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Thermal Performance Analysis of Nanofluid Past an Exponentially Stretching Surface Due to the Electrification Effect of Nanoparticles

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Abstract

The present study deals with the heat transfer performance of Cu-Water nanofluid flow over an exponentially stretching surface due to the combined effect of nanoparticle electrification and viscous dissipation. Buongiorno's model is adopted to formulate the physical model of the problem involving the mechanism of nanoparticle electrification and viscous dissipation. The set of governing partial differential equations are solved numerically using the bvp4c function of MATLAB package after transforming them into non-linear ordinary differential equations with the help of similarity transformation. The impact of different flow quantities on fluid velocity, temperature and the concentration of nanoparticles are analysed and examined through graphs. The physical parameters like skin friction coefficient, rates of heat & mass transfer are derived and presented through tables. It is observed that, the thermal conductivity of working fluid is enhanced due to the influence of charged nanoparticles. Hence, the electrification effect of nanoparticles may be a beneficial mechanism to obtain the expected thermal performance of nanofluids.

Keywords: Exponentially stretching surface, Viscous dissipation, Electrification Effect of nanoparticle and bvp4c function.

1. INTRODUCTION

The main branch of modern fluid dynamics is the study of heat transfer from solid geometry to an ambient fluid due to the continuous stretching of the sheet/surface through the free stream. These types of heat transfer studies have a large number of significant technological applications in various branches of science and engineering process [37] like polymer processing, glass and paper production, crystal growing, geothermal engineering, rolling and industrial of plastic films, tinning and annealing of copper wires, drawing of artificial fibbers, oil reservoirs and metallurgical process] etc as the quality of the final product in these processes depends on the rate of heat transfer at the stretching surface. Motivated by these industrial applications, Sakiadis[15] has first studied the boundary layer flow of fluid over a continuous solid surface moving with a constant velocity and then this investigation has extended by Erickson et al. [5] by adopting the suction/injection effect at a stretched surface moving with a constant velocity. Crane [16] has investigated the boundary layer flow caused by a stretching sheet which moves with a velocity varying linearly with the distance from a fixed point.

Heat transfer plays an important role in many fields due to the heating/cooling process involved. Increasing the heat transfer efficiency in macro- and nano-devices is desirable because by increasing efficiency reduced process time of work and lengthen the working life of equipment. Heat transfer efficiency can be improved by increasing the thermal conductivity of the fluid. Theoretical understanding of the enhancement in thermal conductivity model was initially attempted by Maxwell [19]. The nanoscale solid particles are submerged into the base fluids which change the thermophysical characteristics of conventional heat transfer fluids (such as oil, water, kerosene etc.) and then their enhancement of the heat transfer rate .This fluids are said to be nanofluids. Nanofluids have high potential to heat transfer rate in engineering systems.

Boundary layer flow behaviour over an exponentially stretching sheet have many more engineering applications such as the cooling process of metallic plate, drawing of plastic films, manufacture of foods, continues coating etc.[7,8,9,10,23]. Sohail Nadeem and Changhoon Lee [1] was first to study the boundary layer flow of nanofluid over an exponentially stretching surface. After that, Magyari et al.[13] has investigated the steady boundary layers on an exponentially stretching continuous surface with an exponential temperature distribution. Anuar Ishak [7] has studied the effect of radiation on MHD boundary layer flow of a viscous fluid over an exponentially stretching sheet.

Buongiorno[23] has investigated that the different theories enhanced thermal conductivity characteristics of nanofluid and he developed a seven slip mechanism for nanofluids that can produce a relative velocity between the nanoparticle and base fluids. Based on the size of the particle into the nanometer scale, Brownian motion and thermphoresis are play an important role in heat transfer mechanism and also Buonmgiorno performed a detailed analysis of non-homogeneity on convective transport in nanofluid flow.

Swati Mukhopadhyay [2] has investigated the axi-symmetric laminar boundary layer flow of a viscous incompressible fluid and heat transfer towards a stretching cylinder under the influence of a uniform magnetic field. An analytical solution for MHD boundary layer flow of a viscous incompressible fluid over an exponentially stretching sheet has analysed by Mabood et al.[3]. Raza et al.[8] has investigated the problem of MHD radiation flow over an exponentially sheet through a porous medium. Anwar et al.[9] has considered the radiation effect on magneto hydrodynamics (MHD) stagnation-point flow of a nanofluid over an exponentially stretching sheet under the assumptions of a small magnetic Reynolds number.

From the above literatures, though some few investigators [38-43] have given their efforts towards the investigations regarding electrification effects of nanoparticles on flow and heat transfer of working fluids over several geometries, still there is no consulted effort has given to study such effect on exponentially stretching sheet. In this regards, the current exploration is the extension work of the investigation conducted by Bidin and Nazar [11] and the purpose of our study is to investigate the effects of electrification of nanoparticles on the flow and heat transfer over an exponentially stretching sheet**.** To conduct the observation, we have considered the water as base fluid which is electrically non-conducting and copper (Cu) as nanoparticle. The physical properties of concerned working fluid and nanoparticles are shown in table 1.

2. PHYSICAL MODELING

The steady, incompressible, laminar, two-dimensional boundary layer flow and heat transfer of nanofluid on an exponentially stretching sheet has considered with the ambient values of temperature and concentration denoted by T_∞ and C_∞ respectively.

The cartesian co-ordinate system is considered in such a way that x-axis is taken along the stretching sheet and the y-axis, normal to it. The sheet is exponentially stretched along the x-direction with a velocity $U_W = U_0 e^{\frac{x}{L}}$ defined at y=0. The sheet is maintained at constant temperature and concentration T_W and C_W respectively. The values of T_W and C_W are assumed to be greater than the values of T_∞ and C_∞ respectively. The flow configuration and co-ordinate system of the problem is shown in fig.1.

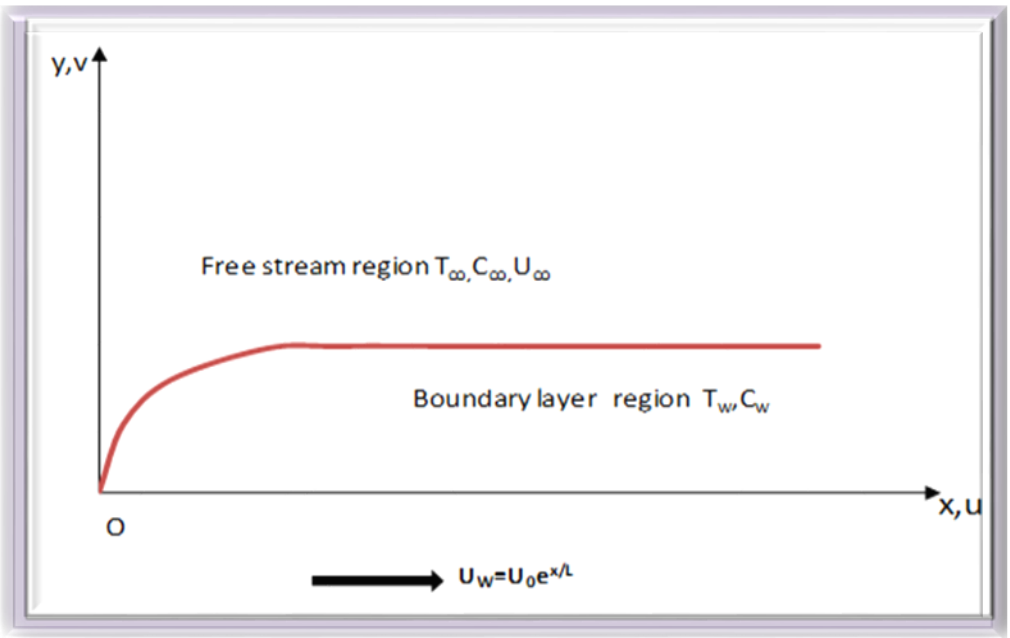

Figure 1. Physical model of co-ordinate system

3. MATHEMATICAL MODELING

3.1. GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

Under the above assumptions, the governing equations describing the momentum, energy and concentration in the presence of electrification of nanoparticle and heat due to the viscous dissipation are given by:

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

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}+\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2}+\left(\frac{q}{m}\right)\frac{1}{F}\left(\frac{\partial (CE_x)}{\partial x}+\frac{\partial (CE_y)}{\partial y}\right) \tag{2}$$

$$\left[u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right]=-\frac{C_\infty \rho_s}{(\rho)_{nf}}\left(\frac{q}{m}\right)E_x+\quad {}_{nf}\frac{\partial^2 u}{\partial y^2}+\frac{C\rho_s}{\rho_{nf}}\left(\frac{q}{m}\right)E_x \tag{3}$$

$$\left[u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right]=\frac{k_{nf}}{(\rho c)_{nf}}\left[\frac{\partial^2 T}{\partial y^2}\right]+\frac{\rho_s c_s}{(\rho c)_{nf}}D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{\rho_s c_s D_T}{(\rho c)_{nf}T}\left(\frac{\partial T}{\partial y}\right)^2+$$
$$\frac{1}{(\rho c)_{nf}}\left(\frac{q}{m}\right)\frac{Cc_s\rho_s}{F}\left(E_x\frac{\partial T}{\partial x}+E_y\frac{\partial T}{\partial y}\right)+\frac{\mu_{nf}}{(\rho c)_{nf}}\left(\frac{\partial u}{\partial y}\right)^2 \tag{4}$$

Here, ρ_{nf} is Effective density, α_{nf} is Thermal diffusivity, $(\rho c_p)_{nf}$ is Heat capacity, μ_{nf} is Effective dynamic viscosity, k_{nf} is thermal conductivity. The relevant boundary conditions applicable to the present problem are

$$y=0, u=U_0e^{\frac{x}{L}}, v=0, T=T_w=T_\infty+T_0e^{\frac{x}{2L}}, C=C_w\ y=\infty, u=0, T=T_\infty, C=C_\infty\ \} \tag{5}$$

3.2. SIMILARITY TRANSFORMATION

Equation (1) is satisfied for the following similarity variables

$$\eta=\sqrt{\frac{U_0}{2\ fL}}\ e^{\frac{x}{2L}}y, u=U_0\ e^{\frac{x}{L}}f', v=-\sqrt{\frac{fU_0}{2L}}\ e^{\frac{x}{2L}}\{f+\eta f'\}, \theta=\frac{T-T_\infty}{T_W-T_\infty}, s=\frac{C-C_\infty}{C_W-C_\infty}\} \tag{6}$$

Where η is the similarity variable, Ψ is the stream function f, θ, s are dimensionless stream function, temperature and concentrations respectively. So, to convert the above partial differential equations (2-4) into ordinary differential equations, the similarity variables are introduced and the corresponding ODEs are as follows.

Momentum equation:

$$f'''+\frac{\left[ff''-2f'^2\right]}{\varphi_1}+2\varphi_2\frac{M\ Nb\ Sc\ S}{\varphi_1 N_F}=0 \tag{7}$$

Energy equation:

$$\theta''+\frac{Pr}{\varphi_3\,\varphi_4}[f'\theta-f\theta']+\frac{Pr\ Nb}{\varphi_4}S'\theta'+\frac{Pr\ Nt}{\varphi_4}\theta'^2+\frac{Pr(S+Nc)\ MNb\ Sc}{\varphi_4}(\theta+\eta\theta')+$$
$$\frac{Pr}{\varphi_4}\frac{2N_F Nb\ Sc\ \eta\theta'}{N_{Re}}+\frac{Pr}{\varphi_4}Ec\varphi_5 f''^2=0 \tag{8}$$

Concentration equation :

$$S'' + ScfS' + \frac{Nt\theta''}{Nb} + M\,ScS'\eta + 2\frac{1}{N_{Re}}N_F Sc(S + Nc + S'\eta) = 0 \tag{9}$$

The boundary conditions are taken as in terms of η

$$\eta = 0, f = 0, f' = 1, \theta = 1, s = 1\ \eta \to \infty, f' \to 0, \theta \to 0, s \to 0\,\} \tag{10}$$

Here, the non dimensional parameters Sc (Schimdt number), Nt (Thermophoresis parameter), Nb (Brownian diffusion parameter), $\frac{1}{N_{Re}}$ (Electric Reynolds number), N_C $(Concentration\ ratio\ parameter)$, N_F (Momentum Transfer number), M(Electrification parameter), Pr (Prandtl number), Ec **(**Eckert number) are defined as follows

$$Sc = \frac{f}{D_B}, Nt = \frac{(\rho c)_s D_T(T_f - T_\infty)}{(\rho c)_f \nu_f}, Nb = \frac{(\rho c)_s D_B(C_W - C_\infty)}{(\rho c)_f \nu_f}, \frac{1}{N_{Re}} = \left(\frac{q}{m}\right)^2 \frac{\rho_s}{\epsilon_0}\frac{L^2}{\left(U_0\, e^{\frac{x}{L}}\right)^2}, N_C = \frac{C_\infty}{(C_W - C_\infty)},$$

$$N_F = \frac{U_0\, e^{\frac{x}{L}}}{FL}, M = \frac{q}{m}\frac{1}{FU_0\, e^{\frac{x}{L}}}E_x, Pr = \frac{\nu_f}{\alpha_f}, Ec = \frac{U_\infty{}^2}{c_f(T_f - T_\infty)},$$

And the thermo physical constants $\varphi_{1,}, \varphi_{2,}\varphi_{3,}\varphi_{4,}\varphi_5$ are defined as follows

$$\frac{nf}{f} = \varphi_{1,}\ \frac{\rho_s}{\rho_{nf}}\frac{(\rho C)_f}{(\rho C)_s} = \varphi_2, \frac{1}{\left[C_\infty \frac{c_s\rho_s}{c_f\rho_f} + (1 - C_\infty)\right]} = \varphi_3, \frac{\alpha_{nf}}{f} = \frac{\varphi_3}{pr}\varphi_4 \text{ and } k_{nf} = \varphi_4, \frac{1}{(1 - C_\infty)^{2.5}} = \varphi_5$$

4. COMPUTATIONAL ANALYSIS

4.1. NUMERICAL COMPUTATION

To solve the non-linear ordinary differential equations (7)-(9) subject to the boundary condition (10), we have adopted the boundary value problem with forth order accuracy (bvp4c) function of Matlab [8]. In this investigation we have considered copper (Cu) nano particles with pure water as a base working fluid. The nano particle volume fraction (φ) is taken as 0.01 and the thermo physical properties of Base fluid (water) and Nano particle (Cu) are shown in the table-1.

Table 1. Thermo physical properties of Base fluid and Nanoparticle [36]

Physical properties	Base fluid	Nanoparticles
	Water	Cu
$C_p(J/kgK)$	4179	385
$\rho(kg/m^3)$	997.1	8933
$k(W/mK)$	0.613	400

4.2. VALIDATION OF RESULTS

To get the validity of our computed results, a comparison of current result for prescribed surface temperature [PST] corresponding to the values of heat transfer coefficient $[-\theta'(0)]$ with *Ec=0,Nb=Nt=M=0* for which the problem reduced to regular fluid flow with the available published results of Magyari and Keller [13],Bidin and Nazar [11],El- Aziz[32] and Ishk [7] is made and presented in table 3. It is observed that, our calculated results are favourable with them, for which we believe that our computed results are correct and accurate.

Table 2. Comparison between numerical results obtained and previous published results at *Ec=0,Nb=Nt=M=0* (Values of $[-\theta'(0)]$ [PST] for several values of prandtl number)

Pr	Magyari and Keller [13]	Bidin and Nazar [11]	El-ziz [32]	Ishk [7]	I.S. Mandal and S. Mukhopdhyay [34]	Present study
1	0.9548	0.9547	0.9548		0.9548	0.95478
2		1.4714			1.4715	1.47146
3	1.8691	1.8691	1.8691	1.8691	1.8691	1.86907
5	2.5001		2.5001	2.5001	2.5001	2.50083
10	3.6604		3.6604	3.6604	3.6603	3.66034

5. DISCUSSION OF RESULTS

The influence of several flow parameters like electrification parameter (*M*), Eckert number (*Ec*), Thermophoresis parameter (*Nt*) and Brownian diffusion parameter (*Nb*) on heat and mass transfer characteristics are investigated and the results are presented through graphs. The numerical computation on reduced Skin Friction, reduced Nusselt number and reduced Sherwood number are presented in tabular form through table 3.

Table 3: Numerical values of $f''(0), -\theta'(0)\ and\ -S'(0)$ for varied values of Flow Parameters

M	Nb	Nt	N_{Re}	N_F	Sc	Ec	Nc	$f''(0)$	$-\theta'(0)$	$S'(0)$
0.01	0.1	0.1	5.0	4.0	0.1	0.1	1.0	1.31083	4.33898	8.57292
		0.2						1.31051	4.30974	12.79083
		0.3						1.31020	4.28060	16.95062
0.01	0.05	0.1	5.0	4.0	0.1	0.1	1.0	1.31276	3.43238	11.06853
	0.09							1.31120	4.15098	8.84462
	0.1							1.31083	4.33898	8.57292
0.01	0.1	0.1	5.0	4.0	0.1	0.1	1.0	1.31083	4.33898	8.57292
						0.2		1.31084	4.09914	8.33400

M	Nb	Nt	N_{Re}	N_F	Sc	Ec	Nc	$f''(0)$	$-\theta'(0)$	$S'(0)$
						0.3		1.31085	3.85964	8.09543
						0.4		1.31086	3.61981	7.85651
0.01								1.31083	4.33898	8.57292
0.1								1.28600	4.07410	7.65512
0.3	0.1	0.1	5.0	4.0	0.1	0.1	1.0	1.25286	3.74994	6.50896
0.5								1.22981	3.55453	5.79971
0.7								1.21145	3.41890	5.29729

From table 3, it is observed that, the reduced skin friction is a decreasing function of all flow parameters *M*, *Nb and Nt* except *Ec* where as the reduced Nusselt Number is decreasing function of *M*, *Ec* and *Nt* but increasing function of *Nb*. Also it is observed that the reduced Sherwood's number is reducing due to the higher values of *M*, *Ec* and *Nb* but increasing function of *Nt.*

5.1. Impact of Electrification Parameter (*M*):

Figure (2), (3 and (4) exhibits the impact of electrification parameter (*M*) on velocity, temperature and concentration profiles respectively. It is noticed that, the velocity of fluid increases with respect to the electrification parameter due to the influence of Lorentz's force in the boundary layer. In fact, the Lorentz's force enhances the flow of particles towards cold region from hotter region which results the increasing of fluid motion and decreases the particle's concentration as detected from figure 2 and 4 respectively. Increasing the velocity of fluid decrease the fluid temperature and movement of particles from as observed from figure 3.

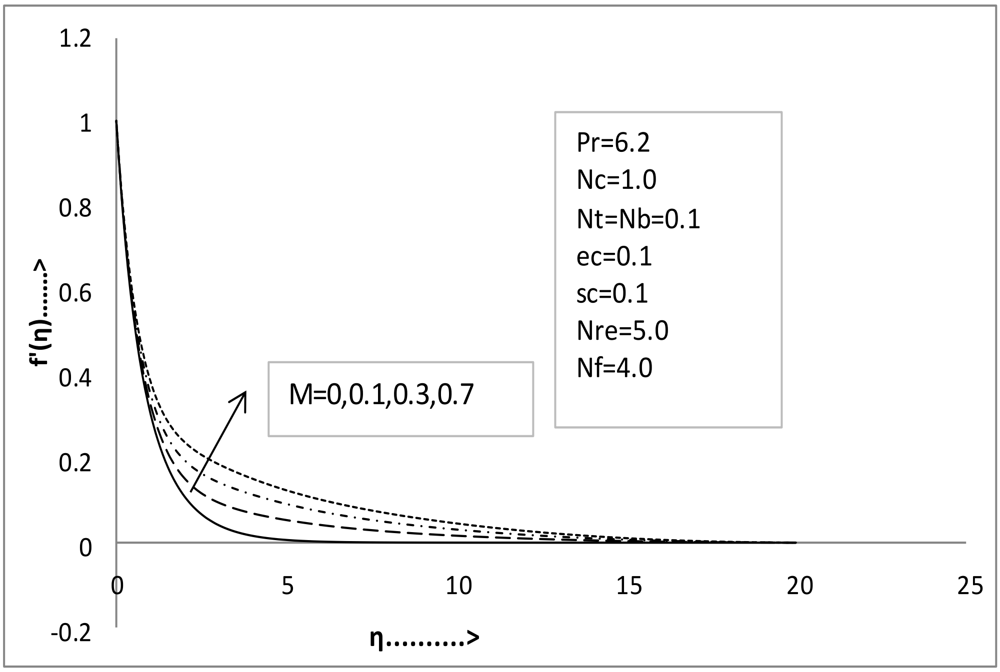

Figure 2. Non-dimensional velocity profile for various values of M

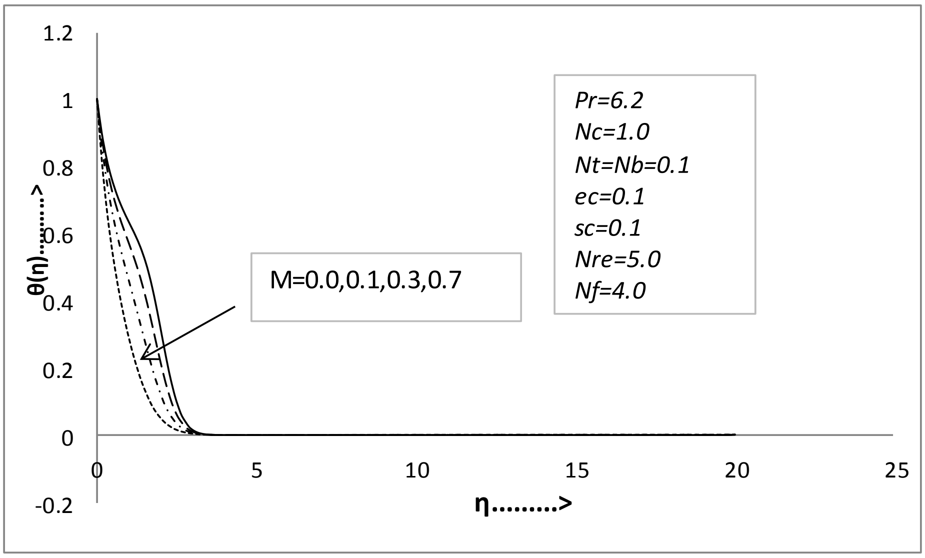

Figure 3. Normalized temperature profile for various values of M

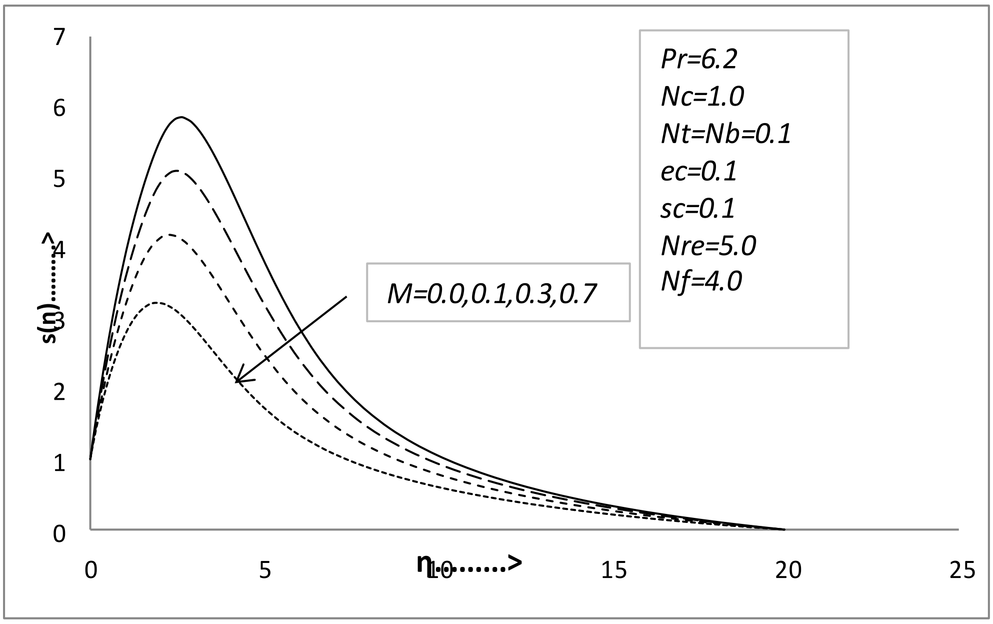

Figure 4. Non-dimensional concentration profile for various values of M

5.2 Impact of Viscous Dissipation Parameter *(Ec):*

The effect of viscous dissipation in terms of Eckert number (*Ec*) on the temperature and concentration profile for *Cu-water* nanofluid has shown through the figure 5 and 6 respectively.

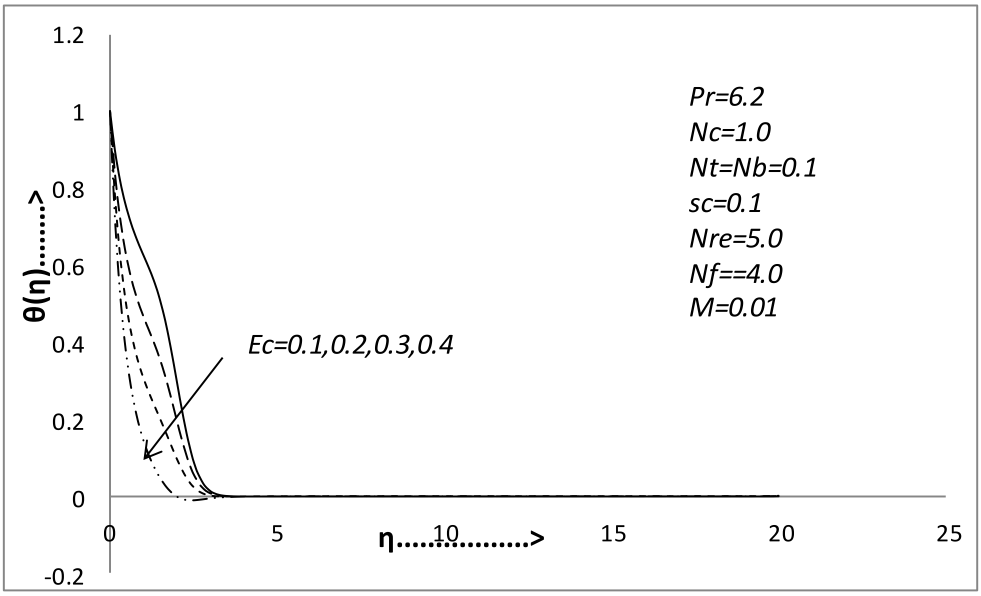

Figure 5. Normalized temperature profile for various values of *Ec*

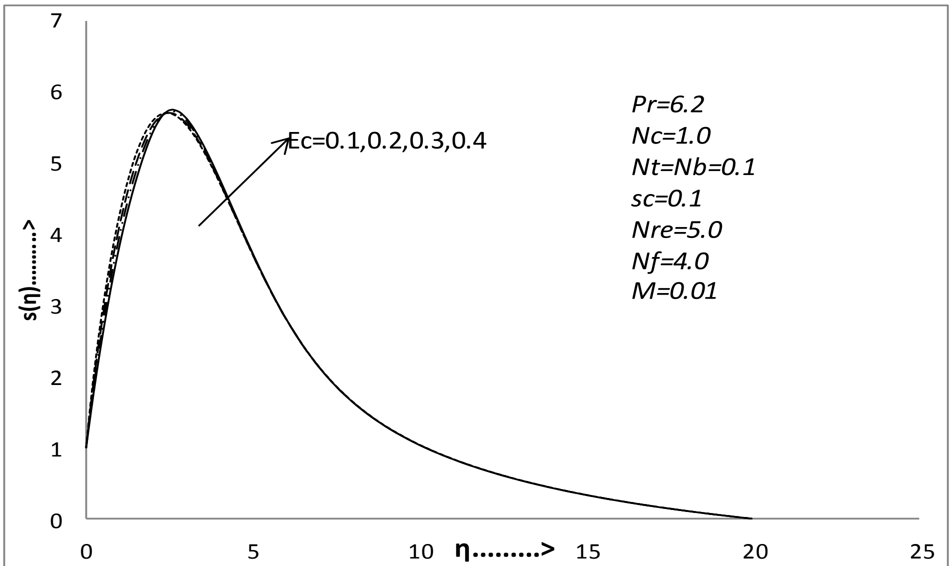

Figure 6. Non-dimensional concentration profile for various value of *Ec*

As it is known that, the viscous dissipation changes the temperature of fluid by playing a role of energy source, it affects the heat transfer rates. Hence, the temperature of nanofluid decreases with an increase in the value of *Ec* as detected from fig(5) and also it is observed from figure (6) that the effect of concentration profile can decreases with the increasing value of viscous dissipation *Ec*.

5.3 Impact of Brownian Diffusion parameter (*Nb*):

Figures 7 and 8 reveal the effects of the Brownian motion parameter (*Nb)* on temperature and concentration profiles respectively. It is depicted that, the temperature and thermal boundary layer thickness are increasing due to the increasing of Brownian motion parameter *Nb.* This is due to the phenomenon of Brownian diffusion which represents the random motion of nanoparticles inside the boundary region. It also leads to decreasing of reduced Nusselt number as represented through figure 8.

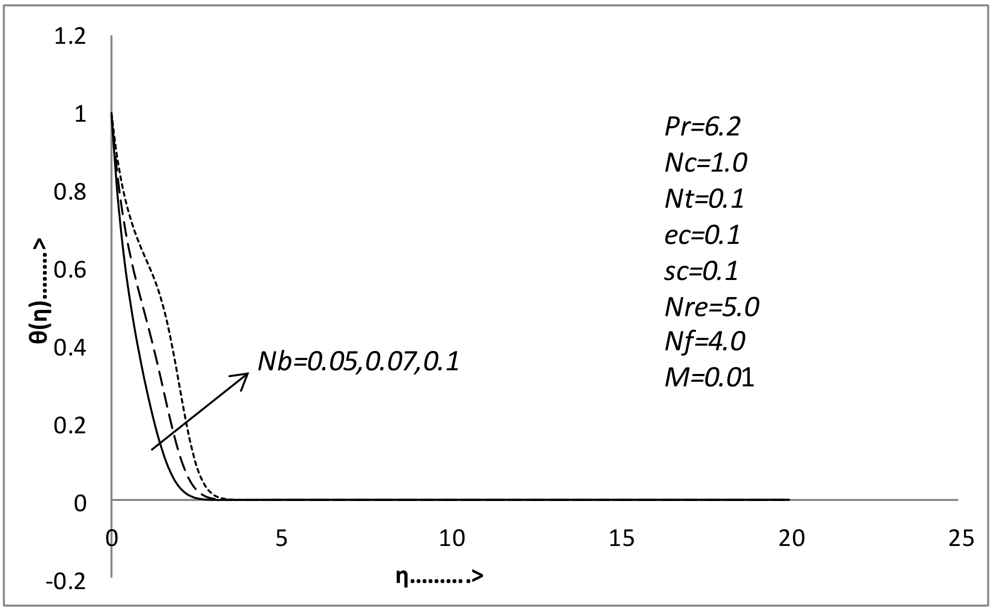

Figure 7. Normalized temperature profile for various values of *Nb*

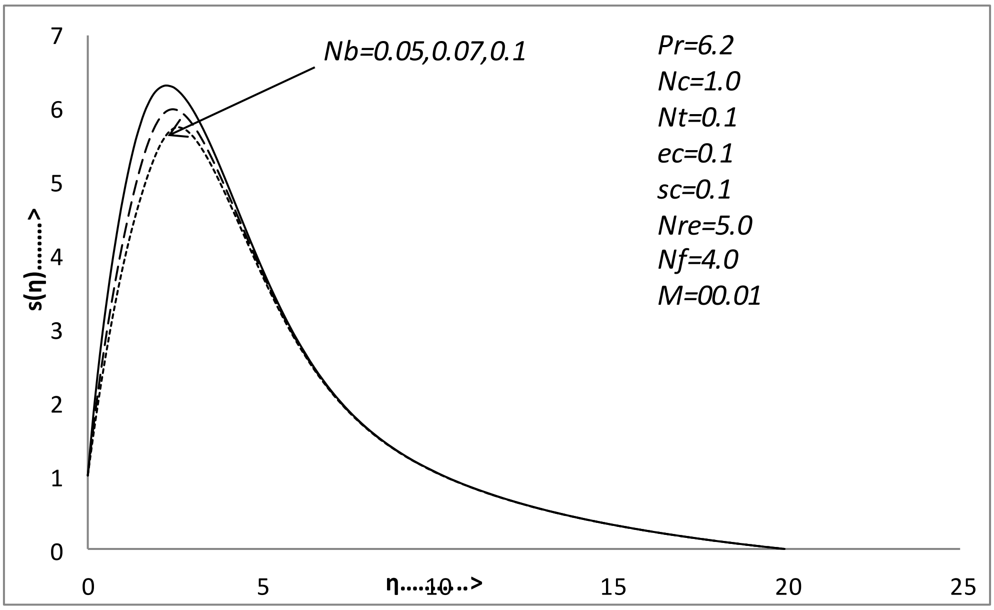

Figure 8. Non-dimensional concentration profile for various values of *Nb*

5.4. Impact of Thermophoresis Parameter (*Nt*):

The temperature profile for different values of the thermophoresis parameter *Nt* is shown in figure 9. It is observed that, the temperature of the flow field decreases due to the enhancement of thermophoretic impact of nanoparticles. It also causes the enhancement of concentration distribution with respect to *Nt* as detected from figure 10.

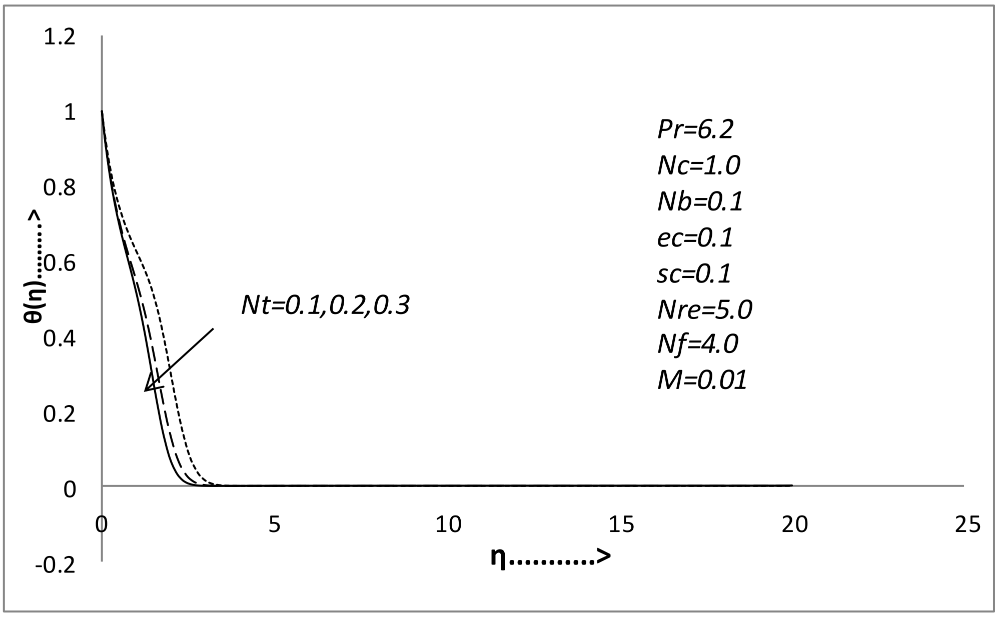

Figure 9.Normalized temperature profile for various values of Nt

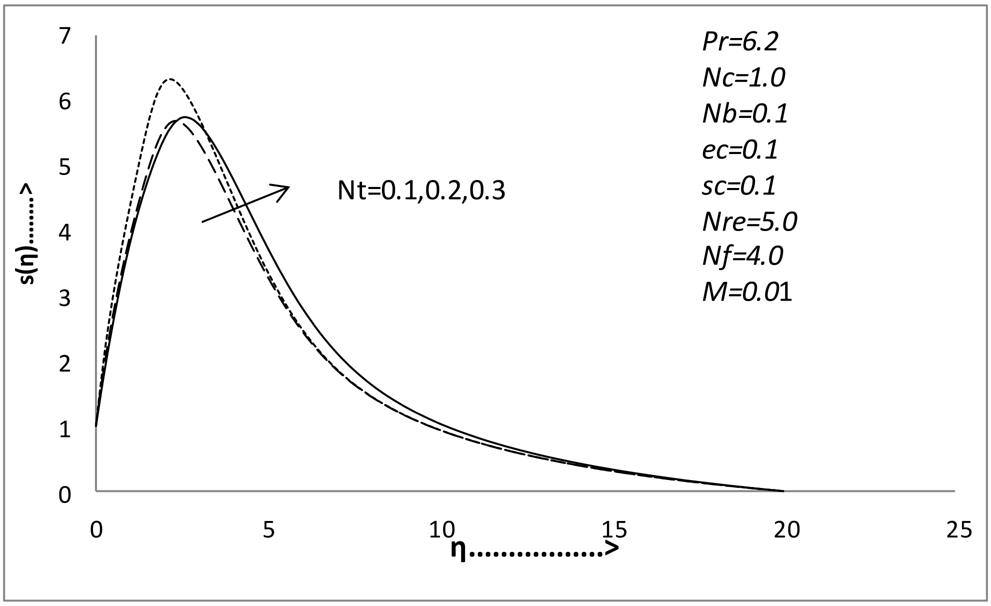

Figure 10. Non-dimensional concentration profile for various values of Nt

6. CONCLUSION

A steady two-dimensional flow of an incompressible fluid due to an exponentially stretching sheet has investigated theoretically in presence of electrification and viscous dissipation effect. The governing non-linear ordinary differential equations along with the subjected boundary conditions are solved numerically using *bvp4c* function of *MATLAB* package. Effects of various flow parameters such as electrification parameter, Eckert number, Brownian motion parameter and Thermophoresis parameter on the flow and heat transfer characteristics have examined. From this investigation, we can draw the following conclusions:

i. The electrification of nanoparticles has an effect to increase the heat transfer at the surface of the stretching sheet as well as the reduction of temperature throughout the boundary layer due to the influence of Lorentz's force. Hence, the electrification of nanoparticles may be a potential mechanism for the Enhancement of thermal conductivity of working fluid.

ii. With regard to the Brownian diffusion impact of nanoparticles, it is observed that the improvement of *Nb* leads to the strong random motion of particles inside the fluid region. For this mechanism, the hotter particles move towards the cold region, which leads to the development of thermal conductivity of the working fluid with respect to *Nb*.

iii. As the thermophoretic effect of nanoparticles defines their migration inside the fluid area due to the temperature gradient, hence it is observed that upsurging the impact of thermophoresis parameter causes the enhancement of fluid temperature.

iv. Physically, viscous dissipation denotes the connecting link of kinetic energy with enthalpy i.e. it converts the kinetic energy into internal energy through the process done against the viscous fluid. Therefore, the higher viscous dissipation raises the temperature profile of working fluid as witnessed in our present investigation.

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