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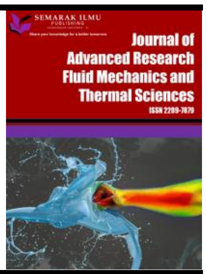

Aligned MHD Jeffrey Fluid Flow Containing Carbon Nanoparticles over Exponential Stretching Sheet with Viscous Dissipation and Newtonian Heating Effects

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ABSTRACT

This study investigates the influence of viscous dissipation on aligned Magnetohydrodynamic (MHD) flow of Jeffry fluid containing Carbon Nanoparticles (CNTs) over an exponential stretching sheet with boundary condition of Newtonian Heating (NH). The model proposed by Tiwari and Das is adopted. The numerical computation using Runge-Kutta Fehlberg (RKF45) method is used to generate the results. The numerical solutions of the several parameters on the velocity and temperature profiles are analysed and presented graphically. It is revealed that an increase in aligned angle, magnetic field, and ratio of relaxation to retardation times leads to the decreasing in velocity and increasing in temperature profiles. Meanwhile, both velocity and temperature profiles increase with a rise in volume fraction parameter.

1. Introduction

The study of heat transfer in the fluid flow over a stretching sheet has become the centre of attraction since it has wider range of applications in the industrial and technological processes [1-3]. For instances, the aerodynamic extrusion of plastic sheets, paper productions and polymer extrusion. Along with this, many researchers can be found considering exponential stretching sheet in their studies for the past years. Sajid and Hayat [4] explored the effect of radiation on the boundary layer flow and heat transfer of a viscous fluid. Another study on boundary layer flow of a viscous fluid was studied by Ishak [5]. By considering magnetic field effect, Mukhopadhyay [6] investigated the slip effects on MHD boundary layer flow with suction/blowing and thermal radiation. Nadeem *et al.,* [7]

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analysed the flow of three-dimensional water-based nanofluid by considering the effects of nanoparticle volume fraction.

Nanofluids can be defined as the addition of nanometer-sized particles in a liquid suspension. The utilization of nanofluids has become popular in the fluid flow since the nanometer-sized particles have higher thermal conductivity than the based-fluid [8-10]. Carbon Nanotubes (CNTs) is one of the nanoparticles in nanofluids that has been widely use in the engineering and industrial applications. Among all nanoparticles, CNTs are suitable for many applications since they have outstanding heat conductivity, electrical conductivity, and mechanical properties. Akbar and Khan [1] explored on the impact of variable thermal radiation and thermal conductivity with CNTs suspended in nanofluid over a stretching sheet with convective slip boundary conditions. Later, Aman *et al.,* [11] investigated the improvement of heat transmission in Maxwell nanofluids flowing in free convection with CNTs. Another study on the effects of CNTs has been conducted by Shah *et al.,* [12] by considering the thermal radiation on electrical MHD rotating flow.

The research related to Magnetohydrodynamics (MHD) has been in the limelight for its broad implementation in physical area such as solar physics, astrophysics, and space plasma physics. The presence of MHD in a fluid can control the flow separation and it also identified to become the agent to transfer heat efficiently. To date, several studies have included MHD in their research because of its special abilities. Aman *et al.,* [13] explored the effect of MHD and porosity on exact solutions and flow of a hybrid Casson-Nanofluid. Meanwhile, Kasim *et al.,* [14] carried out an analysis on the fluid-particle interaction of the aligned MHD dusty Jeffrey fluid which revealed that the fluid velocity and temperature distributions are always higher than dust particles. Recently, Khashi'ie *et al.,* [15] observed the effect of MHD and viscous dissipation on radiative heat transfer of Reiner-Philippoff fluid flow over a nonlinearly shrinking sheet. They found that MHD allows the fluid molecules to gain control of the surface, resulting in the enhancement of heat transfer.

One of the non-Newtonian fluids that emphasizes the crucial aspect of retardation and relaxation times is the Jeffrey fluid. Many researchers have considered Jeffrey fluid in their studies since it is considered as reliable model compared to the other fluid model. Ramzan *et al.,* [16] focused on the Jeffrey fluid flow over an inclined stretched cylinder with suspended nanoparticles and investigated the combined impacts of thermal and concentration stratification, thermal radiation, and heat generation/absorption. Meanwhile, Zokri *et al.,* [17] conducted a study to explore the passive control of nanoparticles on MHD Jeffrey nanofluid past a moving plate that was being heated convectively. In line with this, they further their research on Jeffrey fluid flow over a horizontal circular cylinder with suspended nanoparticles and viscous dissipation effect by considering the Buongiorno model [18].

From the above-mentioned studies, there was no research found that combined the impacts of aligned MHD and CNTs. Therefore, the present study aims to evaluate the flow of aligned MHD Jeffrey fluid embedded with CNTs over an exponential stretching sheet with viscous dissipation and Newtonian Heating (NH) effects. Numerical computation of the current proposed model is conducted by using RKF45 method with the aid of MAPLE software.

2. Problem Formulation

A steady, laminar, incompressible two-dimensional flow of Jeffrey fluid obeying Tiwari and Das model [19] in the presence of an aligned magnetic field over an exponential stretching sheet is considered. In this study, the x-axis is along the exponentially stretching surface and y-axis is normal to the surface. It is assumed that the stretching velocity of the sheet is $u_w(x) = u_0 e^{\frac{x}{L}}$ where u_0 is a constant and L is a reference length in an electrically conducting fluid where the magnetic field is flowing with aligned angle, α .

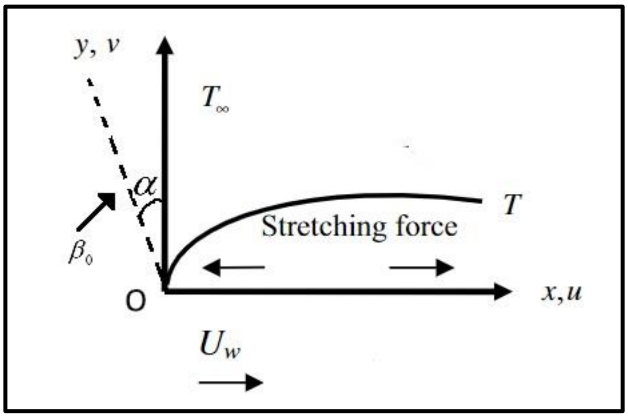

Fig. 1. Figure of flow configuration

The governing equations of Jeffrey fluid containing CNTs can be represented by the following equations (Hayat *et al.,* [20] and Waini *et al.,* [21]).

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{\mu_{nf}}{\rho_{nf}\left(1+\lambda\right)}\left[\frac{\partial^2 u}{\partial y^2}+\lambda_1\left(u\frac{\partial^3 u}{\partial x\partial y^2}+v\frac{\partial^3 u}{\partial y^3}-\frac{\partial u}{\partial x}\frac{\partial^2 u}{\partial y^2}+\frac{\partial u}{\partial y}\frac{\partial^2 u}{\partial x\partial y}\right)\right]-\frac{\sigma_{nf}}{\rho_{nf}}B^2 u\sin^2\alpha \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\kappa_{nf}}{(\rho C_p)_{nf}}\frac{\partial^2 T}{\partial y^2}+\frac{\mu_{nf}}{(\rho C_p)_{nf}\left(1+\lambda\right)}\left[\left(\frac{\partial u}{\partial y}\right)^2+\lambda_1\left(u\frac{\partial u}{\partial y}\frac{\partial^2 u}{\partial x\partial y}+v\frac{\partial u}{\partial y}\frac{\partial^2 u}{\partial y^2}\right)\right] \tag{3}$$

where the velocity components are u and v along x and y-axis directions, correspondingly, $\mu_{nf}, \rho_{nf}, \lambda, \sigma_{nf}, (C_p)_{nf}$ denote the dynamic viscosity, density, retardation time, electrical conductivity and specific heat of nanofluid. Table 1 shows the thermophysical properties of nanofluid.

Table 1
Thermophysical properties of nanofluid

Properties	Nanofluid
Density	$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_{CNT}$
Heat Capacity	$\left(\rho C_p\right)_{nf} = (1-\phi)\left(\rho C_p\right)_f + \phi\left(\rho C_p\right)_{CNT}$
Dynamic Viscosity	$\mu_{nf} = \dfrac{\mu_f}{(1-\phi)^{2.5}}$
Thermal Diffusivity	$\alpha_{nf} = \dfrac{\kappa_{nf}}{(\rho C_p)_{nf}}$
Thermal Conductivity	$\dfrac{\kappa_{nf}}{\kappa_f} = \dfrac{(1-\phi) + 2\phi\left(\dfrac{\kappa_{CNT}}{\kappa_{CNT}-\kappa_f}\right)\ln\left(\dfrac{\kappa_{CNT}-\kappa_f}{2\kappa}\right)}{(1-\phi) + 2\phi\left(\dfrac{\kappa_{CNT}}{\kappa_{CNT}-\kappa_f}\right)\ln\left(\dfrac{\kappa_{CNT}+\kappa_f}{2\kappa}\right)}$
Electric Conductivity	$\dfrac{\sigma_{nf}}{\sigma_f} = 1 + \dfrac{3\left(\dfrac{\sigma_{CNT}}{\sigma_f} - 1\right)\phi}{\left(\dfrac{\sigma_{CNT}}{\sigma_f} + 2\right) - 3\left(\dfrac{\sigma_{CNT}}{\sigma_f} - 1\right)\phi}$

Eq. (1) to Eq. (3) obey the following boundary conditions

$$u = u_w(x) = u_0 e^{\frac{x}{L}}, v = 0, \frac{\partial T}{\partial y} = -h_s T \quad \text{at} \quad y = 0$$

$$u \to 0, \frac{\partial u}{\partial y} \to 0, T \to T_\infty \quad \text{as} \quad y \to \infty \tag{4}$$

where h_s, T, T_∞ are the coefficient of heat transfer and surface and ambient temperature of the Jeffrey fluid. Next, the similarity transformations are introduced as

$$\eta = y\left(\frac{U_0}{2vL}\right)^{\frac{1}{2}} e^{\frac{x}{2L}}, \psi = (U_0 2vL)^{\frac{1}{2}} e^{\frac{x}{2L}} f(\eta), \theta(\eta) = \frac{T - T_\infty}{T_\infty} \text{ (NH)} \tag{5}$$

where η is boundary layer thickness, ψ is the stream function, $f(\eta)$ denotes the similarity function and $\theta(\eta)$ is dimensionless fluid temperature. By using Eq. (5), Eq. (1) to Eq. (3) become

$$\frac{\mu_{nf}/\mu_f}{\rho_{nf}/\rho_f}\left[f''' + \lambda_2\left(f'f''' - \frac{1}{2}ff^{iv} + \frac{3}{2}f''^2\right)\right] + (1+\lambda)\left(ff'' - 2f'^2\right) - \frac{\sigma_{nf}/\sigma_f}{\rho_{nf}/\rho_f}(1+\lambda)Mf'\sin^2\alpha = 0 \tag{6}$$

$$\frac{1}{\Pr}\frac{\kappa_{nf}/\kappa_f}{\left(\rho C_p\right)_{nf}/\left(\rho C_p\right)_f}\theta''+f\theta'+\frac{\mu_{nf}/\mu_f}{\left(\rho C_p\right)_{nf}(1+\lambda)/\left(\rho C_p\right)_f}Ec\left[f''^2+\lambda_2\left(f'f''^2-ff''f'''\right)\right]=0 \tag{7}$$

and the boundary conditions in Eq. (4) can be written as

$$f(0)=0,\ f'(0)=1,\theta'(0)=-\gamma\left(1+\theta(0)\right) \text{ at } \eta=0$$

$$f'(\eta)\to 0,\ f''(\eta)\to 0,\theta(\eta)\to 0 \text{ as } \eta\to\infty \tag{8}$$

where a prime $(')$ denotes the differentiation with respect to η [11] and

$$\lambda_2=\lambda_1\frac{U_0}{L}e^{\frac{x}{L}},M=\frac{2\sigma_f B_o{}^2 L}{\rho_f U_0},\Pr=\frac{(\mu C_p)_f}{\kappa_f},Ec=\frac{U_0{}^2}{(C_p)_f T_\infty}e^{\frac{2x}{L}},\gamma=h_s\left(\frac{2vL}{U_0}\right)^{\frac{1}{2}}e^{\frac{-x}{2L}} \tag{9}$$

represent Deborah number, magnetic field parameter, Prandtl number, Eckert number and conjugate parameter, respectively. Eq. (8) is the transformed boundary conditions where NH is considered. It is worth to mention that the thermal boundary condition of NH is introduced on the surface of the sheet by assuming that the wall temperature and heat transfer rate is proportional to each other. Next, the quantities of physical interest in this work are the shear stress rate (skin friction coefficient, C_f) and heat transfer rate (Nusselt number, Nu_x) which can be denoted as

$$(2\,\mathrm{Re}_x)^{\frac{1}{2}}C_f=\frac{\mu_{nf}}{\mu_f(1+\lambda)}[f''+\lambda_1\frac{U_0}{2L}e^{\frac{x}{L}}(3f'f''-ff''')]$$

$$\left(\frac{\mathrm{Re}_x}{2}\right)^{\frac{-1}{2}}Nu_x X^{-1}=\gamma\frac{k_{nf}}{k_f}\left(\frac{1}{\theta(\eta)}+1\right) \tag{9}$$

where $\mathrm{Re}_x=\dfrac{U_0 e^{\frac{x}{L}}L}{v_f}$ is the Reynolds number and $X^{-1}=\sqrt{\dfrac{x}{L}}$.

3. Numerical Procedure

The RKF45 method is applied for the purpose of obtaining numerical results of the proposed problem. The governing equations in the form of partial differential Eq. (1) to Eq. (3) are first transformed into ordinary differential Eq. (6) to Eq. (8) by using similarity transformation variables as expressed in Eq. (5). The resulting Eq. (6) to Eq. (8) are then translated into programming languages and solved by using RKF45 method. This method is programmed in the MAPLE software using a built-in function, *dsolve* command. A comparison between the generated results and previous published studies is needed to make sure the results is in a good agreement.

4. Results

In this part, the numerical results of the present model by varying the involved parameters of aligned angle (α), magnetic field (M), conjugate parameter of NH (γ), volume fraction (∅) and ratio of relaxation to retardation times (λ_2) on the velocity and temperature profiles are presented graphically. The graphical results for all the parameters will be studied separately and the value of parameter is chosen based on the asymptotically of the graphical results. The numerical computation is carried out for various value of λ_2, M, ∅, α and γ. Table 2 shows the comparison between the present solution and previous published results reported by Hayat *et al.,* [20] and Waini *et al.,* [21] for $f''(0)$. It is found that the obtained results are in a good agreement with the previous published results.

Table 2
Comparison of $f''(0)$ for various values of M when $\theta = M = \lambda = \lambda_2 = 0$

M	Hayat *et al.,* [20]	Waini *et al.,* [21]	Present, $f''(0)$
0.0	-1.2818	-1.28181	-1.28125
0.2	-1.3133	-1.37889	-1.43094
0.4	-1.4030	-1.59824	-1.56550

Figure 2 and Figure 3 illustrate the velocity and temperature profiles for various values of ratio of relaxation to retardation times, λ_2. It can be seen from Figure 2 that the velocity decreases with an increase in λ_2. In contrast, from Figure 3, the temperature profile increases with the raise in λ_2.

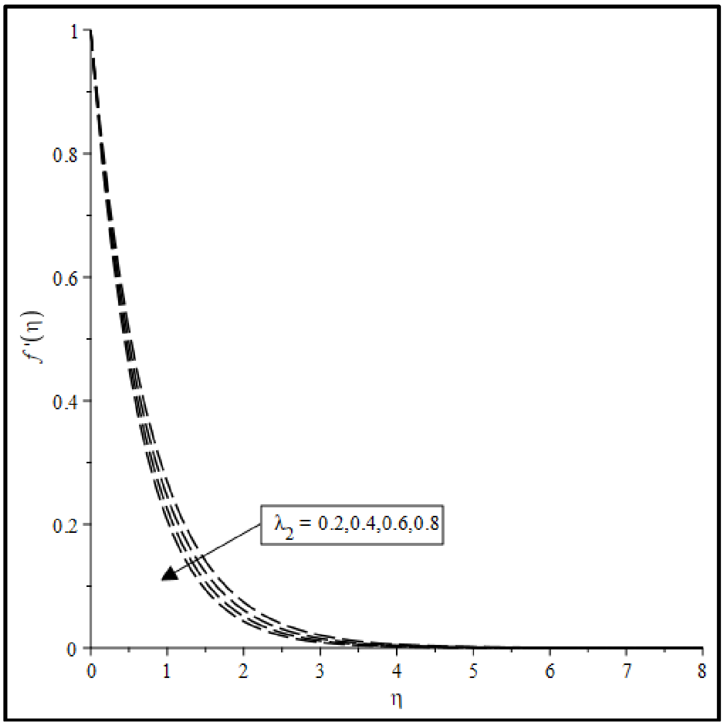

Fig. 2. Velocity profiles for various values of λ_2

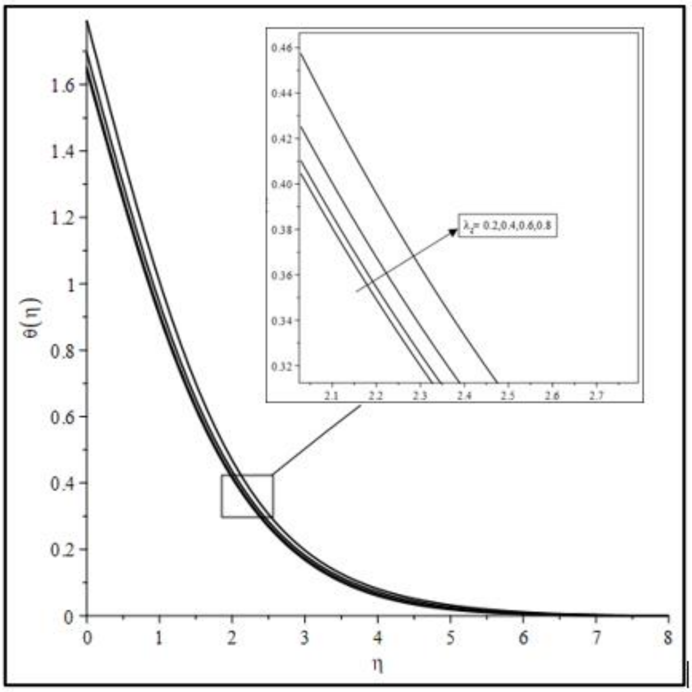

Fig. 3. Temperature profiles for various values of λ_2

Figure 4 and Figure 5 illustrate the velocity and temperature profiles for various values of magnetic field, M . It can be observed from Figure 4 that the velocity diminishes with the increase in the M . In this case, the velocity profile decreases due to the resistance in the fluid flow created by the Lorentz force. Meanwhile, it can be noticed that the temperature profile increases with an increase of M as displayed in Figure 5. An enhancement in magnetic parameter motivates the Lorentz force that causes the temperature to be risen.

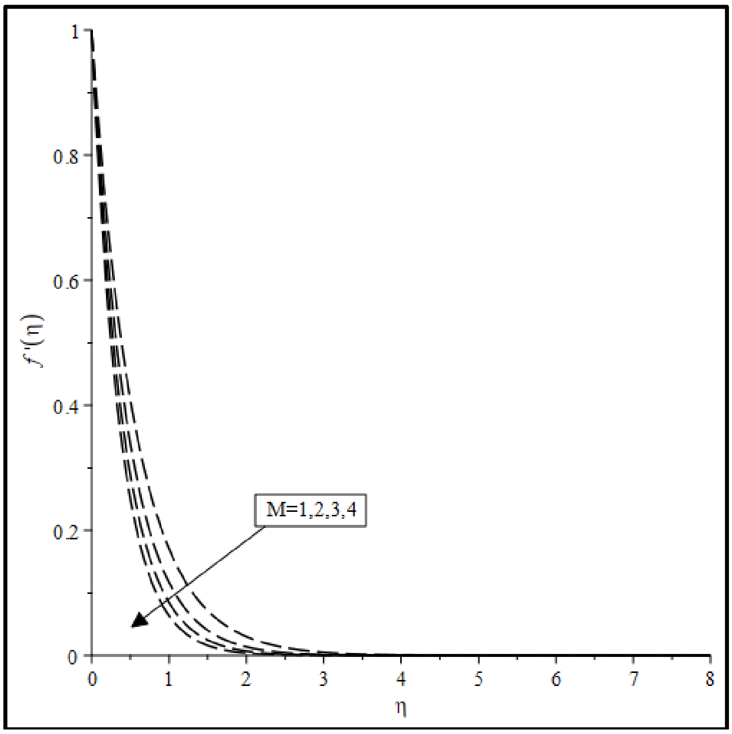

Fig. 4. Velocity profiles for various values of M

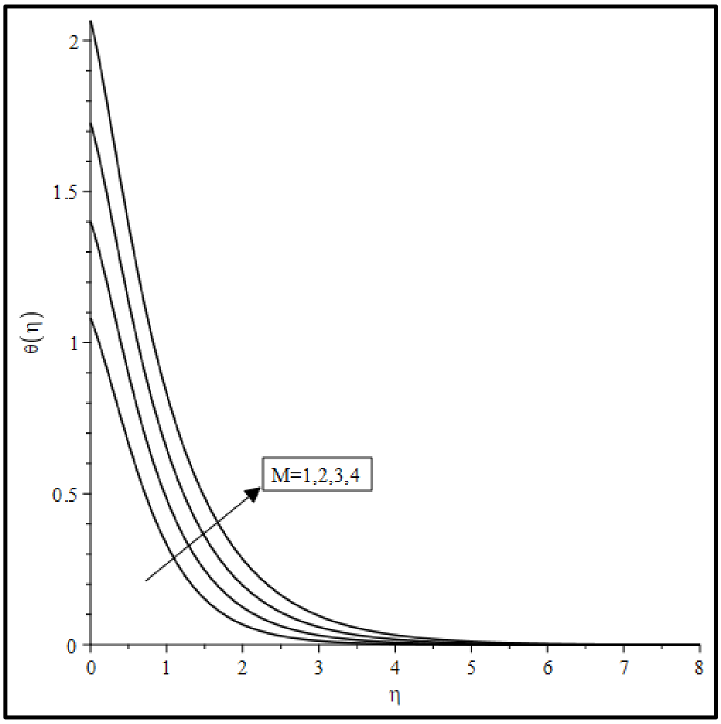

Fig. 5. Temperature profiles for various values of M

Figure 6 and Figure 7 illustrate the velocity and temperature profiles for various values of volume fraction, Ø. It can be observed from both figures that the velocity and temperature profiles increase with a rise in Ø. This result is attributed to an increase in Ø which leads to the increase of the momentum and thermal boundary layer thickness.

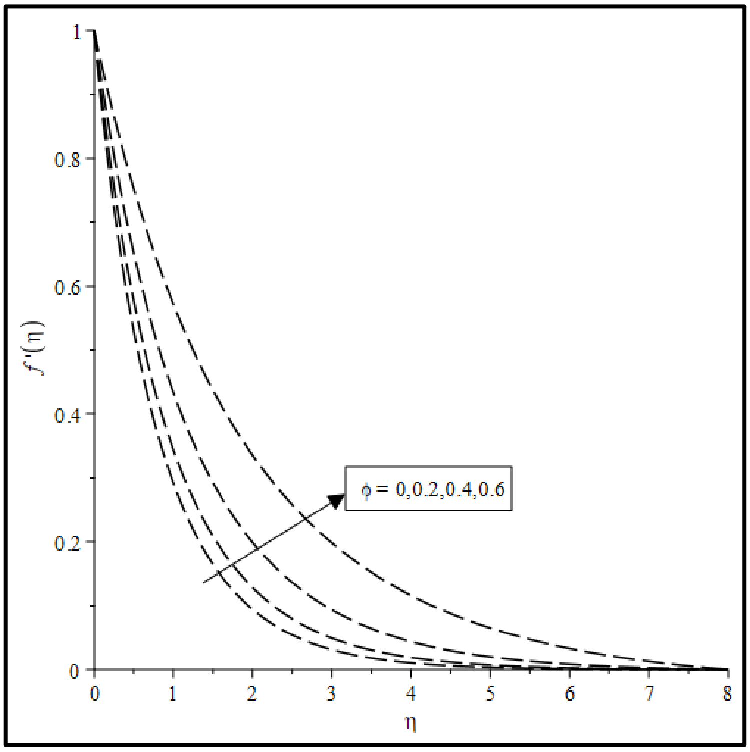

Fig. 6. Velocity profiles for various values of Ø

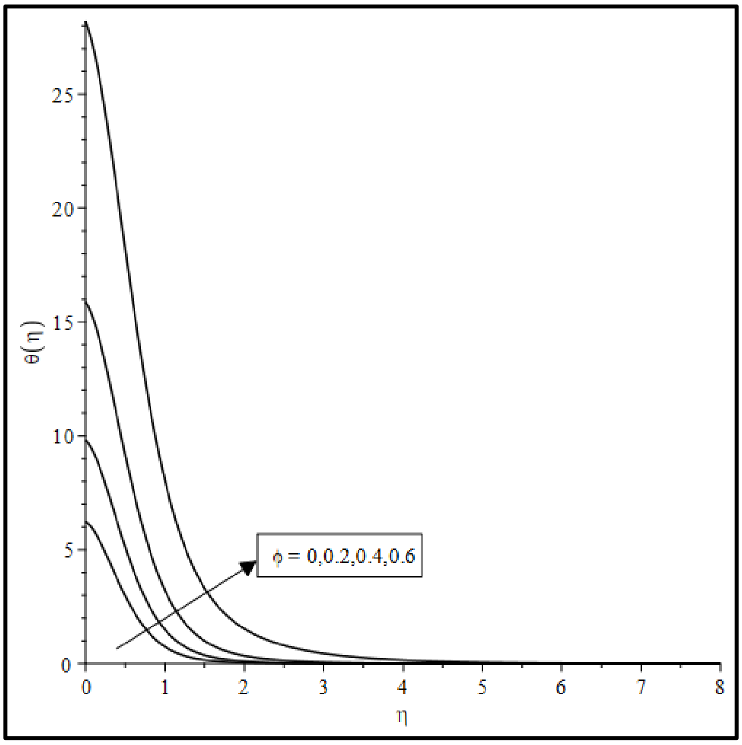

Fig. 7. Temperature profiles for various values of Ø

Figure 8 and Figure 9 illustrate the velocity and temperature profiles for various values of aligned angle, α. It can be seen from Figure 8 that the velocity decreases with an increase of α and the temperature profile increases with an increase of α. The Lorentz force, which acts against the direction of the flow was physically encouraged by the increasing α and eventually caused the velocity profile to decrease. Moreover, it also affects the temperature profile to increase.

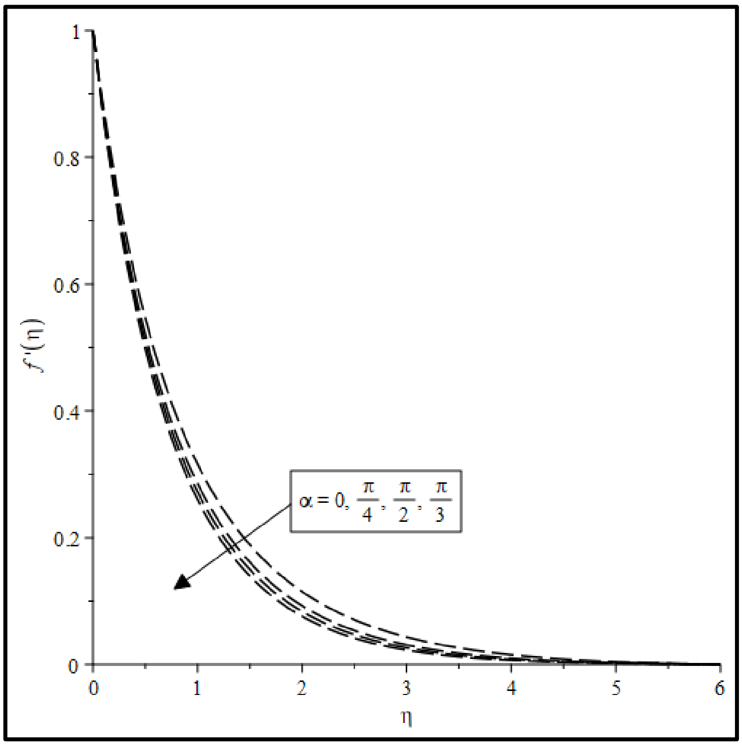

Fig. 8. Velocity profiles for various values of α

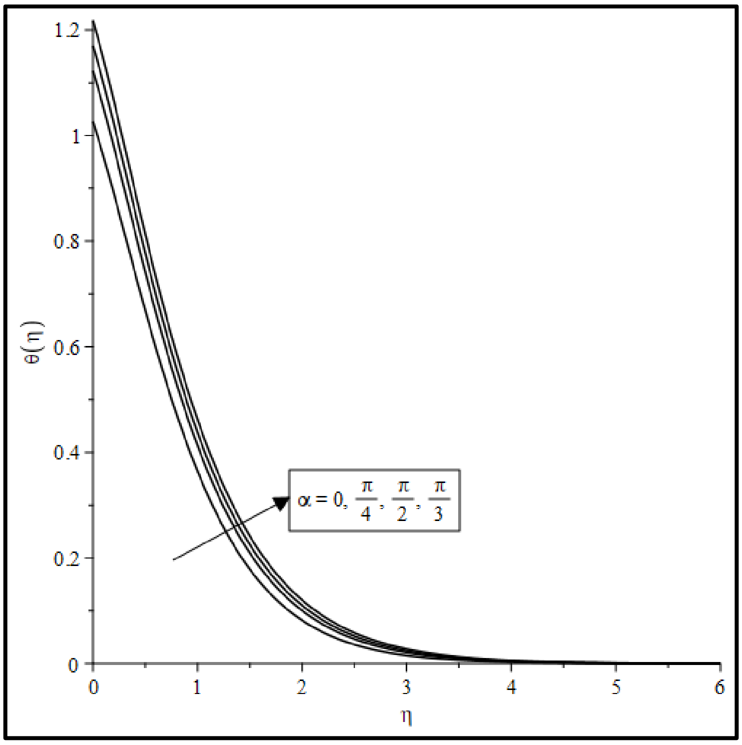

Fig. 9. Temperature profiles for various values of α

Figure 10 and Figure 11 illustrate the velocity and temperature profiles for various values of conjugate parameter of NH, γ. An insignificant change can be noticed in the velocity profile due to the decoupled of the momentum and energy equations. Meanwhile, the temperature profiles improve with an enhance in γ. Physically, the rising in the conjugate parameter improves the heat transfer coefficient which increases the temperature profile.

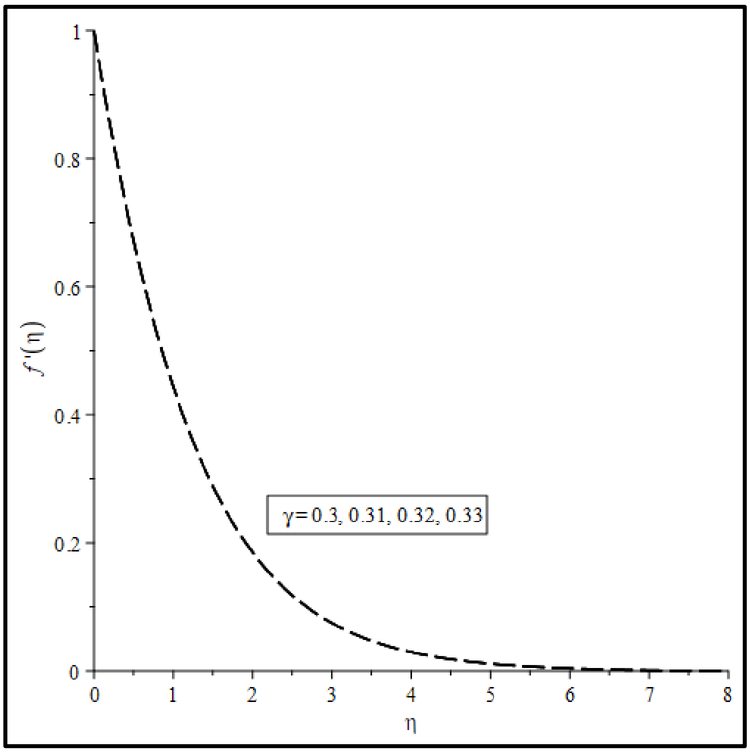

Fig. 10. Velocity profiles for various values of γ

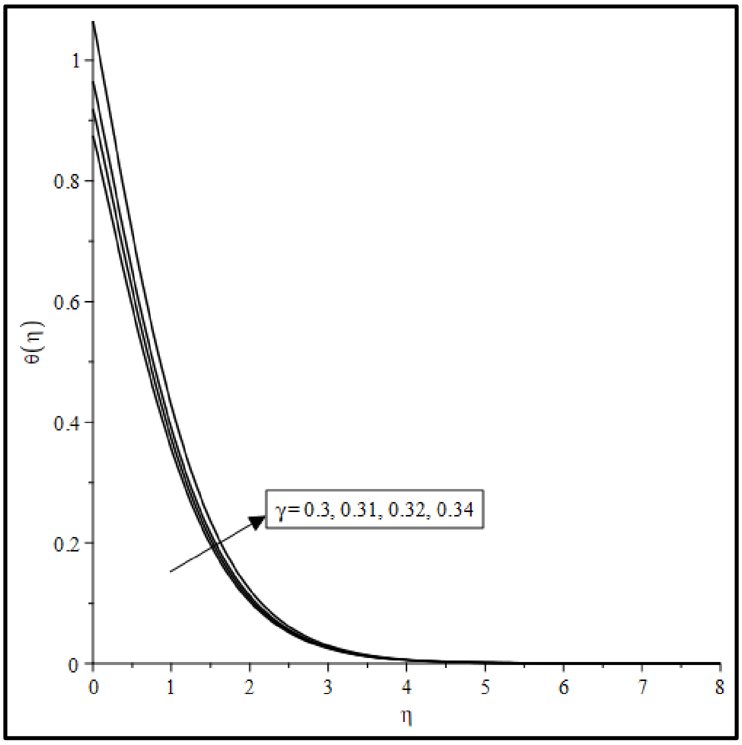

Fig. 11. Temperature profiles for various values of γ

4. Conclusions

In the present study, the influence of viscous dissipation on aligned MHD flow of Jeffry fluid containing CNTs over an exponential stretching sheet with Newtonian Heating effect was considered. It is found that the rise in involved parameters of aligned angle, ratio of relaxation to retardation times and magnetic field lead to the decreasing in velocity profile. Meanwhile, the rise in volume fraction results in the increasing in velocity. It can be observed that the temperature profile increases for an increase in all involved parameters.

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