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Analysis of hydromagnetic hybrid nano fluid flow with iron(II)oxide and iron(III)oxide suspension in human blood

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ABSTRACT

Hybrid nano fluids represent a pioneering approach, achieved by introducing diverse nanoparticles into plain fluids. Hybrid nano fluids have found diverse applications in various industries (including coolants for nuclear reactors, electronic gadgets, refrigerators, and computers), as well as in manufacturing, machinery, and transformers. Given their significance within the biomedical field, hybrid nano fluids find utilization in various applications such as nano sized drug delivery, cancer treatments, cryopreservation, nano cryosurgery, as well as sensing and imaging. The purpose of this study is to analyze the flow of a hydromagnetic hybrid nano fluid containing FeO and Fe₂O₃ suspension in human blood. The non-linear governing equations, as well as the boundary conditions will be made dimensionless through appropriate similarity transformations. The dimensionless equations derived will be analyzed using the Runge-Kutta-Gill method. Simulations using MATLAB's bvp4c will be carried out to determine the influence of key parameters on fluid velocity, skin friction, and heat transfer rate.

Keywords: Hybrid nanofluids, FeO nanoparticles, Fe₂O₃ nanoparticles, Human blood flow, Hydromagnetic flow, Heat transfer

1. Introduction

1.1 The background of the study

Hydromagnetic combines the word “hydro,” which refers to fluid dynamics and “magnetic,” indicating the presence of the magnetic field. [Alfvén \(1942\) \[1\]](#) identified a branch of science focused on studying the behavior of electrically conducting fluids when they traverse a magnetic field. He designated this field as magnetohydrodynamics (MHD), hydro magnetics, or magnetofluid dynamics. This branch of fluid mechanics became significant due to its role in various industrial applications, such as bioreactors, electricity generation, and designing electromagnetic pumps and flowmeters.

Fluid is defined as a substance that deforms steadily in response to the influence of shear stress (lateral force per unit area) or external force. Often categorized as a state of matter, including liquids, vapors, and ionized gases. Flowing substance can be grouped into two fundamental varieties: Newtonian (Linear-viscosity fluids) and non-Newtonian (Fluids with non-linear viscosity). For Linear-viscosity fluids, there is a proportional linear relationship with regard to shear stress and shear strain rate; examples are oil, gasoline, alcohol, water, and air.

Fluids with non-linear viscosity do not exhibit a simple linear relationship with regard to shear stress and shear strain rate. Blood is an example of a fluid with non-linear viscosity that shows shear-thinning behavior (i.e., its viscosity falls as the shear rate goes up). Fluids with non-linear viscosity have broad applications in manufacturing engineering, such as in food processing, the movement of chyme in the digestive tract, and plasma flow, mercury amalgams, and lubrication with heavy oils and greases. According to [Krishnamurthy et al. \(2016\) \[2\]](#), these fluids are divided into categories including liquid metals (e.g., melted iron, mercury, gallium; water; and electrically charged gases such as those present in the sun's outer layers), together with other types, such as saline solutions.

Nano fluid is a term used to describe a suspension of nanoparticles in a base fluid. It has gained substantial emphasis as a result of its one-of-a-kind properties and amidst the context of a nano fluid. The base fluid can be a liquid such as water, oil, or ethylene glycol, while the nanoparticles are solid particles with sizes typically ranging from 1 to 100 nanometers. These nanoparticles are commonly composed of materials such as metals (e.g., iron, silver, copper), metal oxides (e.g., iron oxide, titanium dioxide), carbon nanotubes, or graphene. Because the nanofluid alters the hydraulic and thermal properties of the base fluid and enhances heat transfer. Many researchers have investigated the thermophysical properties of individual types of

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nanofluids. In this context, the objective of this project is to investigate the attributes of the newly formulated hybrid nano fluid. The enhanced heat transfer capabilities of nanofluids have led to their use in diverse applications such as cooling systems, electrical and industrial devices, automotive technology, nuclear reactors, and the biomedical industry. The varied applications led to sparking a curiosity about the existence of a fluid with higher thermal conductivity. Scientists examined several techniques for enhancing thermal conductivity in nanofluids, Suresh *et al.* (2011) [3] introduced a novel category of fluid known as hybrid nanofluids, which established an entirely new domain of fluid studies.

Researcher conducted by Hayat *et al.* (2017) [4], Subhani *et al.* (2018) [5], Sheikholeslami *et al.* (2019) [6], Waini *et al.* (2019), Tassaddiq *et al.* (2020) [7], and Othman *et al.* (2021) [8] began to formulate the core understanding in this discipline area. Potential applications in industries include energy, automotive, and manufacturing. The findings suggest that hybrid nano fluids have significant potential for improving the heat rate of transfer efficiency and reducing energy consumption in industrial processes. The literature review expands upon their research findings. In order to substantiate the project's validity, a series of deterministic experiments were undertaken. The results of these experiments clearly indicate that the hybrid nano fluid outperforms the standard fluid in terms of both thermal and electrical characteristics. Despite the innovative advancements in the field of hybrid fluids, a substantial challenge also surfaced. The body dealt with nanoparticles as foreign entities and this often resulted in adverse effects on healthy cells and tissues.

In their 2016 study, Kameswaran *et al.* examined convective heat transfer by evaluating the effects of the non-linear Boussinesq approximation, thermal stratification, and convective boundary conditions on the non-Darcy nano fluid flow over a vertical wavy surface. They noted that an increase in the amplitude-to-wavelength ratio resulted in an augmentation in the average Nusselt number. Given the diverse applications and numerous cancer cases, comprehending the dynamics of analyzing the hydromagnetic hybrid nano fluid flow with FeO and Fe₂O₃ suspension in human blood is vital for medical applications. Therefore, the objective of this research is to explore the effects of pertinent parameters on the nano fluid flow, the heat transfer rate, and the skin friction.

1.2 Statement of the problem

Hybrid nano fluid flow which is the dispersion of nano particles in a base fluid, which has demonstrated significant potential as a power law the non-Newtonian fluid flow with assumptions of steady and incompressible flow with potential applications in the treatment of cancer due to their unique properties such as enhanced thermal conductivity and increased surface area. In cancer treatment, medical practitioners frequently utilize magnetic nanoparticles; by applying a magnetic field, one can direct iron II oxide and iron III oxide toward cancer cells. Researchers use computational simulations to analyze the MHD flow behavior of the hybrid nano fluid in a micro fluidic channel under the influence of a magnetic field. The research outcomes demonstrated that the addition of the hybrid nano fluid to human blood significantly increase the magnetic susceptibility of the blood, which could potentially enhance the targeting of cancer cells with magnetic nanoparticles. The study also showed the addition of the hybrid nano fluid could affect the flow dynamics of the blood, which could potentially improve the delivery of drugs and other therapeutic agents to cancer cells. Several studies have been done on MHD flow especially on the nano fluid exhibiting properties like higher thermal conductivity, critical heat flux, and efficient heat transfer, establishing it as a promising coolant. This enhances the current study to analyze the treatment of cancer by suspension of FeO and Fe₂O₃ in human blood on MHD flow of hybrid nano fluid on energy dissipation effects in this project.

1.3 The justification for the study

Most studies have focused on analyzing non-Newtonian fluids, particularly in the context of Casson fluids, air, and nano fluids. For instance, they have explored the motion of air over the pointed edges of bullets or car bonnets. However, none of these studies has addressed the suspension of FeO and Fe₂O₃ in human blood. There is a gap in the literature when it comes to researching the treatment of cancer through the suspension of FeO and Fe₂O₃ in human blood using MHD flow analysis of hybrid nano fluid with the Runge-Kutta-Gill's Method.

1.4 Objectives of the study

1.5 General objectives

This research is designed to analyze the hydromagnetic hybrid nano fluid flow with FeO and Fe₂O₃ suspension in human blood.

1.6 Specific objectives

The distinct goals of this research are to:

- i. To formulate the fundamental equations governing the behavior of hybrid nanofluids.
- ii. Convert the control equations to dimensionless form, and the boundary conditions to convert PDE to ODE.
- iii. Evaluate how relevant parameters affect nanofluid flow, temperature, and skin friction.

1.7 The relevance of the research

Given the numerous potential applications of hybrid nano fluids, the aim of this research results will be of help in the medical field especially the treatment of cancer. Knowledge on the behavior of iron particles in human blood will be instrumental in understanding how cancer medicine can be supplied to the affected area without harming other useful cells in the body.

2. Literature review

2.1 Background review

MHD flow of hybrid nano fluid consisting of a suspension of iron II oxide and iron III oxide in human blood is an interesting area of research for cancer treatment. MHD flow technology demonstrates potential for cancer therapy through nano fluid applications in biological environments because it allows for exact tumor cell identification and improved drug delivery methods. A study performed by Xie *et al.* (Wang *et al.* (2014) performed research to understand the MRI contrast agent properties of iron oxide nanoparticles which they studied for medical cancer diagnosis and treatment applications. The researchers proved that iron oxide nanoparticles could identify tumor cells while they monitored cancer treatment effectiveness.

The research conducted by Han *et al.* (The researchers (2016) studied magnetic iron oxide nanoparticles for cancer therapy through their combination with chemotherapy medications. The results of the study showed the combination of the iron oxide nanoparticles and chemotherapy drugs led to increased cancer cell death and reduced tumor growth. A few studies have investigated the use of iron oxide nanoparticles as a potential cancer treatment. One such research by Wu *et al.* (The research by (2017) used iron oxide nanoparticles to create therapeutic delivery systems which provided cancer treatment to patients.

The researchers found out that iron oxide nanoparticles were able to efficiently deliver drugs to cancer cells and induce apoptosis, or cell death, in those cells. In terms of suspension of Iron (II) and iron (III) oxides in human blood, according to the study by Zhang *et al.* (The research by Liu *et al.* (2018) evaluated iron oxide nanoparticle toxicity and biocompatibility through laboratory tests which included cell-based and organism-based studies. The research found that iron (II) oxide and iron (III) oxide particles which entered human blood did not produce any dangerous side effects. The author presents new de

velopments in iron oxide nanoparticle design and medical application preparation according to his recent review.

The article presents a detailed analysis of iron oxide nanoparticle synthesis methods which include co-precipitation and thermal decomposition and sol-gel and hydrothermal methods. Overall, the article by Zhang *et al.* (The research by Sun *et al.* (2018) provides complete information about IONP design approaches and production methods and their medical applications which makes it an essential resource for scientists who work with these materials. The 2017 Nano Medicine: Nanotechnology, Biology, and Medicine study investigated iron oxide nanoparticles for hyperthermia treatment of pancreatic cancer patients. The researchers used polyethylene glycol coating on iron oxide nanoparticles to enhance their blood stability in their research.

Researchers injected the nanoparticles into mice with pancreatic tissue and applied an external magnetic field to elevate the temperature of the nanoparticles and the surrounding tissues. The research showed that iron oxide nanoparticles used in hyperthermia therapy led to major decreases in tumor dimensions. The research conducted by Shakil *et al.* (The authors (2019) studied FeO and Fe₂O₃ nanoparticle-based hybrid nano fluids because they showed promise for cancer cell hyperthermia therapy applications. The research demonstrated that nano fluids produced heat when exposed to an external magnetic field which caused cancer cell temperatures to rise significantly until they died. The research established that hybrid nano fluids show promising potential for medical applications which include cancer treatment.

The research conducted by Kumar *et al.* (2020) [9] studied the MHD flow and temperature effects dissipation characteristics of a hybrid nanofluid in a lid-driven cavity with a magnetic field using numerical simulations. They reported that the heat dissipation rate of the hybrid nanofluid increases with the addition of magnetic fields and the nanoparticle volume fraction. The research conducted by Gireesha *et al.* (2020) [10] experimentally investigated the MHD flow and thermal dynamics of the hybrid nanofluid in a circular pipe under the effect of a magnetic field. The researchers discovered that nanoparticles when combined with magnetic fields produce a hybrid nanofluid which enables enhanced heat transfer rates. Research studies about MHD flow of hybrid nano fluids have used multiple methods which include theoretical approaches and numerical simulations and experimental testing.

In another study, Jain *et al.* (The research conducted by (2020) evaluated Fe₂O₃ nanoparticles as potential cancer-fighting agents. The researchers discovered that nanoparticles showed strong cancer cell toxicity which led to cell death through apoptosis thus making them suitable for medical treatment. The research proved that Fe₂O₃ nanoparticles showed high biocompatibility which makes them suitable for use in biological systems. The research by Tariq *et al.* (The research by Khaled and Al-Najem (2021) used numerical methods to study MHD hybrid nanofluid flow through a rotating channel which received magnetic field application. The researchers discovered that hybrid nano fluids experience changes in their flow behavior and heat transfer performance because of the magnetic field presence.

The researchers found that hybrid nano fluids showed higher velocity and temperature gradient values when magnetic fields were applied. The Lorentz force which acts on charged particles in nano fluids produces modified fluid flow patterns that produce increased gradient values. The researchers found that the magnetic field produced an increase in nano fluid heat transfer rates. A recent investigation by Ahmad *et al.* (2021) examined the effects of MHD flow on the transport of the hybrid nanofluid in human blood vessels for the cancer treatment. The authors used the finite element approach to analyze the MHD flow and found that both the magnetic field strength and the nanoparticle volume fraction significantly affect velocity with temperature distribution on the nano fluid in the blood vessels.

By using the finite element method, the researchers were able to create a computational model of the MHD flow and examine the behavior of the nano fluid under different conditions. The research results show that blood vessel nano fluid transport strongly depends on both the strength of the magnetic field and the quantity of nanoparticles

used. Specifically, the researchers found out that the higher magnetic field strengths and volume fractions of the nanoparticles led to changes in the velocity and temperature profile of the nano fluid. The research established that MHD flow applications would improve the process of delivering therapeutic agents to human cancer cells throughout the body. Based on the formulation literature reviews, it is evident that a research gap exists which shows that there is need to carry out analysis of hydromagnetic hybrid nano fluid flow with FeO and Fe₂O₃ suspension in human blood. This project is motivated to fill this research gap.

3. Materials and Methods

3.1 Introduction

In this chapter equations governing fluid flow are discussed, the equations are; transport, momentum, energy, continuity and Maxwell's. The research has the following assumptions.

3.2 Assumptions

To simplify the analysis, the following assumptions are made:

- The flow is steady and laminar.
- The fluid is Newtonian fluid and incompressible.
- The properties of the hybrid nanofluid are constant except for the density variation in the buoyancy term (Boussinesq approximation).
- The magnetic Reynolds number is small, so the induced magnetic field is negligible.
- The effects of viscous dissipation and Joule heating are negligible.

3.3 Model description

The continuity equation for incompressible MHD flow ensures mass conservation and is expressed as:

$$\nabla \cdot V = 0$$

and the momentum equation is

$\rho \left(\frac{\partial v}{\partial t} + (v \cdot \nabla) v \right) = -\nabla p + \mu \nabla^2 v + (J \times B)$ where ρ is the Density of the fluid, t is the Time, v is the Velocity vector field, representing fluid flow velocity, p is the Pressure of the fluid, J is the Electric current density vector and $B = B_0 + b$ is the total magnetic field which is the sum of the applied magnetic field B_0 and the induced magnetic field b . The Cauchy stress tensor τ within the fluid is

$$\tau = -pl + (\nabla v + (\nabla v)^T)$$

where p is pressure, I is the identity tensor, μ is the dynamic viscosity, ∇v is the velocity gradient tensor and T is the time constant.

The components of the extra stress tensor are

$$\mu \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)$$

Where $i \neq j$

3.4 Governing equations

The following equations governed the flow;

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (3.3.1)$$

Since thermal radiation, applied magnetic field and buoyancy has effect on the velocity, the governing equations are as follows;

(3.3.2)

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{\mu_{nf}}{\rho_{nf}} \left(1 + \frac{1}{\gamma} \right) \frac{\partial^2 u}{\partial y^2} + g\beta_T (T - T_\infty) + g\beta_C (C - C_\infty) - \frac{\sigma_{nf} B_0^2 u}{\rho_{nf}},$$

(3.3.3)

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha_{nf} \frac{\partial^2 T}{\partial y^2} + \tau \left(\frac{D_B}{\Delta C} \frac{\partial C}{\partial y} \frac{\partial T}{\partial y} + \frac{D_T}{T_\infty} \left(\frac{\partial T}{\partial y} \right)^2 \right) + \frac{\mu_{nf}}{\rho_{nf} c_p} \left(\frac{\partial u}{\partial y} \right)^2 + \frac{\sigma_{nf} B_0^2 u^2}{\rho_{nf} c_p},$$

(3.3.4)

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

Governed by limiting conditions

(3.3.6)

$$\text{at } y = 0: u = U_w(x) = ax, v = 0, -k_f \frac{\partial T}{\partial y} = h_f (T_w - T), C = C_w(x),$$

(3.3.7)

$$\text{as } y \rightarrow \infty: u \rightarrow 0, T \rightarrow T_\infty, C \rightarrow C_\infty,$$

under which

$$\alpha_{nf} = \frac{\kappa_{nf}}{\rho_{nf} c_p}, \quad (3.3.8)$$

$$\tau = \frac{\text{density specific heat capacity of nanoparticles}}{\text{density specific heat capacity of base fluid}} = \frac{(\rho c_p)_{np}}{(\rho c_p)_{bf}}, \quad (3.1.9)$$

$$\frac{k_{nf}}{k_{bf}} = \frac{k_{np1} + k_{np2} - \phi(k_{bf} - k_{np1})}{k_{np1} + k_{np2} + \phi(k_{bf} - k_{np1})}, \quad (3.3.10)$$

$$\rho_{nf} = (1 - \phi)\rho_{bf} + \phi_1 \rho_{np1} + \phi_2 \rho_{np2}, \quad (3.3.11)$$

$$(\rho c_p)_{nf} = (1 - \phi)(\rho c_p)_{bf} + \phi_1 (\rho c_p)_{np1} + \phi_2 (\rho c_p)_{np2}, \quad (3.3.12)$$

$$\mu_{nf} = (1 + 8.0\phi + 130\phi^2)\mu_{bf}. \quad (3.3.13)$$

3.5 Similarity variables

The nonlinearity in the governing equations, coupled with the numerous parameters, makes the equations difficult to solve. The number of parameters can be reduced by parametrizing the equations. Hence, adopting the similarity variables, the number of parameters can be reduced and the system can be reduced to ordinary differential equation. Consider the similarity variables

$$\eta = ya^{\frac{1}{2}} \vartheta_{bf}^{-\frac{1}{2}}, \quad (3.4.1)$$

$$u = axf'(\eta), \quad (3.4.2)$$

$$v = -a^{\frac{1}{2}} \vartheta_{bf}^{\frac{1}{2}} f, \quad (3.4.3)$$

$$T - T_\infty = \Theta \Delta T, \quad (3.4.4)$$

$$C - C_\infty = \Phi \Delta C. \quad (3.4.5)$$

Noting that the similarity variable η is dependent only on y , then the derivative with respect to y is found as

$$\frac{d\eta}{dy} = a^{\frac{1}{2}} \vartheta_{bf}^{-\frac{1}{2}}. \quad (3.4.6) \quad \text{The derivatives of the remaining variables with respect to } x \text{ are found below. Then,}$$

$$\frac{du}{dx} = \frac{d}{dx}(axf') = af', \quad \frac{dT}{dx} = 0, \quad \frac{dC}{dx} = 0, \quad (3.4.7)$$

The derivatives with respect to y are;

$$\frac{du}{dy} = \frac{d}{dy}(axf') = ax \frac{d}{d\eta}(f') \frac{d\eta}{dy} = axf'' \times a^{\frac{1}{2}} \vartheta_{bf}^{-\frac{1}{2}} = a^{\frac{3}{2}} \vartheta_{bf}^{-\frac{1}{2}} xf''. \quad (3.2.8)$$

$$\frac{d^2u}{dy^2} = \frac{d}{dy} \left(a^{\frac{3}{2}} \vartheta_{bf}^{-\frac{1}{2}} xf'' \right) = a^{\frac{3}{2}} \vartheta_{bf}^{-\frac{1}{2}} x \frac{d}{d\eta}(f'') \frac{d\eta}{dy} = a^{\frac{3}{2}} \vartheta_{bf}^{-\frac{1}{2}} xf''' \times a^{\frac{1}{2}} \vartheta_{bf}^{-\frac{1}{2}} = a^2 \vartheta_{bf}^{-1} xf''', \quad (3.4.9)$$

$$\frac{dT}{dy} = \frac{d}{dy}(\Theta \Delta T) = \Delta T \frac{d}{d\eta}(\Theta) \frac{d\eta}{dy} = \left(a^{\frac{1}{2}} \vartheta_{bf}^{-\frac{1}{2}} \Delta T \right) \Theta', \quad (3.4.10)$$

$$\frac{d^2T}{dy^2} = \frac{d}{dy} \left(\left(a^{\frac{1}{2}} \vartheta_{bf}^{-\frac{1}{2}} \Delta T \right) \Theta' \right) = \left(a^{\frac{1}{2}} \vartheta_{bf}^{-\frac{1}{2}} \Delta T \right) \frac{d}{d\eta}(\Theta') \frac{d\eta}{dy} = \left(a \vartheta_{bf}^{-1} \Delta T \right) \Theta'', \quad (3.4.11)$$

$$\frac{dC}{dy} = \frac{d}{dy}(\Phi \Delta C) = \Delta C \frac{d}{d\eta}(\Phi) \frac{d\eta}{dy} = \left(a^{\frac{1}{2}} \vartheta_{bf}^{-\frac{1}{2}} \Delta C \right) \Phi', \quad (3.4.12)$$

$$\frac{d^2C}{dy^2} = \frac{d}{dy} \left(\left(a^{\frac{1}{2}} \vartheta_{bf}^{-\frac{1}{2}} \Delta C \right) \Phi' \right) = \left(a^{\frac{1}{2}} \vartheta_{bf}^{-\frac{1}{2}} \Delta C \right) \frac{d}{d\eta}(\Phi') \frac{d\eta}{dy} = \left(a \vartheta_{bf}^{-1} \Delta C \right) \Phi''. \quad (3.4.13)$$

Now, by using equations (3.2.1) – (3.2.5) and (3.2.7) – (3.2.12), equation (3.1.2) becomes

$$(axf')(af') - \left(a^{\frac{1}{2}} \vartheta_{bf}^{-\frac{1}{2}} f \right) \left(a^{\frac{3}{2}} \vartheta_{bf}^{-\frac{1}{2}} xf'' \right) = \frac{\mu_{nf}}{\rho_{nf}} \left(1 + \frac{1}{\gamma} \right) a^2 \vartheta_{bf}^{-1} xf''' + g\beta_T \Theta \Delta T + g\beta_C \Phi \Delta C - \frac{\sigma_{nf} B_0^2}{\rho_{nf}} axf'. \quad (3.4.14)$$

Rearrangement of equation (3.2.14) gives

$$a^2 x (f')^2 - a^2 x f'' f = \frac{\mu_{nf}}{\rho_{nf}} \left(1 + \frac{1}{\gamma} \right) a^2 \vartheta_{bf}^{-1} xf''' + g\beta_T \Theta \Delta T + g\beta_C \Phi \Delta C - \frac{\sigma_{nf} B_0^2}{\rho_{nf}} axf'. \quad (3.4.15)$$

Dividing through equation (3.2.15) by $a^2 x$ gives

$$(f')^2 - f'' f = \frac{\mu_{nf}}{\rho_{nf}} \left(1 + \frac{1}{\gamma} \right) \vartheta_{bf}^{-1} f''' + \frac{g\beta_T \Delta T}{a^2 x} \Theta + \frac{g\beta_C \Delta C}{a^2 x} \Phi - \frac{\sigma_{nf} B_0^2}{a \rho_{nf}} f'. \quad (3.4.16)$$

On rearranging, we have

$$\frac{\mu_{nf}}{\rho_{nf}} \left(1 + \frac{1}{\gamma} \right) \vartheta_{bf}^{-1} f''' - (f')^2 + f'' + \frac{g\beta_T \Delta T}{a^2 x} \Theta + \frac{g\beta_C \Delta C}{a^2 x} \Phi - \frac{\sigma_{nf} B_0^2}{a \rho_{nf}} f' = 0. \quad (3.4.17)$$

By using the viscosity from equations (3.1.11) and density from (3.1.13), it means

$$\begin{aligned}\frac{\mu_{nf}}{\rho_{nf}} &= \frac{(1 + 8.0\phi + 130\phi^2)\mu_{bf}}{(1 - \phi)\rho_{bf} + \phi_1\rho_{np1} + \phi_2\rho_{np2}} = \\ &= \frac{(1 + 8.0\phi + 130\phi^2)\mu_{bf}}{\left(1 - \phi + \phi_1\frac{\rho_{np1}}{\rho_{bf}} + \phi_2\frac{\rho_{np2}}{\rho_{bf}}\right)\rho_{bf}} \\ &= \frac{1 + 8.0\phi + 130\phi^2}{1 - \phi + \phi_1\frac{\rho_{np1}}{\rho_{bf}} + \phi_2\frac{\rho_{np2}}{\rho_{bf}}}\vartheta_{bf} = A_1\vartheta_{bf},\end{aligned}\quad (3.4.18)$$

where

Hence equation (3.2.17) is now rewritten as

$$A_1 = \frac{1 + 8.0\phi + 130\phi^2}{1 - \phi + \phi_1\frac{\rho_{np1}}{\rho_{bf}} + \phi_2\frac{\rho_{np2}}{\rho_{bf}}}.\quad (3.4.19)$$

$$\begin{aligned}A_1\vartheta_{bf}\left(1 + \frac{1}{\gamma}\right)\vartheta_{bf}^{-1}f''' - (f')^2 + f''f + \frac{g\beta_T\Delta T}{a^2x}\Theta + \frac{g\beta_C\Delta C}{a^2x}\Phi - \\ \frac{\sigma_{nf}B_0^2}{a\rho_{nf}}f' = 0,\end{aligned}\quad (3.4.20)$$

$$A_1\left(1 + \frac{1}{\gamma}\right)f''' - (f')^2 + f''f + \frac{g\beta_T\Delta T}{a^2x}\Theta + \frac{g\beta_C\Delta C}{a^2x}\Phi - \frac{\sigma_{nf}B_0^2}{a\rho_{nf}}f' = 0.\quad (3.2.21)$$

Following the dimensionless quantities defined by Juma *et al.* (2022) [11], the thermal Grashof number, solutal Grashof number and magnetic field parameters are as follows

$$G_t = \frac{g\beta_T\Delta T}{a^2x}, \quad G_s = \frac{g\beta_C\Delta C}{a^2x}, \quad M = \frac{\sigma_{nf}B_0^2}{a\rho_{nf}}.\quad (3.4.22)$$

By putting (3.2.22) in (3.2.21), then the dimensionless form of the momentum equation becomes

$$A_1\left(1 + \frac{1}{\gamma}\right)f''' - (f')^2 + f''f + G_t\Theta + G_s\Phi - Mf' = 0.\quad (3.4.23)$$

The next step is to nondimensionalise the energy equation (3.1.3). This is set in motion by substituting the similarity variables (3.2.1) – (3.2.5) and their derivatives (3.2.7) – (3.2.13) into equation (3.1.13) and we have

$$\begin{aligned}(axf')(0) + \left(-a^{\frac{1}{2}}\vartheta_{bf}^{\frac{1}{2}}f\right)\left(a^{\frac{1}{2}}\vartheta_{bf}^{-\frac{1}{2}}\Delta T\right)\Theta' = \alpha_{nf}(a\vartheta_{bf}^{-1}\Delta T)\Theta'' \\ + \tau\left(\frac{D_B}{\Delta C}\left(a^{\frac{1}{2}}\vartheta_{bf}^{-\frac{1}{2}}\Delta C\right)\Phi\left(a^{\frac{1}{2}}\vartheta_{bf}^{-\frac{1}{2}}\Delta T\right)\Theta' + \frac{D_T}{T_\infty}\left(\left(a^{\frac{1}{2}}\vartheta_{bf}^{-\frac{1}{2}}\Delta T\right)\Theta'\right)^2\right) + \\ \frac{\mu_{nf}}{\rho_{nf}c_p}\left(a^{\frac{3}{2}}\vartheta_{bf}^{-\frac{1}{2}}xf'\right)^2 + \frac{\sigma_{nf}B_0^2(axf')^2}{\rho_{nf}c_p}, \\ -a\Delta Tf\Theta' = \alpha_{nf}a\vartheta_{bf}^{-1}\Delta T\Theta'' + \tau\left(D_Ba\vartheta_{bf}^{-1}\Delta T\Phi'\Theta' + \frac{a\vartheta_{bf}^{-1}D_T}{T_\infty}(\Delta T\Theta')^2\right) + \\ \frac{a^3\vartheta_{bf}^{-1}x^2\mu_{nf}}{\rho_{nf}c_p}(f'')^2 + \frac{\sigma_{nf}B_0^2a^2x^2}{\rho_{nf}c_p}(f')^2,\end{aligned}\quad (3.4.24)$$

By dividing through equation (3.2.24) by $a\Delta T$,

$$\alpha_{nf} \vartheta_{bf}^{-1} \Theta'' + \tau D_B \vartheta_{bf}^{-1} \Phi' \Theta' + \frac{\tau \vartheta_{bf}^{-1} D_T \Delta T}{T_\infty} (\Theta')^2 + \frac{a^2 \vartheta_{bf}^{-1} x^2 \mu_{nf}}{\rho_{nf} c_p \Delta T} (f'')^2 + \frac{\sigma_{nf} B_0^2 a x^2}{\rho_{nf} c_p \Delta T} (f')^2 + f \Theta' = 0, \quad (3.4.25)$$

By using the definitions (3.1.8), (3.1.10), and (3.1.12), then

$$\alpha_{nf} = \frac{k_{nf}}{(\rho c_p)_{nf}} = \frac{\frac{k_{np1} + k_{np2} - \phi(k_{bf} - k_{np1})}{k_{np1} + k_{np2} + \phi(k_{bf} - k_{np1})} k_{bf}}{(1 - \phi)(\rho c_p)_{bf} + \phi_1(\rho c_p)_{np1} + \phi_2(\rho c_p)_{np2}} \\ = \frac{\frac{k_{np1} + k_{np2} - \phi(k_{bf} - k_{np1})}{k_{np1} + k_{np2} + \phi(k_{bf} - k_{np1})} k_{bf}}{\left(1 - \phi + \frac{\phi_1(\rho c_p)_{np1}}{(\rho c_p)_{bf}} + \frac{\phi_2(\rho c_p)_{np2}}{(\rho c_p)_{bf}}\right) (\rho c_p)_{bf}} = \frac{A_2}{A_3} \alpha_{bf} \quad (3.4.26)$$

where

$$A_2 = \frac{k_{np1} + k_{np2} - \phi(k_{bf} - k_{np1})}{k_{np1} + k_{np2} + \phi(k_{bf} - k_{np1})}, \quad (3.4.27)$$

$$A_3 = 1 - \phi + \frac{\phi_1(\rho c_p)_{np1}}{(\rho c_p)_{bf}} + \frac{\phi_2(\rho c_p)_{np2}}{(\rho c_p)_{bf}}, \quad (3.4.28)$$

$$\alpha_{bf} = \frac{k_{bf}}{(\rho c_p)_{bf}}. \quad (3.4.29)$$

Also, using (3.1.11) and (3.1.13), we have

$$\frac{\mu_{nf}}{\alpha_{bf} \rho_{nf}} = \frac{(1 + 8.0\phi + 130\phi^2) \mu_{bf}}{\left(1 - \phi + \phi_1 \frac{\rho_{np1}}{\rho_{bf}} + \phi_2 \frac{\rho_{np2}}{\rho_{bf}}\right) \rho_{bf} \alpha_{bf}} = \frac{1 + 8.0\phi + 130\phi^2}{1 - \phi + \phi_1 \frac{\rho_{np1}}{\rho_{bf}} + \phi_2 \frac{\rho_{np2}}{\rho_{bf}}} = A_1 \quad (3.4.30)$$

Hence, equation (3.2.25) becomes

$$\frac{A_2}{A_3} \alpha_{bf} \vartheta_{bf}^{-1} \Theta'' + \tau \left(D_B \vartheta_{bf}^{-1} \Phi' \Theta' + \frac{\vartheta_{bf}^{-1} D_T \Delta T}{T_\infty} (\Theta')^2 \right) + \frac{a^2 \vartheta_{bf}^{-1} x^2 \mu_{nf}}{\rho_{nf} c_p \Delta T} (f'')^2 + \frac{\sigma_{nf} B_0^2 a x^2}{\rho_{nf} c_p \Delta T} (f')^2 + f \Theta' = 0, \quad (3.4.31)$$

$$\frac{A_2}{A_3} \Theta'' + \left(\frac{\tau D_B}{\alpha_{bf}} \Phi' \Theta' + \frac{\tau D_T \Delta T}{T_\infty \alpha_{bf}} (\Theta')^2 \right) + \frac{a^2 x^2 \mu_{nf}}{\alpha_{bf} \rho_{nf} c_p \Delta T} (f'')^2 + \frac{\sigma_{nf} B_0^2 a x^2}{\alpha_{bf} \vartheta_{bf}^{-1} \rho_{nf} c_p \Delta T} (f')^2 + \frac{1}{\alpha_{bf} \vartheta_{bf}^{-1}} f \Theta' = 0, \quad (3.4.32)$$

Setting the Brownian parameter, thermophoretic parameter, Eckert number, and Prandtl number according to Juma *et al.* (2022) [11], as follows;

$$N_b = \frac{\tau D_B}{\alpha_{bf}}, N_t = \frac{\tau D_T \Delta T}{T_\infty \alpha_{bf}}, Ec = \frac{a^2 x^2}{c_p \Delta T}, Pr = \frac{\vartheta_{bf}}{\alpha_{bf}}. \quad (3.4.33)$$

Equation (3.2.32) now becomes

$$\frac{A_2}{A_3} \Theta' + N_b \Phi' \Theta' + N_t (\Theta')^2 + A_1 Ec (f'')^2 + \frac{\sigma_{nf} B_0^2}{a \rho_{nf}} \frac{\vartheta_{bf}}{\alpha_{bf} c_p \Delta T} (f')^2 + \frac{\vartheta_{bf}}{\alpha_{bf}} f \Theta' = 0, \quad (3.4.34)$$

Hence, the dimensionless form of the energy equation is

$$\frac{A_2}{A_3} \Theta' + N_b \Phi' \Theta' + N_t (\Theta')^2 + A_1 Ec (f'')^2 + Pr Ec M (f')^2 + Pr f \Theta' = 0, \quad (3.4.35)$$

The next equation is the concentration equation (3.1.4). On substituting equations (3.2.1) – (3.2.13) into equation (3.1.4) and it gives

$$\begin{aligned} (axf')(0) + \left(-a^{\frac{1}{2}} \vartheta_{bf}^{\frac{1}{2}} f \right) \left(a^{\frac{1}{2}} \vartheta_{bf}^{-\frac{1}{2}} \Delta C \right) \Phi' &= D_B (a \vartheta_{bf}^{-1} \Delta C) \Phi'' + \frac{D_T \Delta C}{T_\infty} (a \vartheta_{bf}^{-1} \Delta T) \Theta'' \\ D_B a \vartheta_{bf}^{-1} \Delta C \Phi'' + \frac{D_T a \vartheta_{bf}^{-1} \Delta T \Delta C}{T_\infty} \Theta'' + a \Delta C f \Phi' &= 0 \\ D_B \vartheta_{bf}^{-1} \Phi'' + \frac{D_T \vartheta_{bf}^{-1} \Delta T}{T_\infty} \Theta'' + f \Phi' &= 0 \end{aligned} \quad (3.4.36)$$

Setting

$$\frac{1}{Sc} = \frac{D_B}{\vartheta_{bf}}, N_t = \frac{\tau D_T \Delta T}{T_\infty \alpha_{bf}}, Ec = \frac{a^2 x^2}{c_p \Delta T}, Pr = \frac{\vartheta_{bf}}{\alpha_{bf}}, \quad (3.4.37)$$

Then equation (3.2.36) become

$$\frac{1}{Sc} \Phi'' + \frac{D_T \vartheta_{bf}^{-1} \Delta T}{T_\infty} \Theta'' + f \Phi' = 0 \quad \frac{1}{Sc} \Phi'' + \frac{N_t}{N_b} \cdot \frac{1}{Sc} \Theta'' + f \Phi' = 0$$

The dimensionless form of the concentration equation is

Note that

$$\Phi'' + \frac{N_t}{N_b} \Theta'' + Sc f \Phi' = 0. \quad (3.4.38)$$

Now, turn to the boundary conditions at $y = 0$. It is clear that $\eta = 0$ when $y = 0$. So, we consider the case $\eta = 0$:

And so,

$$\begin{cases} u = U_w(x) = ax \Rightarrow axf'(0) = ax \Rightarrow f'(0) = 1 \\ v = 0 \Rightarrow -a^{\frac{1}{2}} \vartheta_{bf}^{\frac{1}{2}} f(0) = 0 \Rightarrow f(0) = 0 \\ -k_{nf} \frac{\partial T}{\partial y} = h_{bf} (T_w - T) \Rightarrow -A_2 k_{bf} a^{\frac{1}{2}} \vartheta^{-\frac{1}{2}} \Delta T \cdot \Theta'(0) = h_{bf} (1 - \Theta) \Delta T \end{cases} \quad (3.4.39)$$

Recall that

and set

$$k_{nf} = \frac{k_{np1} + k_{np2} - \phi(k_{bf} - k_{np1})}{k_{np1} + k_{np2} + \phi(k_{bf} - k_{np1})} k_{bf} = A_2 k_{bf} \quad Bi = \frac{h_{bf}}{k_{bf}} \left(\frac{\vartheta}{a} \right)^{\frac{1}{2}}$$

then,

$$\Theta'(0) = -\frac{h_{bf}}{A_2 k_{bf}} \left(\frac{\vartheta}{a} \right)^{\frac{1}{2}} (1 - \Theta) = -\frac{Bi}{A_2} (1 - \Theta(0)) \quad (3.4.40)$$

and the final the wall condition is,

$$C = C_w \Rightarrow C_\infty + \Phi \Delta C = C_w \Rightarrow \Phi \Delta C = C_w - C_\infty = \Delta C \Rightarrow \Phi(0) = 1. \quad (3.2.41)$$

At the free stream $y \rightarrow \infty$, we have $\eta \rightarrow \infty$

$$\begin{cases} u \rightarrow 0 \Rightarrow axf'(\infty) \rightarrow 0 \Rightarrow f'(\infty) \rightarrow 0 \\ T \rightarrow T_\infty \Rightarrow T_\infty + \Theta \Delta T \rightarrow T_\infty \Rightarrow \Theta \Delta T \rightarrow 0 \Rightarrow \Theta \rightarrow 0 \\ C \rightarrow C_\infty \Rightarrow C_\infty + \Phi \Delta C \rightarrow C_\infty \Rightarrow \Phi \Delta C \rightarrow 0 \Rightarrow \Phi \rightarrow 0 \end{cases} \quad (3.4.42)$$

4. Analysis and discussion of results

4.1 Numerical solution

The dimensionless form of the governing equations is

$$A_1 \left(1 + \frac{1}{\gamma}\right) f'' - (f')^2 + f'' f + G_t \Theta + G_s \Phi - M f' = 0,$$

$$\frac{A_2}{A_3} \Theta'' + N_b \Phi' \Theta' + N_t (\Theta')^2 + A_1 Ec (f'')^2 + Pr Ec M (f')^2 + Pr f \Theta' = 0,$$

$$\Phi'' + \frac{N_t}{N_b} \Theta'' + Sc f \Phi' = 0.$$

With the conditions

$$\begin{cases} f = 0, \quad f' = 1, \quad \Theta' = -\frac{Bi}{A_2} (1 - \Theta), \quad \Phi = 1 \quad \text{at } \eta = 0 \\ f' \rightarrow 0, \quad \Theta \rightarrow 0, \quad \Phi \rightarrow 0 \quad \text{as } \eta \rightarrow \infty \end{cases}$$

The dimensionless form of the governing equations is

$$\dot{u}_1 = u_2,$$

$$\dot{u}_2 = u_3,$$

$$\dot{u}_3 = -\frac{-u_2^2 + u_3 u_1 + G_t u_4 + G_s u_6 - M u_2}{A_1 \left(1 + \frac{1}{\gamma}\right)},$$

$$\dot{u}_4 = u_5,$$

$$\dot{u}_5 = \frac{A_3}{A_2} [N_b u_7 u_5 + N_t u_5^2 + A_1 Ec u_3^2 + Pr Ec M u_2^2 + Pr u_1 u_5],$$

$$\dot{u}_6 = u_7,$$

$$\dot{u}_7 = -\frac{N_t}{N_b} \dot{u}_5 - Sc u_1 u_7.$$

with the conditions

$$u_1 = 0, \quad u_2 = 1, \quad u_3 = -\frac{Bi}{A_2}(1 - u_4), \quad u_6 = 1 \quad \text{at } \eta = 0.$$

$$u_2 \rightarrow 0, \quad u_4 \rightarrow 0, \quad u_6 \rightarrow 0 \quad \text{as } \eta \rightarrow \infty.$$

The system of dimensionless ordinary differential equations derived from the governing equations was solved using the MATLAB `bvp4c` function, which employs a collocation method for boundary value problems. The boundary conditions at $\eta = 0$ and $\eta \rightarrow \infty$ were incorporated to ensure the accuracy of the solution. Initial guesses for the solution profiles were carefully chosen to facilitate convergence, given the nonlinearity of the equations. The solutions for primary ve-

locity (f'') and secondary velocity (f) and temperature (Θ) and concentration (Φ) were derived based on the magnetic field parameter (M) and Eckert number (Ec) and nanoparticle volume fraction (Φ). The computational process required multiple iterations to achieve the minimum residuals of both governing equations and boundary conditions which produced stable numerical results. The default values for the parameters are as follows;

$$\gamma = 0.10; \quad Gt = 1.00; \quad Gs = 1.00; \quad M = 2.00; \quad Nb = 0.10; \quad Nt = 0.10;$$

$$Ec = 0.10; \quad Pr = 4.00; \quad Sc = 0.62; \quad Bi = 0.10; \quad \eta_\infty = 10.00;$$

The thermophysical properties of the nanofluid are also provided in Table 1.

4.2 Discussion of results

The numerical simulation produced essential data which showed how various essential parameters influence hydromagnetic hybrid nanofluid flow. The research investigates how three parameters which include magnetic field parameter (M) and Eckert number (Ec) and nanoparticle volume fraction (ϕ) affect the flow patterns. The velocity profiles and temperature distributions and concentration levels in the fluid become determined by these essential factors.

The magnetic field parameter (M) produces a major impact on fluid dynamics because it creates a Lorentz force which works against fluid flow. The system experiences resistance which affects both the fluid velocity and temperature distribution patterns. The magnetic field strength increase leads to a significant decrease in both primary velocity and secondary velocity according to Figures 4.1 and 4.2. The magnetic field creates two opposing forces which reduce fluid motion through its resistive and damping effects. The Lorentz force appears because charged particles in the fluid experience magnetic field interactions which generate a force that resists fluid movement and decreases its kinetic energy. The observed effect exists in actual situations which generate beneficial results but simultaneously generates detrimental effects. The decreased fluid velocity in cooling systems allows the fluid to stay longer near heat exchangers which could lead to better heat transfer performance. The magnetic field strength creates obstacles for processes which need fast fluid movement because it affects their operational efficiency in chemical reactors and mixing systems. The magnetic field strength causes fluid velocities to decrease but the temperature and concentration profiles show opposite behavior according to Figures 4.3 and 4.4. The increase in temperature can be attributed to enhanced thermal energy retention. The magnetic field creates opposition to fluid movement which produces increased heat through the process of viscous dissipation that occurs within the fluid. The thermal energy which builds up from this process becomes useful for medical procedures which need exact temperature control in their thermal management systems. The magnetic field generates a concentration gradient which produces higher solutal retention across the entire fluid surface area. The opposition to movement enables solutes to spread evenly which could enhance reaction speed in mass transfer based processes. The behavior reaches

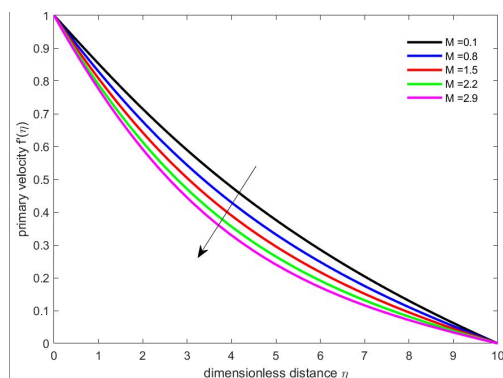
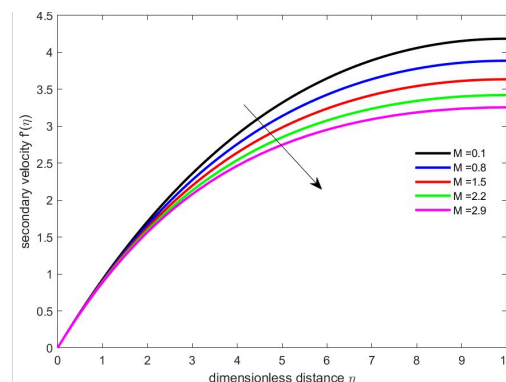
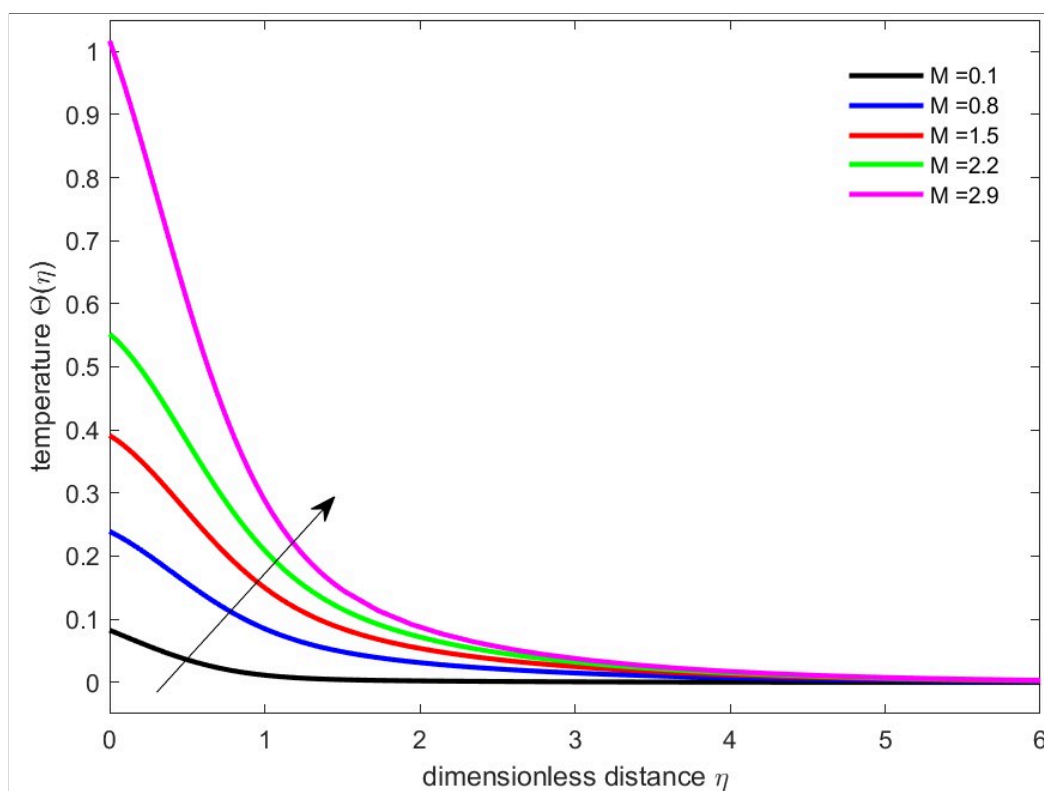
its peak intensity at this particular time and significant in applications like electrochemical cells and various forms of chemical synthesis, where localized concentration gradients can critically influence efficiency and yield.

The Eckert number (Ec) shows how fluid viscosity affects the distribution of temperature and velocity which occurs in fluid systems. The graph illustrated in Figures 4.5 and 4.6 indicate a direct correlation between an increase in the Eckert number and the enhancement of both the primary and secondary velocity fields. The observed increase in velocity results from the conversion of kinetic energy into thermal energy which enables better fluid flow. The temperature profile shows an increase in temperature values which match the rising Eckert numbers according to Figure 4.7. The process of viscous dissipation produces extra heat which results in higher thermal energy levels within the fluid. The thermal elevation creates effects which reach past temperature measurement because Figure 4.8 shows that elevated Eckert numbers lead to increased concentration profiles. The system shows better solute transport because the increased fluid speed and stronger thermal energy work together to enhance the process.

The flow velocities together with temperature and concentration profiles in fluid systems experience major changes because of the amount of nanoparticles which exist in the solution. As illustrated in Figures 4.9 and 4.10, there is a noteworthy correlation between the nanoparticle volume fraction and the primary and secondary velocities of the flow. The improved fluid velocity results from nanoparticles which show better thermal conductivity properties that enhance energy transfer in the fluid to produce faster fluid movement. The temperature profile shows an upward trend when the volume fraction of nanoparticles increases according to Figure 4.11. The trend shows better heat transfer efficiency because nanoparticles optimize thermal performance for improved efficiency. The nanoparticles enhance thermal contact between particles which results in uniform fluid temperature distribution that engineers need for their thermal management work. The concentration profile shows a decrease in its values when the volume fraction of the solution increases according to Figure 4.12. The concentration gradient becomes smaller because nanoparticle concentrations rise which leads to this decrease in concentration. The presence of a higher volume fraction of nanoparticles tends to favour thermal diffusion over solutal diffusion, thereby disrupting the conventional concentration distribution.

Table 4.1. Thermophysical properties of the nanofluid

	ρ (kg/m ³)	c_p (j/kgK)	κ (W/mK)	Source
Fe_3O_4	5200	670.0	6.00	Ly <i>et al.</i> , 2021
Fe_2O_3	5242	681	20	Giwa <i>et al.</i> , 2021
Blood	1093	3210	0.451	Oke <i>et al.</i> , 2023

**Figure 4.1.** Primary velocity with Magnetic Field Strength**Figure 4.2.** Secondary velocity with Magnetic Field Strength**Figure 4.3.** Temperature with Magnetic Field Strength

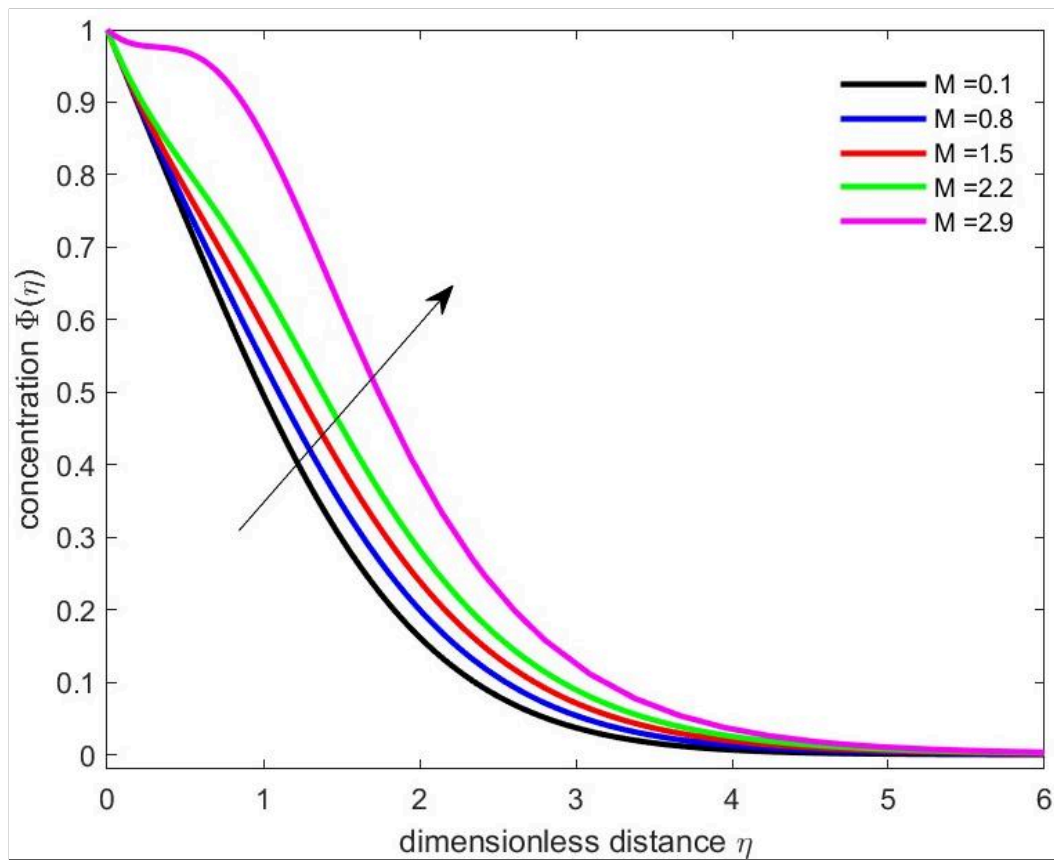


Figure 4.4. Concentration with Magnetic Field Strength

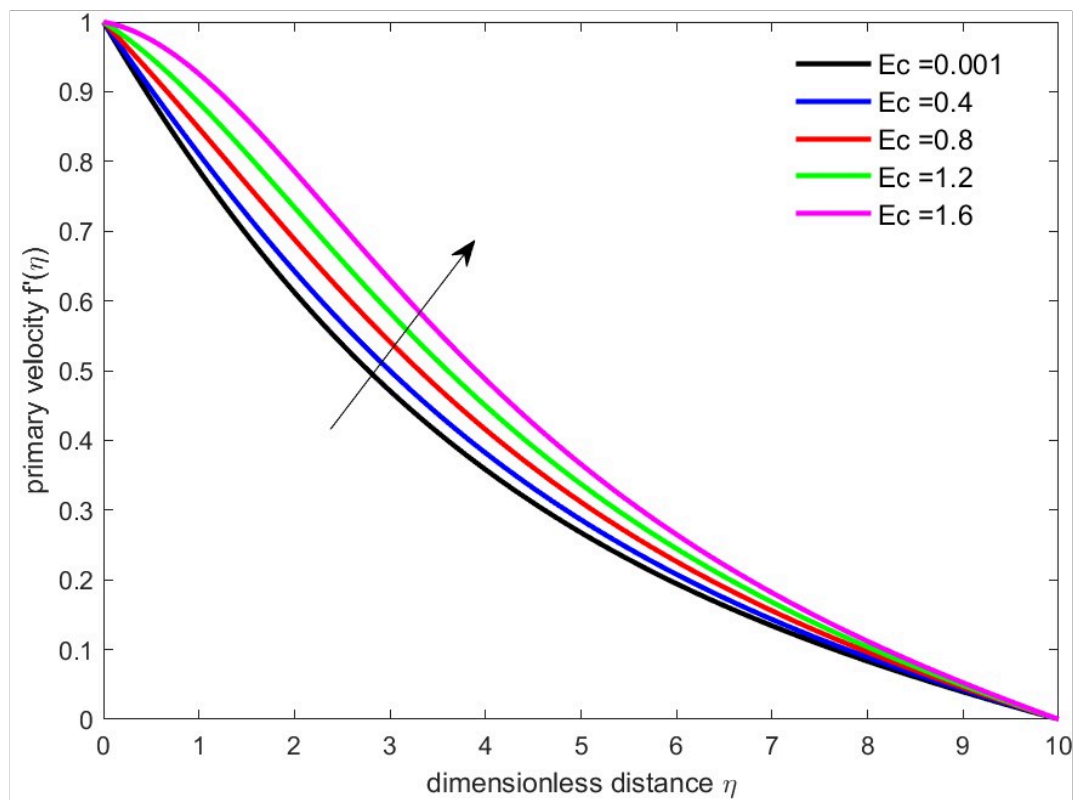


Figure 4.5. Primary velocity with Eckert number

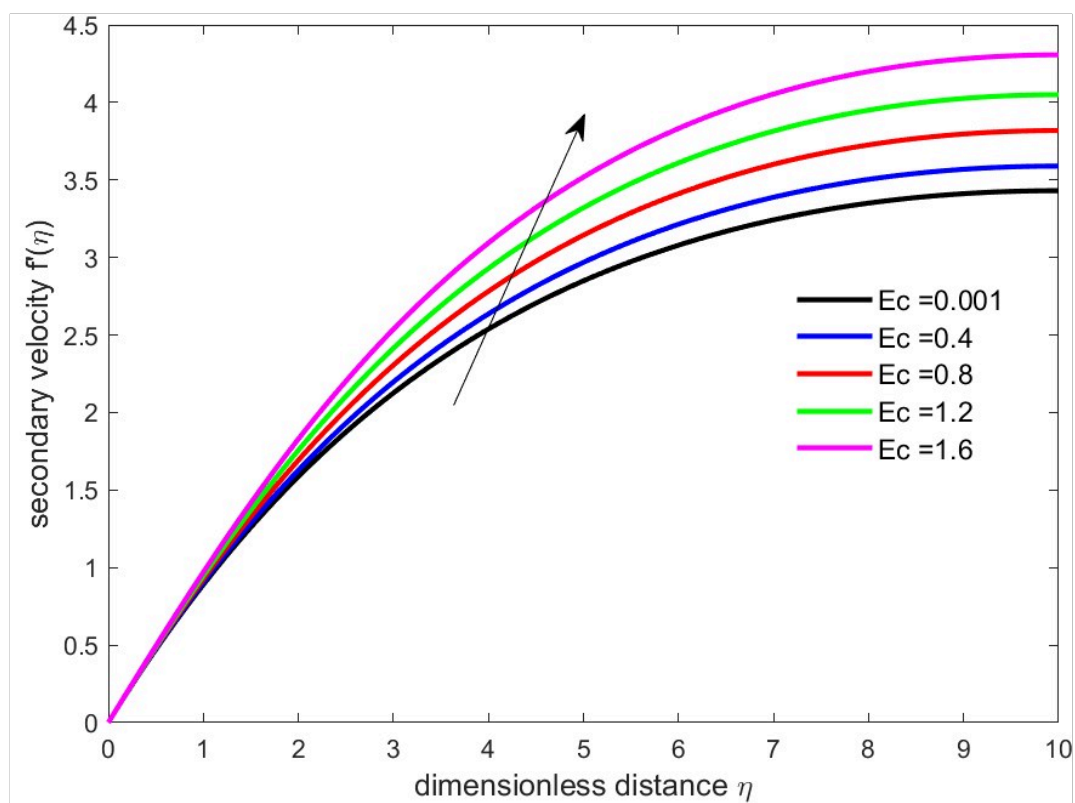


Figure 4.6. Secondary velocity with Eckert number

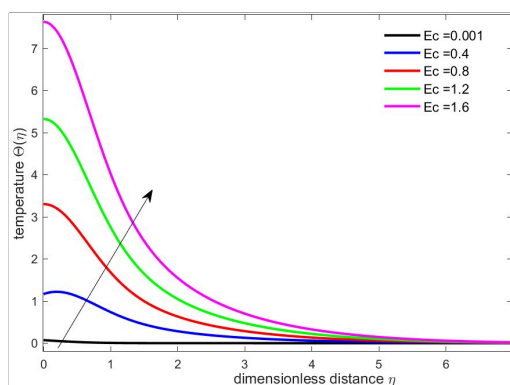


Figure 4.7. Temperature with Eckert number

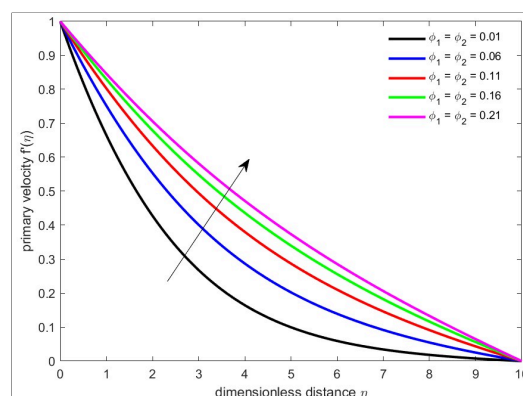


Figure 4.9. Primary velocity with volume fraction

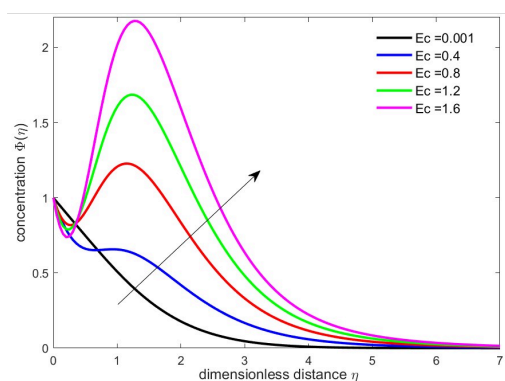


Figure 4.8. Concentration with Eckert number

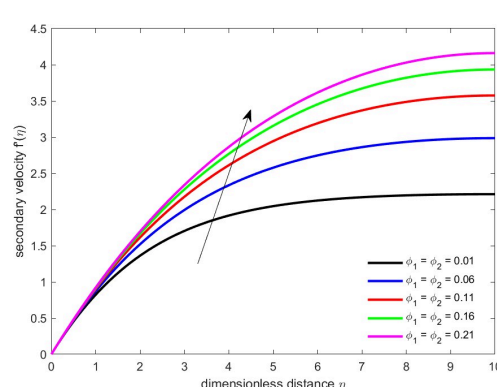


Figure 4.10. Secondary velocity with volume fraction

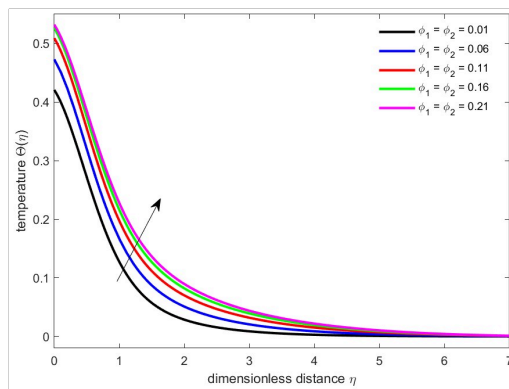


Figure 4.11. Temperature with volume fraction

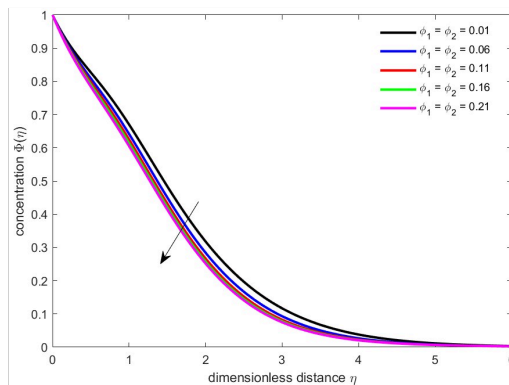


Figure 4.12. Concentration with volume fraction

4.3 Conclusions

The research investigated hydromagnetic flow patterns which occur when iron (II, III) oxide (Fe_3O_4) and iron (III) oxide (Fe_2O_3) nanoparticles are dispersed in human blood. The research studied how magnetic field strength and Eckert number and nanoparticle volume fraction affect both flow patterns and temperature and concentration distribution. The research findings effectively solved all the particular research questions which were established at the beginning of the investigation. The fundamental equations which describe hybrid nanofluids behavior were developed through applications of fluid mechanics and thermodynamics principles. The model consisted of four basic equations which handled continuity and momentum and energy and concentration behavior and incorporated magnetic field effects and buoyancy force impacts. The research achieves its first specific goal through the creation of a strong theoretical model which explains hybrid nanofluid behavior. The governing equations underwent dimensionless transformation through the application of similarity variables. The method successfully transformed the system of partial differential equations (PDEs) into ordinary differential equations (ODEs) which allowed for quick numerical solution methods. The boundary conditions were also converted to a dimensionless form to align with the reduced system. The solution fulfills the second particular goal by showing how similarity transformations help users solve complicated fluid flow problems through simplification. Finally, the influence of key parameters on the flow of the velocity, temperature, and concentration of the hybrid nanofluid flow was analysed. The results showed that increasing the magnetic field parameter reduced both primary and secondary velocities while enhancing the temperature and concentration profiles due to the resistive Lorentz force. The Eckert number produced higher velocities and temperatures because of viscous dissipation but it also increased concentration levels. The nanoparticle volume fraction led to better velocities and temperature results but it caused the concentration profile to deteriorate because thermal diffusion became the dominant factor. These findings satisfy the third specific objective by providing a detailed evaluation of the parameter effects on the hybrid nanofluid flow. The numerical results

were obtained using MATLAB's `bvp4c` solver, which proved to be a reliable tool for solving the nonlinear ODEs. The research findings from this study will produce major effects which will benefit both biomedical and industrial sectors. The research results can help developers create better drug delivery systems and improve magnetic hyperthermia treatments and electromagnetic pump and cooling system performance.

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