducted to predict the special influence of nanofluid in enhancement of convective heat transfer. AbuBakar *et al.,* [3] presented the numerical study of steady nanofluid in rectangular microchannel and estimated that heat transfer process inside microchannel will increase with the addition of

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nanoparticles to the base fluid. Muhammad and Sidik [4] predicted that nanofluid will increase the heat transfer coefficient to a certain magnitude besides having higher thermal conductivity than water. Buongiorno [5] introduced a model of nanofluid that includes thermophoresis and Brownian motion as two important slip mechanisms that formed relative velocity between base fluid and nanoparticles. This model has been extensively employed by many researchers in their studies of different type of problem relating convective transport of nanofluid. Nield and Kuznetsov [6] and Kuznetsov and Nield [7] applied the model that features Brownian motion and thermophoresis in their studies to examine the natural convective boundary layer flow of nanofluid past a porous medium and vertical plate. Chamka *et al.,* [8] displayed that flow, heat and nanoparticle volume fraction in a non-Darcy porous medium saturated with nanofluid could be affected by viscous dissipation effect and MHD. Hussain *et al.,* [9] examined the effects of viscous dissipation and Joule heating on MHD Sisko nanofluid over a stretching cylinder. Ibrahim [10] investigated the effect of melting on heat and mass transfer of MHD boundary layer stagnation point flow of nanofluid past a stretching sheet. The results revealed that velocity, thermal, and concentration boundary layer thickness increased as melting parameter increases.

Revised model of nanofluid was first introduced by Kuznetsov and Nield [11]. In their study, new boundary condition was introduced considering nanoparticle volume fraction is passively controlled rather than actively control. It is assumed that nanoparticle flux at the wall is zero. The model that was used previously has assumed that the nanoparticle fraction could be controlled in similar way as the temperature can be controlled. However, it can be difficult to control nanoparticle volume fraction at the boundary besides there is no suggestion has been made on how the nanoparticle volume fraction at the boundary can be held constant [12]. A few recent study includes Ishfaq *et al.,* [13] has revisited previous model for the boundary layer nanofluid flow past a stretching surface with a specified nanoparticle volume fraction on the surface. Waqas *et al.,* [14] investigated the magnetohydrodynamics (MHD) flow of Carreau nanofluid by exponentially convected stretchable surface. They discovered that thermal boundary layer and nanoparticle volume fraction enhanced with increasing thermophoresis parameter. Jahan *et al.,* [15] noticed that Brownian motion does not have influence on heat transfer rate. Pop *et al.,* [12] stated that an increase in thermophoresis parameter has a decreasing effect on heat transfer rate but an increasing effect on the mass transfer rate. Further, Jusoh *et al.,* [16] investigated the 3D flow of a nanofluid over a stretching sheet by employing Buongiorno’s model. Afterwards, Zokri *et al.,* [17] analyzed the flow over a moving plate in MHD Jeffrey nanofluid. It is demonstrated that the temperature profile increase with rising thermophoresis parameter but decrease with an increasing Jeffrey fluid parameter and plate velocity parameter. Tripathi *et al.,* [18] analyzed the effect of viscous dissipation in the study of double diffusive flow of a hydromagnetic nanofluid in a rotating channel. They concluded that the nanoparticle volume fraction has negative value due to the influence of passively control nanoparticles.

Viscous dissipation is the process when the viscosity of the fluid provides resistance to the fluid motion and irreversibly converted the mechanical energy into internal energy. This effect are often considered as a negligible effect but it becomes significant for the fluid with high viscous flow and moderate velocity, high velocity and fluid that has average velocities and Prandtl number Mohamed *et al.,* [19]. Viscous dissipation causes an increase in the fluid temperature. It has a significant role as an energy sources which make a difference in temperature distribution hence affecting the heat transfer rate Hayat *et al.,* [20]. Makinde [21] investigated the effects of Newtonian heating and viscous dissipation over a moving plate in nanofluid. Next, Ferdows *et al.,* [22] examined the viscous dissipation effects over a permeable unsteady stretching sheet in nanofluid. The results indicated a significant increase in temperature profile with the presence of viscous dissipation. Chamkha *et al.,*

[8] stated that rise in the viscous dissipation parameter is increasing nanoparticle mass transfer rate and velocity profile while reducing the heat transfer rate and nanoparticle volume fraction. Zokri *et al.,* [23] demonstrated that nanoparticle volume fraction is in decreasing function with the increase in Lewis number and Brownian motion. Mohamed *et al.,* [19] investigated the effect of viscous dissipation on forced convection flow over a moving plate. The result indicated that the presence of viscous dissipation decreased the velocity of plate parameter.

The problem of flow over a moving plate has varied applications in industry such as in polymer and metal extrusion, hot rolling, glass blowing, electrotinning of steel sheets and copper wire. This problem was first study by Sakiadis [24] who investigated boundary layer behavior on a moving continuous surface. The flow over a moving flat plate in an ambient fluid was found to be different than the Blasius flow over a fixed surface. This study were later extended experimentally by Tsou *et al.,* [25] who investigated temperature profile and flow in the boundary layer for both laminar and turbulent situations. Pop *et al.,* [26] analyzed the effect of vary viscosity of fluid and pointed out that the viscosity varied because of the variation of temperature. Rosca and Pop [27] explored the unsteady boundary layer flow past moving plate in an external uniform free stream and Dzulkifli *et al.,* [28] extended the study and considered the influence of partial slip condition. Mohamed *et al.,* [19] demonstrated thermal boundary layer thickness and nanoparticle volume fraction reduced with an increasing plate velocity parameter and this is supported by [17].

The present paper aims to investigate the passive control of nanoparticle at the boundary in nanofluid with viscous dissipation effect over a moving plate. The model proposed by Mohamed *et al.,* [19] on the effect of viscous dissipation on boundary layer flow immersed in nanofluid is revisited. Buongiorno's nanofluid model is applied and nanoparticle flux at the boundary is assumed to be zero. The governing nonlinear partial differential equations were transformed to ordinary differential equations by using similarity equations and solved numerically using Runge-Kutta Felhberg (RKF) technique. The results for temperature and nanoparticle volume fraction graphs were further analysed and discussed. To the best of our knowledge, the present study has not been published before and therefore it is new.

2. Mathematical Formulations

A steady, laminar two-dimensional flow over a moving plate immersed in nanofluid is considered in this problem. The plate is moving with constant velocity $u_w(x) = \varepsilon U_\infty$ where u_w is the plate velocity, ε is plate velocity parameter and x and y are the coordinates system measured along the moving plate as presented in Figure 1. U_∞, T_∞ and C_∞ represents undisturbed free stream velocity, ambient temperature and ambient nanoparticle concentration while C, C_w, T and T_w refers to nanoparticle volume fraction, nanoparticle volume fraction at the surface, temperature inside the boundary layer and temperature at the wall. The effect of viscous dissipation is considered in this study and the nanoparticle volume fraction at the boundary is assumed to be passively control. Based on the boundary layer approximation and physical conditions, the governing boundary layer equations are:

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2}+\tau\left[D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right]+\frac{\mu}{\rho C_p}\left(\frac{\partial u}{\partial y}\right)^2 \quad (3)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}+\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2} \quad (4)$$

subjected to the boundary condition,

$$\begin{aligned} &u=u_w(x)=\varepsilon U_\infty,\ \ v=0, T=T_w,\quad D_B\frac{\partial C}{\partial y}+\frac{D_T}{T_\infty}\frac{\partial T}{\partial y}=0 \quad \text{at} \quad y=0 \\ &u=U_\infty, T\to T_\infty, C\to C_\infty \quad \text{as} \quad y\to\infty \end{aligned} \quad (5)$$

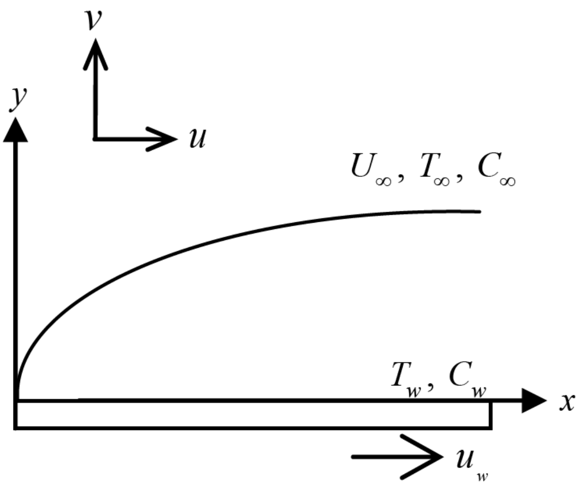

Fig. 1. Physical model of the coordinate system

where u and v are the velocity components along the x and y axes. ρ represents the density of nanofluid, v is the kinematic viscosity, μ is the dynamic viscosity and k is the thermal conductivity. Additionally, τ represents heat capacity, D_B is the Brownian diffusion coefficient and D_τ is the thermophoretic diffusion coefficient.

In order to obtain the similarity solution for Eq. (1) until (4), we consider the following similarity transformation variables

$$\eta=\left(\frac{U_\infty}{2\nu x}\right)^{1/2} y, \psi=\left(2U_\infty \nu x\right)^{1/2} f(\eta), \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty}, \ \phi(\eta)=\frac{C-C_\infty}{C_\infty} \quad (6)$$

where ψ is the stream function defined as $u=\frac{\partial\psi}{\partial y}$ and $v=\frac{\partial\psi}{\partial x}$. After substituting Eq. (5) and (6) into (1) to (4), we found that (1) is identically satisfied while Eq. (2) to (4) become

$$f'''+ff''=0 \quad (7)$$

$$\frac{1}{\Pr}\theta'' + f\theta' + N_b\theta'\phi' + N_t\theta'^2 + Ec\left(f''\right)^2 = 0 \tag{8}$$

$$\phi'' + \frac{N_t}{N_b}\theta'' + Lef\phi' = 0 \tag{9}$$

the boundary condition (5) becomes

$$f(0) = 0,\ f'(0) = \varepsilon, \theta(0) = 1, N_b\phi'(0) + N_t\theta'(0) = 0 \tag{10}$$

$$f'(\eta) \to 1, \theta(\eta) \to 0, \phi(\eta) \to 0 \tag{11}$$

where

$Pr = \frac{\nu\rho c_p}{k}$, $N_b = \frac{\tau D_B C_\infty}{\upsilon}$, $N_t = \frac{\tau D_t(T_w - T_\infty)}{T_\infty \upsilon}$, $Ec = \frac{(U_\infty)^2}{C_p(T_w - T_\infty)}$ and $Le = \frac{\upsilon}{D_B}$ denote the Prandtl number, Brownian motion parameter, thermophoresis parameter, Eckert number and Lewis number respectively.

3. Results

In this study, five parameters will be considered, namely plate velocity parameter ε, the Brownian motion parameter N_b, the thermophoresis parameter N_t, the Eckert number Ec and the Lewis number Le. We solved using Runge-Kutta Felhberg (RKF) technique for the ordinary differential Eq. (7) until (9) and boundary conditions (10). The results of viscous dissipation effects Ec, Brownian motion N_b, thermophoresis N_t on thermal boundary layer and nanoparticle volume fraction were analysed and discussed. In this study, the values of the parameter are as stated here unless mentioned otherwise: Pr= 7, ε= 0.5, N_b= 0.1, N_t= 0.1, Ec = 0.1, Le = 10.

Table 1
Comparative values of $-\theta'(0)/\sqrt{2}$ for dissimilar values of Pr when $\varepsilon = N_t = N_b = Ec = Le = 0$

Pr	Rosca and Pop [27]	Mohamed *et al.,* [19]	Present
0.7	0.29268	0.292680	0.292680
0.8	0.30691	0.306917	0.306917
1	0.33205	0.332057	0.332057
5	0.57668	0.576689	0.576689
10	0.72814	0.728141	0.728141

We computed the values of $-\theta'(0)/\sqrt{2}$ to compare with the limiting cases from previous study in order to confirm the validity of the present values. Table 1 presents the existing results done by Mohamed *et al.,* [19] and Rosca and Pop [27]. They solved using Keller box method and bvp4c function in MATLAB whereas the present results were computed using Runge-Kutta Felhberg method. All of them are found to be in a good agreement which prove the accurateness of the present results.

Figure 2 presented the effect of thermophoresis diffusion parameter on thermal boundary layer. The thermal boundary layer thickness increase with an increase of thermophoresis diffusion parameter. Waqas *et al.,* [14] stated that in thermophoresis, the particle from the heated region is transferred to the cold region. Thus, this causes the nanofluid temperature to be increasing due to huge number of nanoparticles shifted from the hot region which enhance the fluid temperature. In Figure 3, it is noticed that Brownian motion parameter does not put any effect on temperature profile. This is probably due to zero nanoparticle flux condition where in this condition the nanoparticle flux is suppressed and does not give any influence on the temperature [13]. Therefore, the effect of Brownian motion is concluded to be negligible on the temperature.

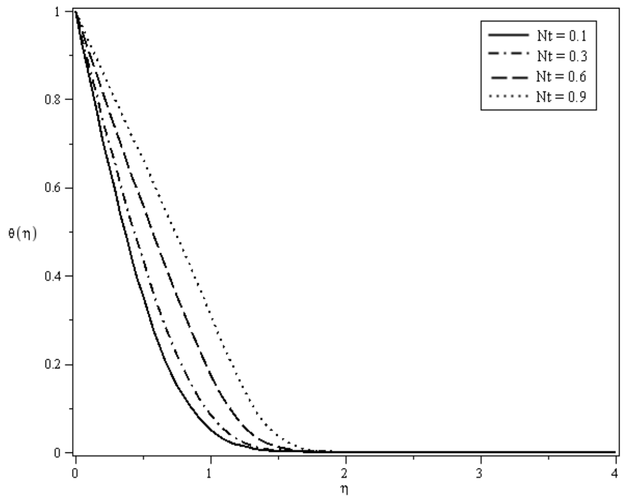

Fig. 2. Temperature profiles $\theta(\eta)$ with different values of N_t

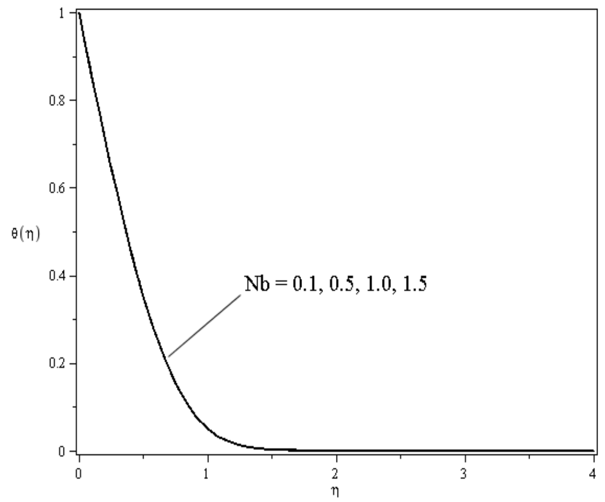

Fig. 3. Temperature profiles $\theta(\eta)$ with different values of N_b

Figure 4 illustrates an increase of thermal boundary layer thickness with an increase in Eckert number. Enhancement of Eckert number means more kinetic energy is converted to internal energy and more dissipated heat is stored in the liquid thus causes the temperature profile to increase [23]. On the other hand, Figure 5 shows that Lewis number have negligible effect on temperature. This is due to the relationship between Lewis number and Brownian diffusion. An increase in Lewis number will cause a weaker Brownian diffusion coefficient and vice versa [19]. Hence, due to the zero nanoparticle condition that applied in this study, Lewis number Le, do not give any impact on the temperature.

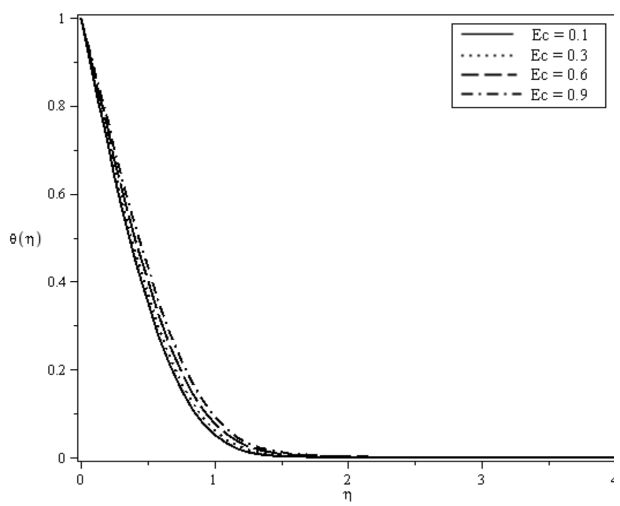

Fig. 4. Temperature profiles $\theta(\eta)$ with different values of Ec

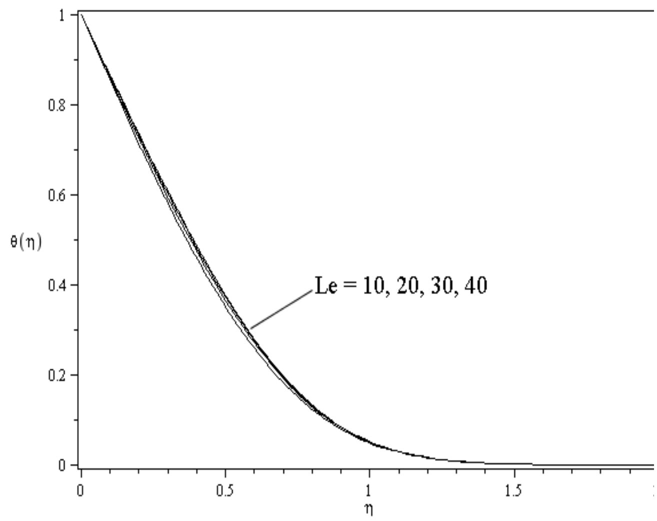

Fig. 5. Temperature profiles $\theta(\eta)$ with different values of Le

It is observed that a rise in the value of velocity plate parameter $(\varepsilon > 0)$ would result to the decrease of thermal boundary layer thickness in Figure 6. When the plate velocity parameter increase, the difference between ratio velocity of plate and fluid will arises. This help the fluid to flow over the region faster and shrink the thermal boundary layer thickness [19]. On the other hand, Figure 7 and Figure 8 displayed the value of nanoparticle volume fraction which in negative value. In Figure 7, increase in Brownian motion decrease the nanoparticle volume fraction. In contrary, increase in thermophoresis parameter in Figure 8, increase the nanoparticle volume fraction. This occur due to the condition of zero nanoparticle flux implying the passive control of nanoparticle flux at the surface [13]. In Figure 9, it is observed an increase in Eckert number reduced the nanoparticle concentration profile.

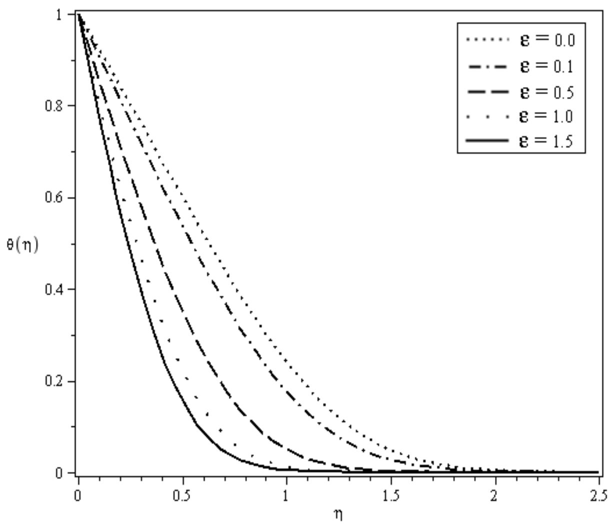

Fig. 6. Temperature profiles $\theta(\eta)$ with different values of ε

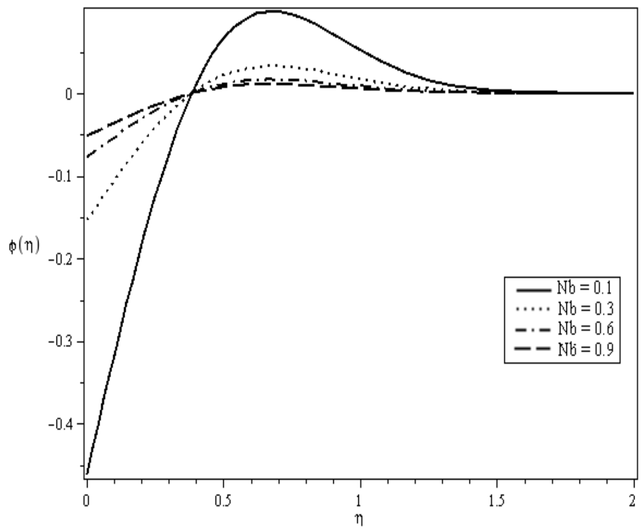

Fig. 7. Nanoparticle volume fraction $\emptyset(\eta)$ with different values of N_b

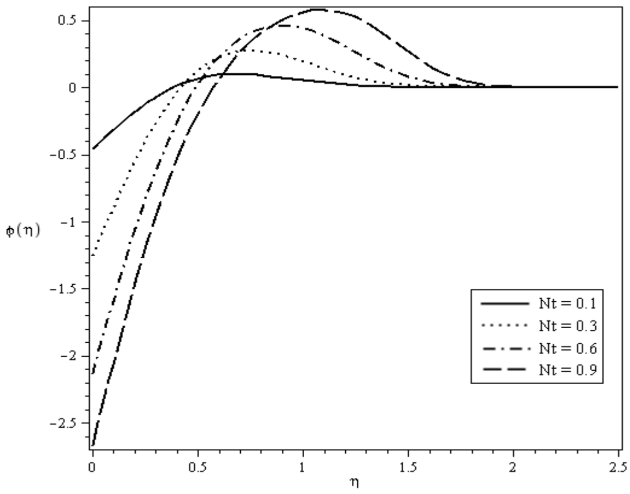

Fig. 8. Nanoparticle volume fraction $\emptyset(\eta)$ with different values of N_t

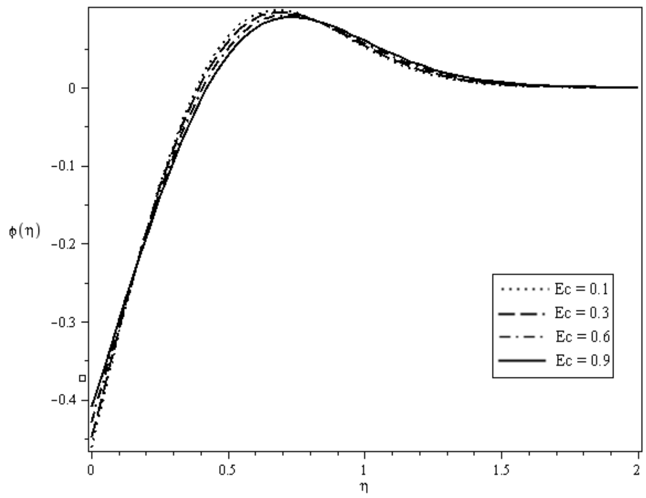

Fig. 9. Nanoparticle volume fraction $\emptyset(\eta)$ with different values of Ec

4. Conclusions

In this study, the problem of passive control of nanoparticle at the boundary in nanofluid with viscous dissipation effect over a moving plate has been solved via numerical approach. A new boundary condition with more realistic condition was formulated which assumes the nanoparticle at the boundary is passively rather than actively control. The results of this investigation can be concluded in the following details

i. Temperature profile increase with the presence of viscous dissipation effect. However, the nanoparticle volume fraction was decreased with an increase in Eckert number.
ii. Brownian motion parameter N_b produced negligible effects on temperature profile.
iii. Increment in thermophoresis parameter N_t increased the temperature profile and nanoparticle volume fraction.
iv. A variation in Lewis number Le have negligible effect on the temperature profile.
v. Increase in the value of velocity plate parameter $(\varepsilon > 0)$ would result to the decrease of thermal boundary layer thickness.
vi. The value of nanoparticle volume fraction for revised model is in negative value after we tested with different values of $N_b$andN_t. An increase in Brownian $N_b$motion reduced the nanoparticle volume fraction.
vii. Increase in thermophoresis parameter N_t increased the nanoparticle volume fraction.

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