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Research Paper

A Study of Modified Nanofluid Flow Over an Exponentially Stretching Surface With Inclined Magnetic Field and Porous Media

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ABSTRACT

A numerical study of $Fe_3O_4 - \mathrm{TiO_2} - Ni/\mathrm{C_2H_6O_2}$ modified nanofluid's flow through a stretched surface is presented in the current work with an applied angled magnetic field. In the subsequent form of hybrid nanofluid, known as modified nanofluid, three distinct suspended nanoparticles in a base fluid are taken into consideration. Iron Oxide, Nical, and Titanium Dioxide nanoparticles are suspended in ethanol glycol, which is used as a base liquid. One way to improve heat transfer rates in MHD flow over a stretched surface with variable viscosity is to utilize modified nanofluids. This is useful in a number of sectors, including energy systems, thermal management in aircraft, and cooling electronic systems. By applying the proper similarity transformations, the Runga-Kutta fourth order technique encounters the mathematical framework of the flow. One important finding is that, in contrast to nanofluids and hybrid nanofluids, the modified nanofluid has a larger capacity for heat transmission. The modified nanofluid's heat transfer capabilities exhibit intriguing behavior that calls for more research on it. There are numerical solutions that are displayed graphically. Increases in the volume fraction parameter and the inclination angle parameter of the magnetic field have been found to cause a drop in the velocity field of the modified nanofluid.

Keywords: Heat Transfer; MHD; Modified Nanofluid; Porous Media; Stretching Sheet

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1. Introduction

Non-Newtonian fluids have been applied in several industrial processes in recent years. Numerous sectors, including the pharmaceutical, chemical, biological, and petroleum industries, are benefiting from the unique qualities of non-Newtonian fluids. Non-Newtonian fluids have a wide range of uses, which has led to a fast growth in their study. In many industrial applications, regular fluids like water, ethylene-glycol, propylene-glycol, and engine-oil are used for heat transmission. Enhancing these liquids' ability to transport heat can lower the cost of goods, power, processing time, and size, and increase device operating time. The fact that traditional heat exchangers require low temperatures to operate is one issue with heat exchange systems. The thermal conductivity of this liquid may be optimized with the distribution of solid particles. Thermal conductivity of heterogeneous two-components system was investigated by R. Hamilton [1]. The thermal conductivities of a variety of heterogeneous two-component systems were studied by researchers in 1962.The empirical shape factor, which is dependent on the thermal conductivities of the phases and the included particle's shape, can be determined with accuracy using an equation. A review on nanofluid was written by W. Yu and H. Xie [2]. Preparations and stability factors were discussed by the authors in their review. They also discuss the opportunity for future of nanofluid. Nanofluids square measure dispersion of nano-materials (such as nano-fibers, nano-tubes, nanoparticles nano-rods, nano-wires, nano-sheets, or droplets) in fundamental fluids. Due in large part to the early observations of aberrant thermal physical phenomena (k) advancement of nanofluids with any low fraction of nanoparticles, nanofluids have garnered considerable interest over the past ten years. With numerous reports of unusual improvements in thermal physical phenomena and numerous other reports of increases in thermal physical phenomena at intervals with the traditional Maxwell intermixture model, this field has generated a lot of debate. Both experimentally and theoretically, the effects of mobility, surface resistance, shape of suspended nanoparticles, and aggregating behavior are examined. Many researchers are also looking into the heat energy capabilities of nanofluids since this may be necessary to understand in order for them to be used effectively in heat transfer applications. The focus has now changed from the original study of the thermophysical characteristics of nanofluids to the commercialization of new nanofluids with extremely high thermal conductivities [3,4].

Afterwards, the researchers created hybrid nanofluids through the mixing of two different nanoparticles with a basic liquid. Better heat/mass transfer outcomes can be achieved by carefully blending or combining nanoparticle-sized particles suspended in the basic fluid. This is because hybrid nanofluids allow for the management of the benefits and drawbacks of nanoparticles. The radiative MHD transfer of heat of hybrid nanofluids along Joule heating impact was investigated by Chamkha et al. [5]. The impacts of angled MHD of hybrid nanofluid's flowing across a slippery surface were examined by Acharya et al. [6]. Heat transmission for hybrid nanofluids across a permeable shrinking/stretching surface was demonstrated by Waini et al. [7]. A comparison of heat transfer analyses between $\mathrm{MoS_2/C_2H_6O_2}$ nanofluid and $\mathrm{MoS_2-SiO_2/C_2H_6O_2}$ hybrid nanofluid with natural convection and an angled MHD was given by Dadheech et al. [8]. The researchers come to the conclusion that, in contrast to nanofluids, hybrid nanofluids are more efficient in transferring heat because they can harness the unique features of nanoparticles to improve thermal conductivity.

To maximize the heat transmission capacity, researchers have started combining three diverse varieties of nanoparticles to suspend them in a base fluid known as "modified nanofluid" in response to these theories. When it comes to heat transmission, modified nanofluids outperform hybrid and nanofluid scenarios, according to research by Nadeem et al.[9] on the phenomena of heat transmission on modified nanofluid in porous media with MHD. Additionally, Nadeem et al. [10] reported that temperature-dependent viscosity of modified nanofluids flows via a stretched Rega plate.

Nonetheless, unitary nanofluids can be used in a variety of situations to boost heat transmission capacity or to cool down nanomaterials. To promote heat transfer, a mixer of several nanoparticles dissolved in a basic liquid, however, may be more successful. The goal of this work is to determine how modified nanofluids, $Fe_3O_4-\mathrm{TiO_2}-Ni/\mathrm{C_2H_6O_2}$, move across an exponentially stretched surface under the influence of an angled MHD. To the best of the authors' knowledge, no research has been done using the parameters reported in this work on the combination of nanoparticles with ethanol glycol base fluid. This type of flow is used in the production of glass fiber, biomedicine, hot rolling, food processing, systems, electronics for cooling nuclear reactors, and heat transportation. The presenting of trustworthy conclusions results in a superb concurrence.

2. Mathematical Modeling

A two-dimensional, viscous, incompressible boundary layer of modified nanofluid, $Fe_3O_4-\mathrm{TiO_2}-Ni/\mathrm{C_2H_6O_2}$, passes across a surface that is exponentially stretching. A homogeneous magnetic field is applied with an inclination angle of α. Three nanoparticles of Iron Oxide, Nical, and Titanium Dioxide are suspended in ethanol glycol, which serves as the base fluid.

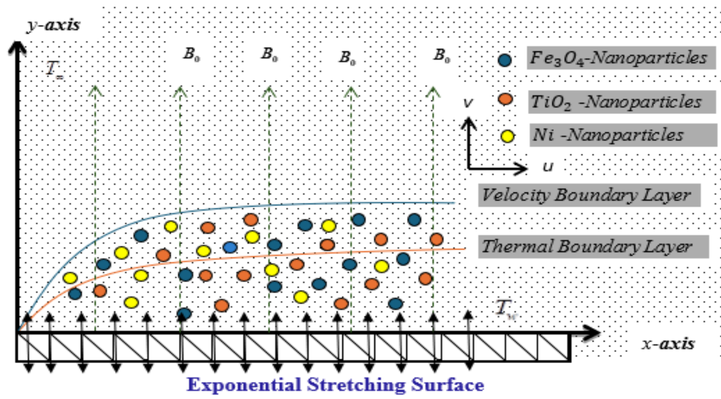

Figure 1. Physical representation of, $Fe_3O_4-\mathrm{TiO_2}-Ni/\mathrm{C_2H_6O_2}$ nanofluid flow.

Laminar flow of base fluid and nanoparticles are presumed to be thermally stable. The wall and ambient temperatures are T_w and T_∞, accordingly. According the physical model Figure 1, the horizontal axis is set across the surface and the vertical axis is regarded of as normal to it because it is assumed that fluids flow with y ≥ 0. Considering the previously described hypotheses and case, the convective flow and heat transfer mathematical model for nanoliquid may be described as follows: [8]:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=\frac{\mu_{mnf}}{\rho_{mnf}}\frac{\partial^2 u}{\partial y^2}-\frac{\sigma_{mnf}B_0^2 u\mathrm{Sin}^2\alpha}{\rho_{mnf}}-\frac{\mu_{nf}}{\rho_{nf}k}u. \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\kappa_{mnf}}{\left(\rho C_p\right)_{mnf}}\frac{\partial^2 T}{\partial y^2}. \tag{3}$$

The boundary conditions for this flow model:

$$\begin{array}{llll} u=u_w & v=0, & T=T_w, & \text{at} \quad y=0, \\ u\rightarrow 0, & T\rightarrow T_\infty & \text{as} y\rightarrow\infty. & \end{array} \tag{4}$$

Where u and v, respectively, are the velocity variables along the x and y axes, also $C_s$is reffered as surface heat capacity. ρ_{mnf} referred to density of modified nanofluid, μ_{mnf} reffered to viscosity of modified nanofluid, κ_{mnf} reffered to thermal conductivity,σ_{mnf} reffered to electrical conductivity and $\left(\rho C_p\right)$ referred to heat capacity of modified nanofluid. Magnetic field is B_0 and $U_w=U_0e^{x/l}$,$T_w=T_\infty+T_0e^{x/2l}$.

The terms modified nanofluids, hybrid nanofluids, nanofluids, and base fluids are denoted by the subscripts mnf, hnf, nf, and f, accordingly. The thermophysical properties and Thermo-physical values of modified nanofluids are shown in Table 1 and Table 2 respectively and these properties are used in the solution of the present mathematical model.

Table 1. Thermo-physical characteristics of modified nanofluid: [8,10]

$\boldsymbol{\mu_{mnf} = \dfrac{\mu_f}{(1-\phi_1)^{2.5}(1-\phi_2)^{2.5}(1-\phi_3)^{2.5}}}$	Effective dynamic viscosity
$\boldsymbol{\rho_{mnf} = (1-\phi_3)\left[\left\{\left[(1-\phi_1)\rho_f + \phi_1\rho_{s1}\right](1-\phi_2)\right\} + \phi_2\rho_{s2}\right] + \phi_3\rho_{s3},}$	Effective density
$\boldsymbol{\sigma_{mnf} = \left\{\frac{2\sigma_{hnf}+\sigma_{s3}-2(\sigma_{hnf}-\sigma_{s3})\phi_3}{2\sigma_{hnf}+\sigma_{s3}+(\sigma_{hnf}-\sigma_{s3})\phi_3}\right\}\sigma_{hnf}}$ where $\boldsymbol{\sigma_{hnf} = \left\{\dfrac{2\sigma_{nf}+\sigma_{s2}-2(\sigma_{nf}-\sigma_{s2})\phi_2}{2\sigma_{nf}+\sigma_{s2}+(\sigma_{nf}-\sigma_{s2})\phi_2}\right\}\sigma_{nf}}$ and $\boldsymbol{\sigma_{nf} = \left\{\frac{\sigma_{s1}+2\sigma_f-2\phi_1(\sigma_f-\sigma_{s1})}{\sigma_{s1}+2\sigma_f+\phi_1(\sigma_f-\sigma_{s1})}\right\}\sigma_f}$	Electrical conductivity
$\boldsymbol{\kappa_{mnf} = \left\{\frac{\kappa_{s3}+(n-1)\kappa_{hnf}-(n-1)(\kappa_{hnf}-\kappa_{s3})\phi_3}{\kappa_{s3}+(n-1)\kappa_{hnf}+(\kappa_{hnf}-\kappa_{s3})\phi_3}\right\}\kappa_{hnf}}$ where $\boldsymbol{\kappa_{hnf} = \left\{\frac{\kappa_{s2}+(n-1)\kappa_{nf}-(n-1)(\kappa_{nf}-\kappa_{s2})\phi_2}{\kappa_{s2}+(n-1)\kappa_{nf}+(\kappa_{nf}-\kappa_{s2})\phi_2}\right\}\kappa_{nf},}$ $\boldsymbol{\kappa_{nf} = \left\{\dfrac{\kappa_{s1}+(n-1)\kappa_f-(n-1)(\kappa_f-\kappa_s)\phi_1}{\kappa_{s1}+(n-1)\kappa_f+(\kappa_f-\kappa_{s1})\phi_1}\right\}\kappa_f}$	Thermal conductivity
$\boldsymbol{(\rho C_p)_{mnf} = (1-\phi_3)\left[\left\{(1-\phi_2)\left[(1-\phi_1)(\rho C_p)_f + (\rho C_p)_{s1}\phi_1\right]\right\} + (\rho C_p)_{s2}\phi_2\right] + \phi_3(\rho C_p)_{s3},}$	Heat capacitance

Table 2 Thermo-physical values: [2, 6, 7, 11]

	$\boldsymbol{\rho\ (kg/m^3)}$	$\boldsymbol{C_p\ (J/kg\ K)}$	$\boldsymbol{k\ (W/m\ K)}$	$\boldsymbol{\sigma (S/m)}$
$\boldsymbol{C_2H_6O_2}$	1116.6	2382	0.249	0.01485
$\boldsymbol{Fe_3O_4}$	5200	670	9.8	0.74×10^6
$\boldsymbol{Ni}$	8900	444	90.7	1.7×10^7
$\boldsymbol{TiO_2}$	4175	692	8.4	6.27×10^{-5}

2.1. Similarity transformation

To solve our model, we apply the similarity transformation below[11]:

$$u = U_0 e^{\frac{x}{l}} f'(\eta), v = -\sqrt{\frac{\nu_f U_0}{2l}} e^{x/2l}[f(\eta) + \eta f'(\eta)]$$

and $(\eta) = \frac{T-T_\infty}{T_w - T_\infty}$. (5)

Where $\eta = y\sqrt{\frac{U_0}{2l\nu_f}} e^{x/2l}$ andusing the aforementioned transformations, the nonlinear equations of the flow have been incorporated into the subsequent ordinary differential equations.

$$Af''' + B(ff'' - 2f'^2) - \frac{\sigma_{mnf}}{\sigma_f} M \mathrm{Sin}^2\alpha f' = 0. \quad (6)$$

$$\frac{1}{\mathrm{Pr}}\frac{\kappa_{mnf}}{\kappa_f} C\theta'' + f\theta' - f'\theta = 0.. \quad (7)$$

Here

$$A = \frac{1}{(1-\phi_1)^{2.5}(1-\phi_2)^{2.5}(1-\phi_3)^{2.5}},$$

$$B = (1-\phi_3)\left[\left\{(1-\phi_2)\left[(1-\phi_1) + \phi_1\frac{\rho_{s1}}{\rho_f}\right]\right\} + \phi_2\frac{\rho_{s2}}{\rho_f}\right] + \phi_3$$

and

$$C = \left[(1-\phi_3)\left[\left\{(1-\phi_2)\left[(1-\phi_1) + \phi_1\frac{(\rho C_p)_{s1}}{(\rho C_p)_f}\right]\right\} + \phi_2\frac{(\rho C_p)_{s2}}{(\rho C_p)_f}\right] + \phi_3\frac{(\rho C_p)_{s3}}{(\rho C_p)_f}\right]^{-1}.$$

Boundary condition (5) is also modified using the aforementioned transformations as:

$$\theta(0) = 1, f(0) = 0, f'(0) = 1, \theta(\infty) = 0, f'(\infty) = 0. \quad (8)$$

Where $M = \frac{2lB_0^2\sigma_f}{U_0\rho_f e^{x/l}}$ is Magnetic parameter, $\mathrm{Pr} = \frac{(\rho C_p)_f \nu_f}{\kappa_f}$ is Prandtl number. An additional physical measure is the local Nusselt number, which is provided by

$$Nu_x = -\left(\frac{\kappa_{hnf}}{\kappa_f} + \frac{4R}{3}\right)\psi_1 x\theta'(0). \quad (9)$$

3. Numerical Solution

Moreover, Eq. (6) and Eq. (7) and boundary conditions Eq. (8) have been recast as first-order initial value problems, using the following definitions:

$f' = h_2, f'' = h_3, \theta = h_4, \theta' = h_5, h'_3 = \frac{B}{A}(2h_2^2 - h_1h_3) + \frac{M}{A}\frac{\sigma_{hnf}}{\sigma_f} h_2 \mathrm{Sin}^2\alpha$ and $h'_5 = \frac{\mathrm{Pr}}{C}\frac{\kappa_f}{\kappa_{mnf}}(h_2h_4 - h_1h_5)$.

With boundary condition, $h_1(0) = 0, h_2(0) = 1, \quad h_2(0) = 1, h_4(0) = 1$.

For numerical solutions these ODE's are converted into first ordered IVP. In this IVP only three initial conditions are present, but five are required for the solution as $h_3(0)$ and$h_5(0)$. Assuming the initial guess values for $h_3(0)$ and$h_5(0)$ and suitable finite value of $\eta(\to\infty)$, say η_∞ numerical solutions by Runge-Kutta method are obtained. Then computations for $f'(\eta)$ and $\theta(\eta)$ at $\eta_\infty(\cong 10)$ along with conditions of boundary $f'(\eta_\infty) = 0$ and $\theta(\eta_\infty) = 0$are performed. Approximated (degree of accuracy is 10^{-6}) solutions have obtained by adjusting the values of $f''(0)$ and $\theta'(0)$ by considering step size $\Delta\eta = 0.01$. This technique uses an iterated strategy to provide accurate findings up to 10^{-7} accuracy.

4. Result and Discussions

The flow characterization through an exponentially stretched sheet of modified nanofluids is investigated. Various inclination angles are used while applying a magnetic field. Further, the variation of several contributing parameters on the fluid velocity and temperature profiles are presented via graphs.

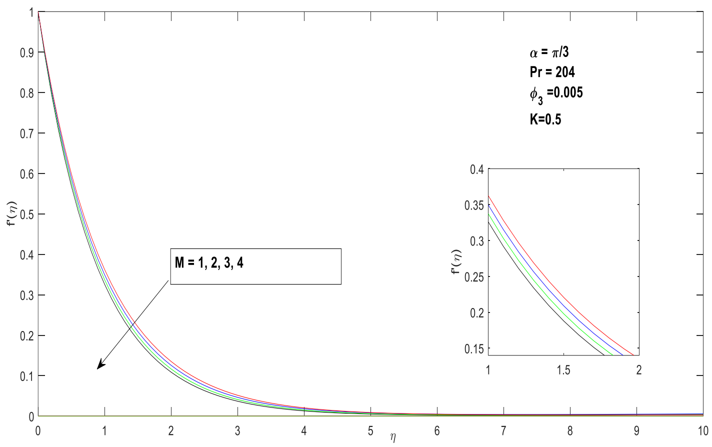

Figure 2. Velocity profile for the magnetic field parameter M.

The consequence of M on $f'(\eta)$ for the modified nanofluid $Fe_3O_4 - Ni - \mathrm{TiO}_2/C_2H_6O_2$ is shown in Figure 2. The velocity profile decreases as M increases, according to the findings. The magnetic field produced by the movement of an electrically conducting fluid creates a Lorentz force, which has the retardation feature. This is the reason for the diminishing appearance of the velocity profile. As M rises, the retardation strength of all the three nanofluids grows. As a result, velocity decreases as well.

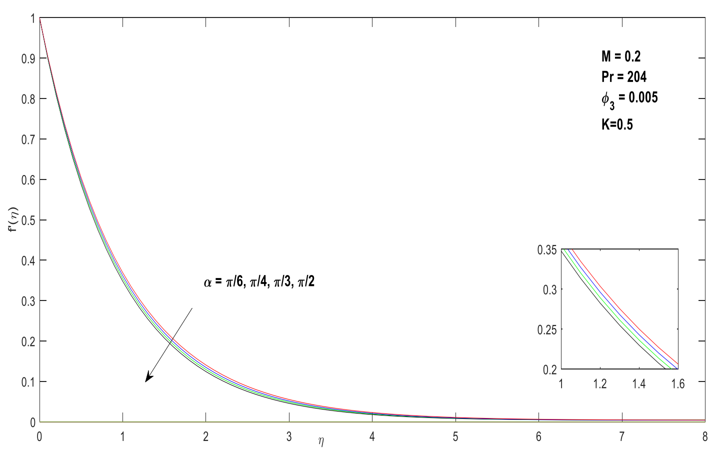

Figure 3. Velocity profile for the inclination angle parameter α.

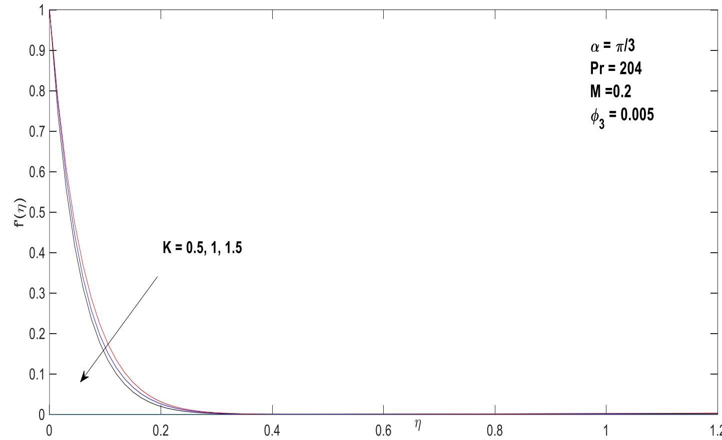

Figure 4. Velocity profile for the permeability parameter K.

Figure 3 shows the impact of the α on $f'(\eta)$. When the parameter is increased, the $f'(\eta)$ profile falls. This is due to the fact that as the angle of inclination increases, the magnetic field becomes stronger and the Lorentz force reduces the velocity field. The influence of the permeability parameter K on the velocity profile is illustrated in Figure 4. A distinct decline in velocity within the flow pattern is noticed. The impact of volume friction ϕ_3 on $f'(\eta)$is shown in Figure 5.

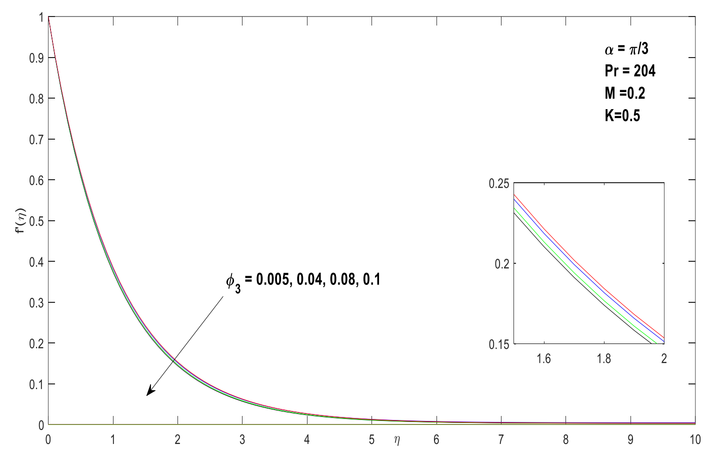

Figure 5. Velocity profile for the parameter ϕ_3.

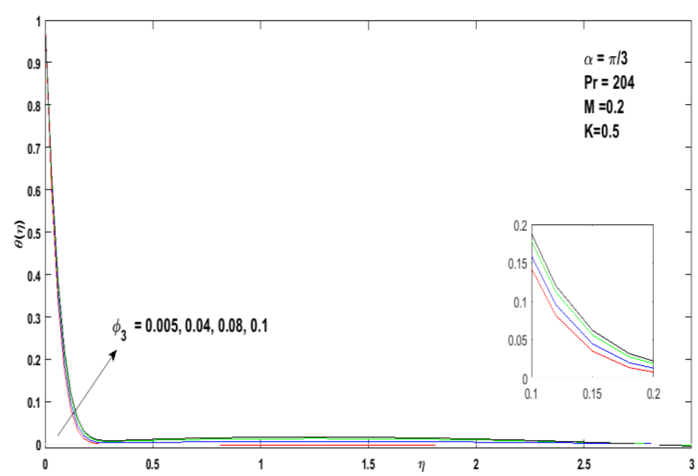

Figure 6. Temperature profile for the parameter ϕ_3.

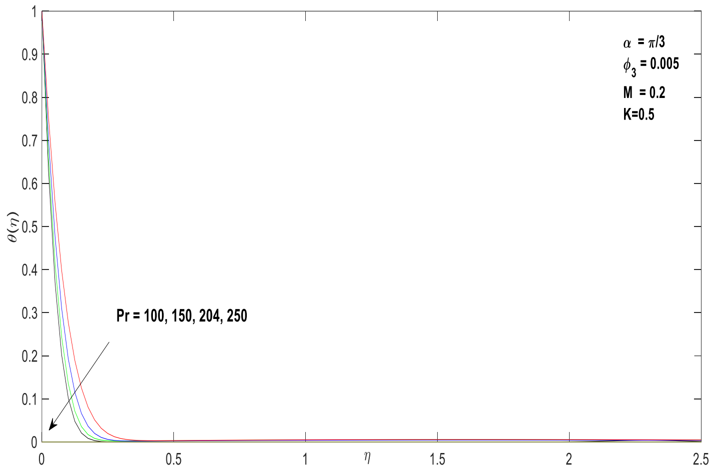

Figure 7. Temperature profile for the parameter ϕ_3.

It is seen that a drop in the velocity profile occurs with an increase in ϕ_3. Additionally, it is noted for ϕ_3 that the fluid's speed increases with increasing ϕ_3 away from the sheet and decreases in its immediate vicinity. Figure 6 illustrates how ϕ_3 affects $\theta(\eta)$).

It has been shown that for changed naofluids, an enhanced temperature profile results from increased ϕ_3. A higher temperature field may arise from the extraction of more energy from a greater number of nanoparticles. The influence of Pr on $\theta(\eta)$ is shown in Figure 7. The figures indicate that a reduction in the temperature profile $\theta(\eta)$. is noticed with an increase in Pr.

5. Conclusions

The impact of heat transfer of modified nanofluids flowing past an exponentially extending surface under the influence of an applied angled magnetic field has been studied. A modified nanofluid composed of ethylene glycol that contains a suspension of $Fe_3O_4 - \mathrm{TiO_2} - Ni$ nanoparticles have been visually displayed. By applying the proper similarity transformations, the Runga-Kutta fourth order technique solves the flow's governing models.

The key results that follow are achieved.

- A decrease in the velocity field has been observed for the modified nanofluid with an increase in the inclination angle and magnetic field parameter.
- The velocity curve for ϕ_3 shows that the fluid velocity increases away from the sheet and reduces toward the wall.
- A decrease is observed with an increase in the velocity field's ϕ_3, but a reversal of this impact is shown in the temperature profile.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

N. Jain: Conceptualization, Mathematical modeling, Writing-original draft **M. Gaur:** Conceptualization, Supervision **Priyanka Agrawal:** Validation, Software, result analysis **P.K. Dadheech:** Data curation, Formal analysis, revisions.

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