

Research Article

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Melting phenomenon of thermally stratified MHD Powell–Eyring nanofluid with variable porosity past a stretching Riga plate

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Abstract: Recently, experts have become particularly interested in the treatment of disorders caused by magnesium shortage. Hypomagnesemia is produced by a magnesium deficit in the blood, which is an additional stimulation for different diseases such as vomiting, drowsiness, nausea, loss of appetite, and so on. To compensate for this shortage, magnesium is injected as a nanoparticle in the blood (base fluid). The properties of these magnesium nanoparticles specifically their size, dispersion, and surface characteristics are crucial for optimizing their bioavailability and therapeutic efficacy. Advanced material characterization techniques ensure the stability and enhanced performance of these nanoparticles in the physiological environment. Based on these applications, the current research aims to address magnesium deficiency *via* Powell–Eyring nanofluid flow distorted by the linearly stretchable sheet in the region of the stagnation point. Linear thermal stratification, viscous

dissipation, and Joule heating are used to reveal the heat transport features. The magnetic field is applied to the nanofluid at an angle α to further control the fluid dynamics and nanoparticle behavior. Transformations are used to create a set of dimensionless governing equations. Comparative graphs are used to explain the physical behaviors of temperature and velocity fields, demonstrating how material properties impact fluid dynamics. The well-known convergence method (homotopy analysis method) is used to solve the model by comparing graphs.

Keywords: melting rheology, thermal stratification, Powell–Eyring nanofluid, analytical solution, mixed convective flow

Nomenclature

a	stretching rate
B_0	magnetic field strength
C_b	inertia coefficient
C_f	skin friction coefficient
C_p	specific heat
d, d_1	dimensional constants
Ec	Eckert number
e_1, e_2	dimensional constants
Ha	magnetic parameter
h_0	applied current density in electrodes
j_1	width of magnets between electrodes
K	thermal conductivity of nanofluid
$K(y)$	variable permeability of porous medium
M	melting parameter
m_0	magnetization of the permanent magnets
Nu_x	local Nusselt number
nf	nanofluid
Pr	Prandtl number
Q_0	heat source
S_1	stratified thermal factor
T	temperature
T_∞	surrounding temperature

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T_0	reference temperature
T_m	melting temperature
U_w	stretching velocity
U_∞	free stream velocity
u, v	velocity components
x, y	displacement in Cartesian coordinate system
μ	dynamic viscosity
$B_0\beta, C_1$	material parameters
$\beta(y)$	variable porosity
σ	electrical conductivity
λ	latent heat of fluid
ρ	density
α	angle of inclination
θ	dimensionless temperature
η	similarity variable

1 Introduction

Studies of flow models for non-Newtonian liquids, which are widely used in manufacturing and industrial settings have gained the attention of scholars and researchers in recent years. Various industries, including fusion reactors, planetary research, metallurgy, paper manufacture, oil engineering storage, polymeric solutions, nuclear power, chemical production, bioengineering, geophysics, and pharmaceuticals, have utilized non-Newtonian liquids for a variety of purposes. Many researchers have explored non-Newtonian flow phenomena in a variety of geometries because of the many technological and industrial applications that these phenomena have. One benefit of the non-Newtonian fluid model proposed by scientists Powell and Eyring in 1944 is that it behaves like a viscous fluid at high shear rates. The model is drawn from the kinetic theory of gases rather than empirical formulas. Jabeen *et al.* [1] studied the crucial role that stratification phenomena caused by an inclined sheet that is stretched linearly play in Powell–Eyring fluid flow. For instance, the Powell–Eyring model is a popular rheological model used to explain the flow characteristics of non-Newtonian fluids, especially those that behave as shear-thinning. Based on the idea of a yield stress fluid, this model allows material to flow only upon exceeding a specific threshold stress, or yield stress. Under this limit, the substance exhibits no flow and behaves like a solid. Lund *et al.* [2] investigated the various solutions for the unsteady flow of a Cu–Al₂O₃/water-based hybrid nanofluid within a Darcy–Forchheimer porous medium, considering the impacts of Joule heating and viscous dissipation. Rehman *et al.* [3] concentrated on the features of the melting heat phenomena in the Powell–

Eyring fluid flow that was distorted around the stagnation point by the linearly stretchable sheet. In the presence of a magnetic field, Hatami *et al.* [4] performed analytical and numerical simulations of heat transfer and flow analysis for a non-Newtonian third-grade nanofluid flow in a porous medium in a hollow vessel. The addition of gold (Au) nanoparticles to blood is thought of as the base third-grade non-Newtonian fluid. Numerical analysis is performed on a three-dimensional non-Newtonian nanofluid flow with nonlinear thermal radiation and heat absorption. With the above in mind, Tarakaramu *et al.* [5] considered the nonlinear heat absorption and radiation on porous stretched sheets. Shahzad *et al.* [6] demonstrated a non-Newtonian cross-fluid that is asymmetrically flowing over a radially expanding sheet. The flow of nanofluid is additionally represented by Buongiorno model for tiny particles, a physical problem. Using ethylene glycol as a base fluid and a non-Newtonian Maxwell fluid model, Jeelani and Abbas [7] investigated how to improve energy/heat transfer by dispersing copper and alumina nanoparticles in a cylindrical shape. The present work investigates the effects on a Maxwell hybrid nanofluid of plate suction, MHD, and solar radiation.

Contemporary scientists are increasingly drawn to nanotechnology due to the remarkable optical, electrical, and chemical characteristics exhibited by materials at the nanoscale. Recent advancements have facilitated the dispersion of nanoparticles within conventional heat-transfer fluids, including water, ethylene glycol, and motor oil, thereby introducing a novel category of highly efficient heat transfer liquids. Vinodkumar Reddy *et al.* [8] explored the MHD stagnation point flow of Williamson hybrid nanofluid across a stretching sheet in a porous medium, incorporating a heat source and chemical reaction. Further, Al-Farhany *et al.* [9] conducted a numerical analysis on mixed convective double diffusion in a tilt curvilinear lid-driven cavity using a Fe₃O₄-water-based nanofluid, considering the influence of an inclined magnetic field. Further applications of nanofluid discussed in previous literature [10–12]. Furthermore, Gorla *et al.* [13] provided a boundary layer analysis for mixed convection across a vertical wedge in a porous media saturated with nanofluid. A laminar, steady, natural convection boundary-layer flow was investigated by Chamkha and Rashad [14] over a permeable vertical cone contained in a porous media saturated with a nanofluid, with uniform lateral mass flux. Khan *et al.* [15] performed a computational investigation into the boundary layer flow and heat transfer characteristics of fractional Maxwell viscoelastic nanofluids and their hybrids on a porous vertical surface. Hussain *et al.* [16] employed response surface methodology to conduct a sensitivity analysis of the flow of gold nanoparticles in blood over a spinning

disc while accounting for slippage, Joule heating, nonlinear thermal radiation, and viscous dissipation. Rafique *et al.* [17] investigated the impact of numerous variables, including thermal stratification, viscous dissipation, velocity slip conditions, ternary hybrid nanofluid, MHD stagnation point flow, and variable viscosity, on coolant applications. Lone *et al.* [18] focused on the Casson nanofluid's gyrotactic bioconvection flow on a bidirectional linear stretching sheet while considering the effects of an angled magnetic field.

Stratification, both in industrial processes and natural settings, plays a crucial role in various operations. It occurs due to changes in concentration, temperature, or the presence of fluids with differing densities within fluid systems. Double stratification arises when mass and heat transfer operations occur simultaneously. In natural bodies of water such as seas and reservoirs, thermal layering manifests as stratification, while salinity gradients are observable in rivers, canals, groundwater dams, and oceans. Environmental contexts and numerous commercial food preparation and production activities also feature heterogeneous mixes. Gravity-induced density variations significantly influence the mixing and dynamics of such heterogeneous liquids. Anoxic conditions may arise from biological processes, such as when thermal stratification limits the oxygen supply to deeper water levels in reservoirs. Overall, stratification largely regulates the temperature and concentration levels in ponds and lakes, demonstrating its critical role in various natural and industrial processes. Kandasamy *et al.* [19] examined the flow of MHD nanofluid on a porous plate that was oriented vertically. He used the RK technique to study temperature declines with an enhanced thermal stratification parameter. Ahmad *et al.* [20] analyzed the unstable bio-convective hybridized micropolar nanofluid flow across a vertically increasing surface under stratification circumstances. Rehman *et al.* [21] evaluated the Casson fluid flow that emerges from a stretched cylinder with heat generation coming from both convection and thermal stratification. Jabeen *et al.* [22] highlighted the properties of mixed convection in Powell–Eyring fluid under stretchy sheet deformation with an inclined inclination. The features of heat transfer are shown by thermal stratification. To shed light on the nature of mass transfer, fluid viscosity stratification and first-order chemical processes are also taken into consideration. Bilal *et al.* [23] presented interesting aspects of thermal stratification in order to explore the flow properties of the Carreau fluid. Flow field equations are derived from the combination of infinite shear rate viscosity and magnetic field effects.

The flow of conductive fluids is studied in MHDs. Its use is broad and encompasses disciplines such as cosmic plasmas and liquid metals. Applications for this technology include MHD pumps and power generators, electrostatic

precipitation, petroleum industry use, crude oil purification, aerodynamic heating, geophysics exploration, plasma physics, and fluid droplet dispersion [24]. Krishna *et al.* [25] examined the behavior of radiative unsteady MHD flow in a non-Newtonian Casson hybrid nanofluid that is both incompressible and viscous. This flow occurs over a surface moving vertically with exponential acceleration, extending infinitely. Additionally, slip velocity and rotation effects were taken into account within the analysis. Madhu *et al.* [26] considered the investigation of the phenomenon involving the unsteady MHD boundary layer flow of a non-Newtonian Maxwell nanofluid over a stretching surface, incorporating thermal radiation. Hafez *et al.* [27] investigated the electroosmosis-modulated Darcy–Forchheimer flow of Casson nanofluid over stretching sheets, considering the effects of Newtonian heating. Bhadauria *et al.* [28] examined the thermal instability of tri-hybrid Casson nanofluid within various enclosures featuring a thermally radiating saturated porous medium. Felicita *et al.* [29] explored the mixed convective flow of Casson nanofluid in a microchannel, analyzing the impact of couple stresses and irreversibility. Kulkarni and Shankar [30] conducted a numerical study on the mixed convective flow of Williamson nanofluid over a stretching/shrinking wedge, considering the influence of a chemical reaction parameter and liquid hydrogen diffusion. Reddy *et al.* [31] investigated the effects of radiation, velocity, and thermal slips on the MHD boundary layer flow, involving heat and mass transport of Williamson nanofluid through a porous medium. Akram and Afzal [32] researched the impacts of thermal and concentration convection and an induced magnetic field on the peristaltic flow of Williamson nanofluid in an inclined uniform channel.

Assessing the effect of Powell–Eyring nanofluid in a state of stagnation moving under an angled magnetic field is the main goal of this work. The base fluid is blood, and magnesium (Mg) nanoparticles are added to it. Since this fluid model exhibits the characteristics of shear-thinning fluids, blood was used here to simulate Powell–Eyring fluid. Due to the fact that the blood exhibits shear thinning characteristics with rising shear stress, it is even more important to pay notice to this aspect. For instance, to pump blood into the arteries, the heart applies additional shear stress to the blood. Shear thinning, which prevents clots from forming in the veins, is the reason for its swift, clot free flow. The impacts of viscous dissolution, Joule heating, and a more realistic aspect of melting the transfer of heat are replaced in order to examine heat transmission. The melting point of the skin on the foot is between 0 and 10°C, while the fat inside the body melts between 30 and 35°C. The melting point of several different kinds of lipids is

greater than the average human body temperature of 37°C. In the current work, we used blood as a base fluid and added magnesium particles to raise the temperature and act as a temperature regulator. Blood temperature is greater than the walls of veins. As a result, the fats within the vein wall begin to melt as the temperature rises. To examine the true image of blood flow in veins, particularly in the aorta, the melting condition is therefore favored in this investigation [33]. Linear stratification is used to examine heat transmission in a better way. First, the necessary transformations are used to create the resultant non-dimensional governing equations, and then the technique of homotopy analysis is used to identify convergent solutions. Various parameters are depicted in graphical form to display temperature and velocity profiles. Table 1 demonstrates the variations between the present work and published literature.

2 Statement of the problem

Let us consider the steady, incompressible, MHD Powell–Eyring nanofluid flow with variable porosity along with a stretchable Riga plate close to the stagnation point. The magnetic field is applied at a certain angle α . The magnetic Reynolds number is supposed to be small; therefore, the induced magnetic field is neglected while the ion slips and Hall effects is assumed to be negligible. The porous medium is transparent and in thermal equilibrium state with fluid. Melting rheology is taken to improve the heat transport characteristics. In this phenomenon, the ambient temperature T_∞ is smaller than the fluid temperature T_m , *i.e.*, ($T_m > T_\infty$). Thermal slip, Joule heating, viscous dissipation, and thermal stratification impact are grasped here to increase the heat transfer. We supposed that the fluid phase and nanoparticles are in thermal equilibrium state. To treat disorders, magnesium nanoparticles are plucked into a base fluid (blood) to recover the diseases caused by the deficiency of magnesium in the human body. The problem's geometric representation is illustrated in Scheme 1. Using normal boundary layer approximations, one can achieve the governing equations, which are shown as follows [3]:

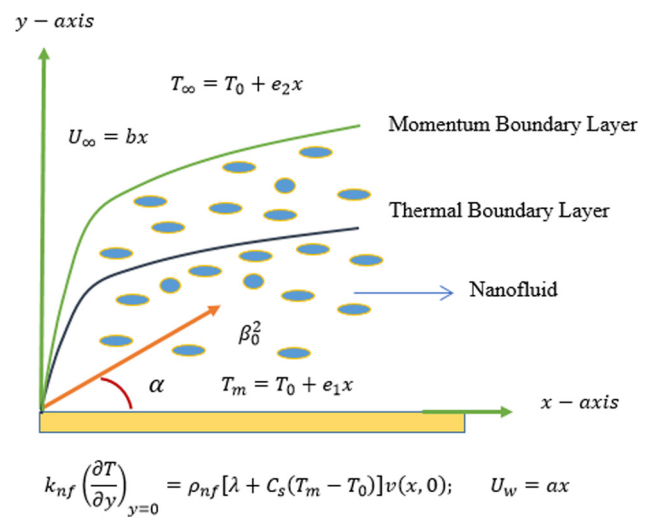
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (1)$$

$$\begin{aligned} \rho_{nf} \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = & U_\infty \frac{dU_\infty}{dx} + \left(\mu_{nf} + \frac{1}{\beta C_1} \right) \frac{\partial^2 u}{\partial y^2} \\ & - \frac{1}{2\beta C_1^3} \left(\frac{\partial u}{\partial y} \right)^2 \times \frac{\partial^2 u}{\partial y^2} - \frac{\mu_{nf} \beta(y)}{K(y)} u \\ & - \frac{\rho_{nf} C_b \beta^2(y)}{\sqrt{K(y)}} u^2 - \sigma_{nf} B_0^2 \sin^2(\alpha) (u \\ & - U_\infty) + \frac{\pi m_0 h_0}{8} e^{\left(-\frac{\pi}{h} \right) y}, \end{aligned} \quad (2)$$

$$\begin{aligned} (\rho C_p)_{nf} \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = & K_{nf} \frac{\partial^2 T}{\partial y^2} + \left(\mu_{nf} + \frac{1}{\beta C_1} \right) \left(\frac{\partial u}{\partial y} \right)^2 - \frac{1}{6\beta C_1^3} \left(\frac{\partial u}{\partial y} \right)^4 \\ & + \sigma_{nf} B_0^2 \sin^2(\alpha) (u - U_\infty)^2 + Q_0 (T - T_m). \end{aligned} \quad (3)$$

According to the boundary conditions executed [3],

$$\begin{aligned} u &= U_w(x) = ax, \quad T = T_m \text{ as } y \rightarrow 0, \\ u &= U_\infty(x) = bx, \quad T = T_\infty \text{ as } y \rightarrow \infty, \end{aligned} \quad (4)$$



Scheme 1: Geometry of the problem.

Table 1: The novelty of present work

Effects	Nisar <i>et al.</i> [34]	Rehman <i>et al.</i> [3]	Saif <i>et al.</i> [35]	Farooq and Javed [36]
Melting heat transfer	No	Yes	No	Yes
Thermal stratification	No	Yes	No	Yes
Variable porosity and permeability	No	No	Yes	No
Stagnation point	No	Yes	No	Yes
Inclined magnetic field	No	Yes	Yes	No
Nanofluid	Yes	No	No	Yes

$$K_{nf} \frac{\partial T}{\partial y} \Big|_{y=0} = \rho_{nf} [\lambda + C_s(T_m - T_0)] v(x, 0), \quad (5)$$

where

$$T_m = T_0 + e_1 x, \quad T_\infty = T_0 + e_2 x.$$

where u and v are the components of the velocity in horizontal and vertical directions respectively. U_w is the stretching velocity, U_∞ is the free stream velocity, T is the temperature of a fluid, T_0 is the reference temperature, T_m is the temperature of the melting surface, T_∞ is the ambient temperature, ρ_{nf} denotes the density of a fluid, σ_f denotes the electrical conductivity of the base fluid, σ_{nf} denotes the electrical conductivity of nanofluid, ρ_f denotes the density of the base fluid, μ_f denotes the viscosity of the base fluid, μ_{nf} denotes the dynamic viscosity of the nanofluid, B_0 is the applied magnetic field, α is the inclination angle, λ is the latent heat of fluid, C_b is the inertia coefficient, C_1 and β denote the material factor, C_s is the heat capacity of solid surface, K_{nf} represents the thermal conductivity of nanofluid, $(C_p)_{nf}$ denotes the specific heat of nanofluid, $\beta(y)$ and $K(y)$ are, respectively, variable porosity and permeability of porous medium, Q_0 denotes the heat generation/absorption coefficient, d and d_1 are the dimensionless constants, σ_s and K_s are the electrical and thermal conductivity of the nanoparticles respectively, and ρ_s is the density of the nanoparticles. The variable porosity and permeability are given as [35,37]

$$\beta(\eta) = \beta_0(1 + de^{-\eta}), \quad K(\eta) = K_0(1 + d_1 e^{-\eta}),$$

where β_0 denotes the porosity at the boundary layer and K_0 denotes the permeability at the boundary layer.

The above partial differential equations (PDEs) are transformed into ordinary differential equations (ODEs) by using the similarity transformations listed below:

$$\eta = y \sqrt{\frac{a}{\nu_f}}, \quad u = axf'(\eta), \quad v = -\sqrt{a\nu_f} f(\eta), \quad (6)$$

$$\theta(\eta) = \frac{T - T_m}{T_\infty - T_0}.$$

Continuity Eq. (1) satisfies, while Eqs (2) and (3) become

$$\begin{aligned} & (B_2 + \varepsilon) f'''(\eta) - \varepsilon \delta f''^2(\eta) - B_1 [f'^2(\eta) - f(\eta)f''(\eta)] \\ & - B_3 Ha \sin^2(\alpha) [f'(\eta) - A] + A^2 \\ & - \frac{B_2}{\sigma Re} \frac{(1 + de^{-\eta})}{(1 + d_1 e^{-\eta})} f'(\eta) \\ & - \beta^* B_1 \frac{(1 + de^{-\eta})^2}{\sqrt{(1 + d_1 e^{-\eta})}} f'^2(\eta) + Qe^{(-\beta\eta)} = 0, \end{aligned} \quad (7)$$

$$\begin{aligned} & B_5 \theta''(\eta) - B_4 Pr [S_1 f'(\eta) + f'(\eta) \theta(\eta) - \theta'(\eta) f(\eta)] \\ & + Ec Pr \left[(B_2 + \varepsilon) f''^2(\eta) - \frac{1}{3} \varepsilon \delta f''^4(\eta) \right] \\ & + B_3 Ha. Ec Pr \sin^2(\alpha) (f'(\eta) - A)^2 + \delta_1 Pr \theta(\eta) = 0. \end{aligned} \quad (8)$$

Boundary conditions in the dimensionless form are

$$f'(0) = 1; f'(\infty) = A; \theta(0) = 0; \theta(\infty) = 1 - S_1, \quad (9)$$

$$Pr f(0) + \frac{B_5}{B_1} M \theta'(0) = 0, \quad (10)$$

where Ha represents the magnetic factor, M denotes the melting parameter, Ec is the Eckert number, Pr is the Prandtl number, ε and δ denotes the material factors, S_1 is the stratified thermal parameter, and A is the ratio of free stream velocity to stretching velocity. These parameters are represented below:

$$\begin{aligned} Ha &= \frac{\sigma_f B_0^2}{\rho_f C}; \quad M = \frac{(C_p)_f (T_\infty - T_0)}{\lambda + C_s (T_m - T_0)}; \\ Ec &= \frac{U_w^2}{(C_p)_f (T_\infty - T_0)}; \quad Pr = \frac{(\mu C_p)_f}{K_f}; \quad \varepsilon = \frac{1}{\beta C_1 \mu_f}; \\ \delta &= \frac{U_w^2 C}{2 \nu_f C_1^2}; \quad S_1 = \frac{d_1}{d_2}; \quad A = \frac{b}{a}; \\ B_1 &= (1 - \phi) + \phi \frac{\rho_s}{\rho_f}; \quad B_2 = (1 - \phi)^{-2.5}; \quad B_3 = \frac{\sigma_{nf}}{\sigma_f}; \\ B_4 &= (1 - \phi) + \phi \frac{(\rho C_p)_s}{(\rho C_p)_f}; \quad B_5 = \frac{K_{nf}}{K_f}; \\ \rho_{nf} &= (1 - \phi) \rho_f + \phi \rho_s; \quad \mu_{nf} = (1 - \phi)^{-2.5} \mu_f \\ (\rho C_p)_{nf} &= (1 - \phi) (\rho C_p)_f + \phi (\rho C_p)_s; \\ \frac{k_{nf}}{k_f} &= \frac{(k_s + 2k_f) - 2\phi(k_f - k_s)}{(k_s + 2k_f) + \phi(k_f - k_s)}; \\ \text{and } \frac{\sigma_{nf}}{\sigma_f} &= \frac{(\sigma_s + 2\sigma_f) - 2\phi(\sigma_f - \sigma_s)}{(\sigma_s + 2\sigma_f) + \phi(\sigma_f - \sigma_s)}. \end{aligned}$$

The following form is used to analyze the local Nusselt number and skin friction coefficient:

$$Nu_x = \frac{x q_w}{k_f (T_\infty - T_m)} \quad \text{and} \quad C_f = \frac{\tau_w}{\rho_{nf} U_w^2},$$

where q_w represents the heat flux and τ_w represents the wall shear stress and

where

$$\tau_w = \left(\mu_{nf} + \frac{1}{\beta C_1} \right) \left(\frac{\partial u}{\partial y} \right) - \left(\frac{1}{6 \beta C_1^3} \right) \left(\frac{\partial u}{\partial y} \right)^3 \quad \text{and} \quad q_w = -k_{nf} \left(\frac{\partial T}{\partial y} \right) \quad \text{as } y \rightarrow 0.$$

The above quantities in unit less form are as follows:

$$C_f Re_x^{1/2} = (B_2 + \varepsilon) f''(0) - \frac{1}{3} \varepsilon \delta f''^3(0) \quad \text{and,}$$

$$Nu_x = - \frac{B_5 \theta'(0)}{Re_x^{-1/2} (1 - s_1)},$$

The following form represents the local Reynolds number: $Re_x = \frac{U_w x}{\nu_f}$ (Table 2).

3 Methodology (homotopy analysis method, HAM)

In 1992, Liao was the one who initially proposed using the homotopy method. Finding nonlinear model solutions using the homotopic method is the recommended approach. In contrast to past perturbations and non-perturbative processes, the homotopy assessment approach allows us to quickly adjust to new circumstances and change the convergence position and the charges associated with previously learned approximations. In a nutshell, the homotopy evaluation comes with the following additional benefits: It is valid even if a particular nonlinear issue does not contain any little or extended parameters at all, and it can provide us with a straightforward approach to adjust and manipulate the convergence place and charge of estimation collection when it is required to do so. Selecting particular units of base functions allows one to guess the solution to a nonlinear issue using this method.

3.1 Limitations of HAM

HAM is a powerful mathematical technique for solving nonlinear differential equations. Like any method, it is not without its flaws. The main problems with using HAM are:

- 1) It is important to note that the HAM series solution will not necessarily converge in response to all types of problems. There is a remote possibility that the series will not converge at all or will only converge extremely slowly, resulting in findings that are either erroneous or irrelevant. The behavior of convergence is impacted both by the structure of the problem and by the auxiliary linear operator that is chosen.
- 2) The auxiliary linear operator and the initial approximation are responsible for a sizeable portion of the HAM solution's overall effect. The combination of these parameters can be chosen arbitrarily to yield a wide range of results. No systematic procedure can be followed to arrive at the perfect numbers, and it could be challenging.
- 3) The HAM model has the potential to have a high computational complexity, particularly for problems involving many nonlinear components. Calculating the coefficients of the series solution could take a significant amount of time and require a great deal of computer resources.
- 4) HAM may experience difficulties addressing singularities in the problem domain, such as poles or essential

Table 2: Characteristics of nanoparticles and base fluid are illustrated below [18,38]

Physical properties	Base fluid (blood)	Nanoparticles (magnesium)
$\sigma(\text{S} \cdot \text{m}^{-1})$	0.18	2.3×10^7
$C_p(\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1})$	3,594	1046.7
$\rho(\text{kg} \cdot \text{m}^{-3})$	1,053	1,738
$k(\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1})$	0.492	156

singularities. Singularities can change the behavior of the series solution as it converges and requires a specific approach.

- 5) HAM can only be used in certain situations. It best solves differential equations with few or no dimensions or disturbances. It might not work well for problems with a lot of or strong nonlinearity. Although HAM has been successfully applied to problems involving just a single dimension, the higher the dimensions, the greater the complexity and computational power required.
- 6) The HAM does not have a trustworthy mechanism for estimating or preventing mistakes, hence it cannot do a rigorous error analysis. It may be challenging to evaluate the accuracy or dependability of the answers that have been found.

Despite these limitations, the HAM is an effective tool for dealing with a wide variety of nonlinear problems. The scientific community is continually developing novel variants and improvements to address some of these limitations and expand the method's scope of applicability. The analytical solution to the higher-order ODEs can be obtained using the homotopy analysis approach in Mathematica 13. The following is an explanation of what is meant by initial hunches and linear operators:

$$f_0(\eta) = A\eta + (1 - A)(1 - e^{-\eta}) - \frac{B_5}{B_1} \left(\frac{M(1 - S_1)}{\text{Pr}} \right), \quad (11)$$

$$\theta_0(\eta) = (1 - S_1)(1 - e^{-\eta}),$$

$$\Xi_f(f) = \frac{df^3}{d\xi^3} - \frac{df}{d\xi}, \quad \Xi_\theta(\theta) = \frac{d\theta^2}{d\xi^2} - \theta, \quad (12)$$

with

$$\Xi_f(J_1 + J_2 e^{-\eta} + J_3 e^{\eta}) = 0, \quad (13)$$

$$\Xi_\theta(J_4 e^{-\eta} + J_5 e^{\eta}) = 0, \quad (14)$$

where J_n ($n = 1, 2, \dots, 5$) are constants.

The final solution f_m, θ_m in terms of corresponding solutions $f_m^\Lambda, \theta_m^\Lambda$ are written as

$$f_m(\eta) = f_m^\Lambda(\eta) + J_1 + J_2 e^{-\eta} + J_3 e^\eta, \quad (15)$$

$$\theta_m(\eta) = \theta_m^\Lambda(\eta) + J_4 e^{-\eta} + J_5 e^\eta. \quad (16)$$

3.2 Convergence analysis

In this subsection, we study the convergence criterion of the method for the above problem. The convergence area occurs parallel to the h -axis, as depicted in Scheme 2. So, the convergence zone for velocity profile is $-1.9 \leq h \leq -0.1$ while for temperature, the convergence area is $-1.8 \leq h \leq 0.1$.

4 Parametric study

The main goal of this part is to look at how some important factors, like velocity and temperature field, behave physically and graphically. The dimensions of Powell–Eyring fluid parameters are ε and δ in this case. Blood has a value of 1,345 for ε . While δ is not always the same because it changes with stretching [39]. Figure 1 shows what happens to the $f'(\eta)$ of a nanofluid when we change ratio parameter A . The fluid's thickness is analyzed and displayed to be opposing the velocity of A . Additionally, the velocity limit layer's thickness exhibits the same stretching and recessive behavior as the fluid's free stream velocity. When the velocity of the fluid and its surface are equal for $A = 0.8$, there is no boundary layer present. For $A < 0.8$, the fluid thickness is greater near the wall, resulting in a higher velocity at the surface. Conversely, for $A > 0.8$, the fluid thickness is greater outside the wall, resulting in a higher velocity away from the surface. The stagnation point is where the fluid velocity decreases due to the thickness caused by inflammation on the inner walls of the arteries or the point at which veins are obstructed. This can lead to reduced blood

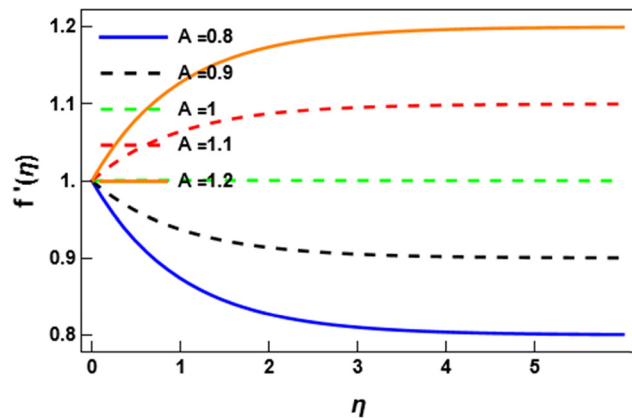
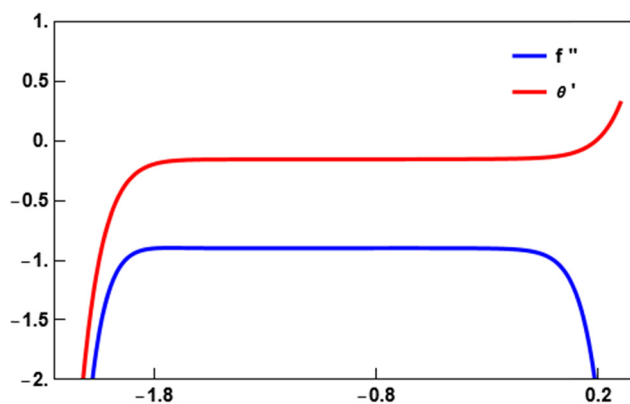


Figure 1: Velocity field for various values of A .

circulation within arteries. Whereas with such blockages, fluid velocity reaches its highest level, leading to a thickness or heart attack.

We can find these blocked arteries using variations in graphs. Figure 2 shows how α changes the speed field of a nanofluid made of blood and magnesium. As the angle of slope goes up, the velocity field goes down. This makes both the Lorentz force and magnetic field bigger. So, this force fights against the flow of blood and slowly declines. Due to the slow transfer of nanofluid, patients with hypomagnesemia take a long time to get better. A magnetic field could be made at the injury site to draw the highest amount of magnesium particles there and speed up the healing process.

Figure 3 shows how inertial parameters β affect velocity dispersion. We investigated how inertia causes velocity to increase because a porous media presents increased flow resistance. Figure 4 shows how M affects the velocity field for a blood magnesium nanofluid. As the melting parameter, M , is raised, both $f'(\eta)$ and the wall layer's improve. Because of the dominant melting parameter, there is more convective flow toward a cooling surface. Because of this, the velocity field increases. It is useful for removing things like plaque or fats from the inside walls of veins. The characteristics of the nanofluid volume fraction parameter ϕ on the velocity outline are shown in Figure 5. As ϕ increases, it becomes clear that the velocity decreases. It makes physical sense since nanoparticles speed up the heat transfer rate, which boosts the convective motion of nanofluid. So, the speed goes down gradually. This shows that people with a lack of magnesium get better quickly when they get more magnesium nanoparticles. As can be seen in Figure 6, the horizontal velocity of the nanofluid is affected by the magnetic parameter Ha . The boundary layer's thickness and velocity contour both decrease when magnetic factor Ha increases. Lorentz force



Scheme 2: Convergence curve for velocity and temperature.

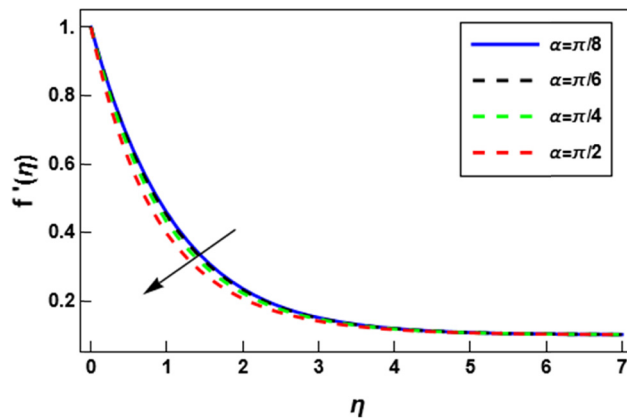


Figure 2: Velocity field for various values of α .

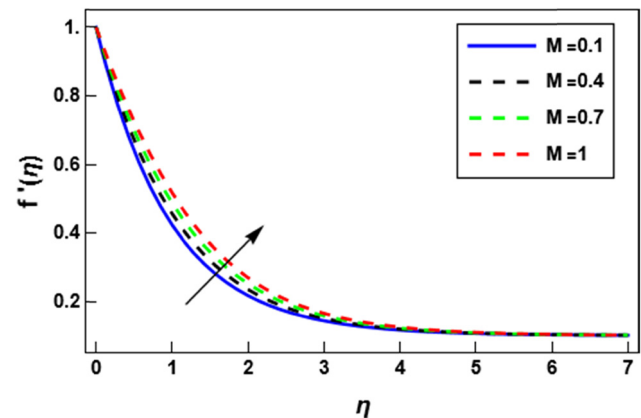


Figure 4: Velocity field for various values of M .

creates retarding forces that act as drag forces in the direction opposite to the flow, making this a physical reality. As a result, less blood flows. Figures 7 and 8 depict the effects of uniform/variable porosity and permeability on velocity distribution. The velocity distribution decreases with the increase in porosity, while increases with the increase in the uniform/variable porosity.

For the nanofluid blood-magnesium, the influence of Ec on $\theta(\eta)$ is depicted in Figure 9. The temperature distribution steadily improves as the Eckert number increases. Forces of repulsion between particles in a fluid are responsible for this behavior because they transform mechanical momentum into thermal energy. This causes the temperature field to expand. The influence of Ha , the magnetic factor, on the nanofluid $\theta(\eta)$ is shown in Figure 10. The temperature profile increases as the magnetic factor is varied. Additionally, the heat transfer boundary layer increases as time passes. Because of this, blood flow becomes more resistant, and heat is produced. Therefore, the temperatures of individual blood cells are raised. Figure 11 shows how the

melting factor, M affects the temperature contour for a blood-based magnesium nanofluid. As the melting value goes up, the temperature value becomes a function that goes down. When the melting value goes up, the thermal border layer gets thicker. Physically, a larger melting parameter makes it easier for heat to move faster from the heated liquid to the cold wall. This means that more heat is lost to the environment, which causes the temperature to drop. Also, when there is a further transfer of heat to the top of veins, fats or plaques on the inside walls melt. So, more melting makes the obstacle to blood flow smaller.

Figure 12 shows how the volume fraction ϕ changes as the temperature changes. It is important to note that when the nanofluid has high numbers, the temperature goes up. Physically, this is because nanofluids are better at moving heat around. Improving the way heat moves through the body is important for keeping the blood at the right temperature and keeping people from getting problems like thin blood, high blood pressure, hemophilia, and other problems. Figure 13 depicts the thermal stratification

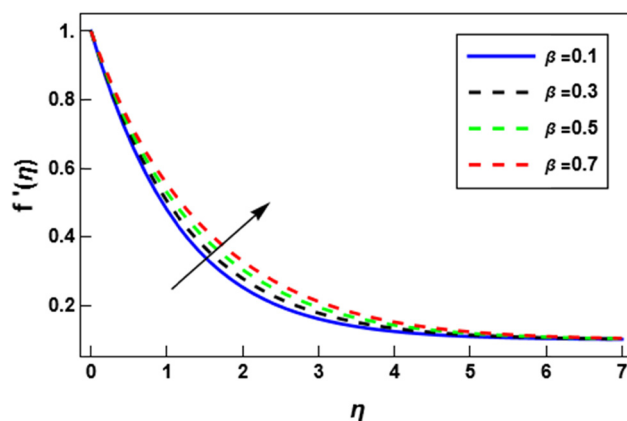


Figure 3: Velocity field for various values of β .

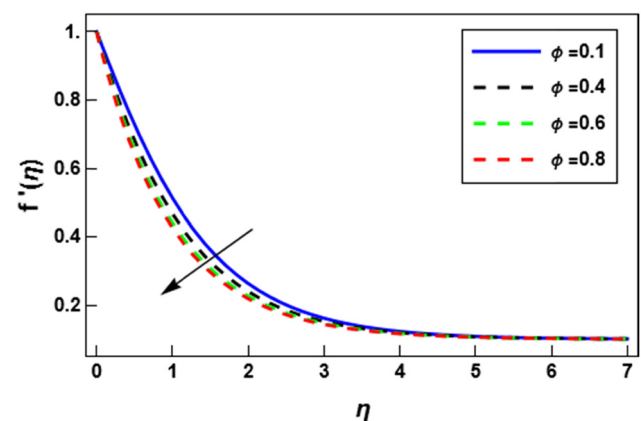
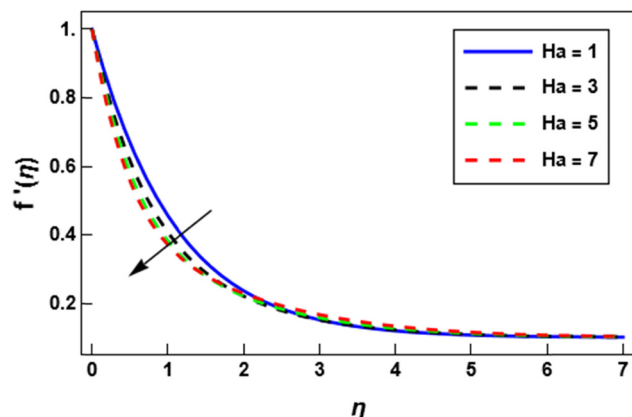
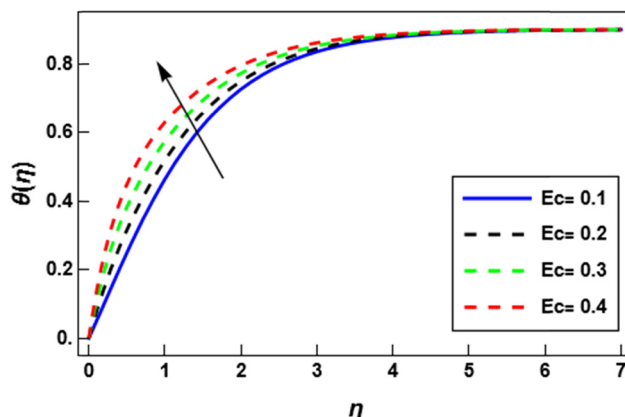
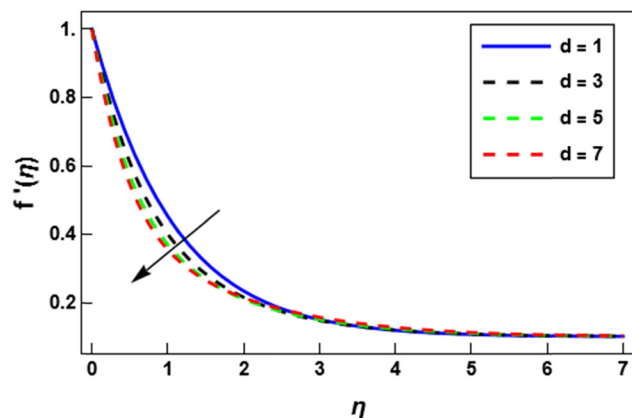
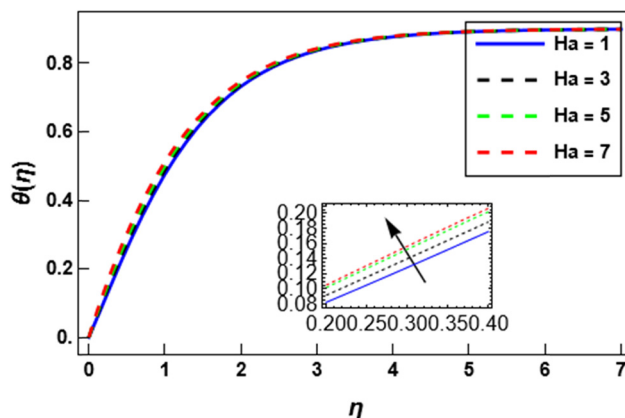
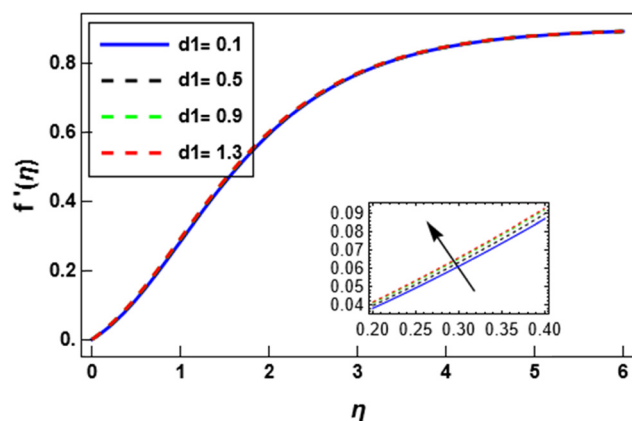
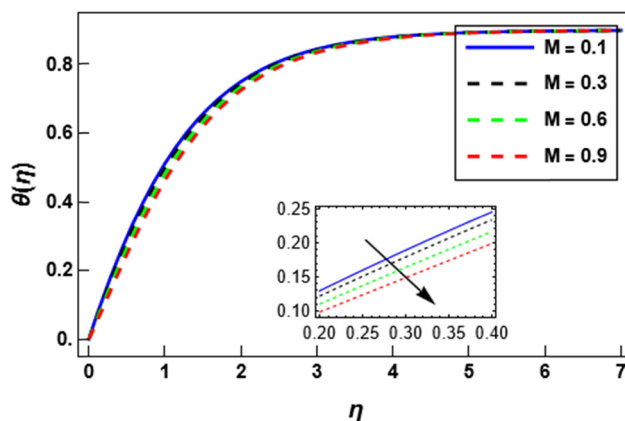


Figure 5: Velocity field for various values of ϕ .

Figure 6: Velocity field for various values of Ha .Figure 9: Temperature field for various values of Ec .Figure 7: Velocity field for various values of d .Figure 10: Temperature field for various values of Ha .

features on (η) . It can be seen that as the magnitude of s_1 increases, the temperature distribution decreases. As the stratification parameter increases, different density regions prevent heat transport inside the blood. Figure 14 shows

how varying thermal conductivity δ affects temperature distribution θ . We looked at whether rising δ causes temperatures to rise. Greater thermal conductivity is correlated with larger δ , which improves the temperature profile.

Figure 8: Velocity field for various values of d_1 .Figure 11: Temperature field for various values of M .

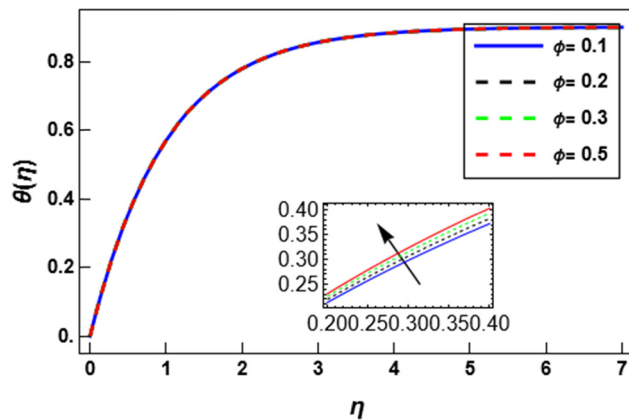
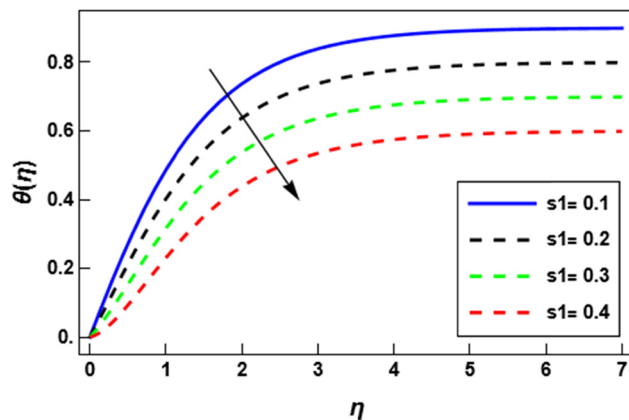
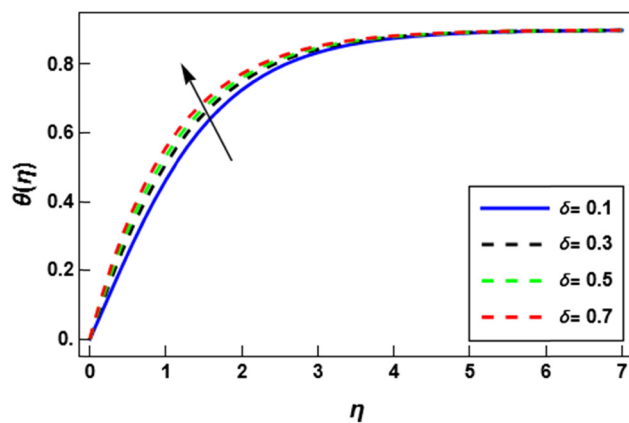
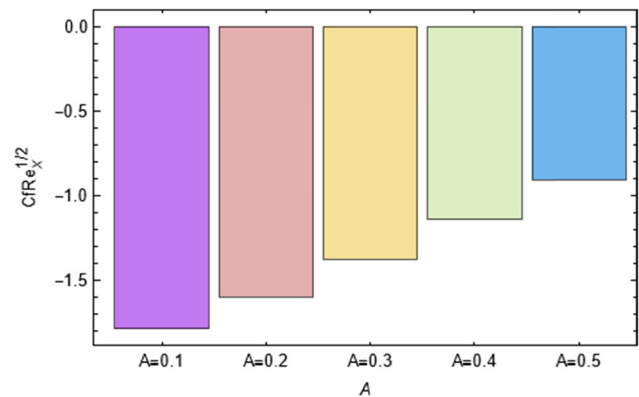
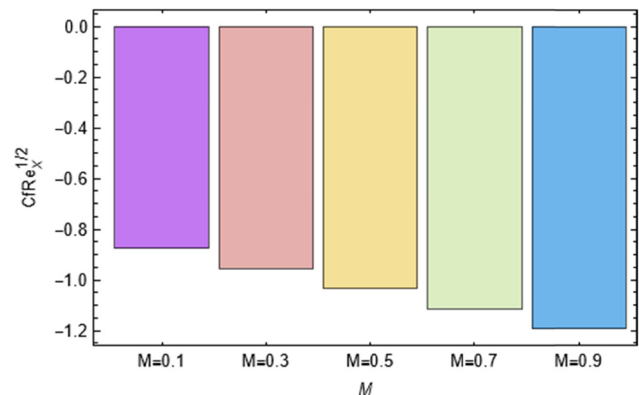
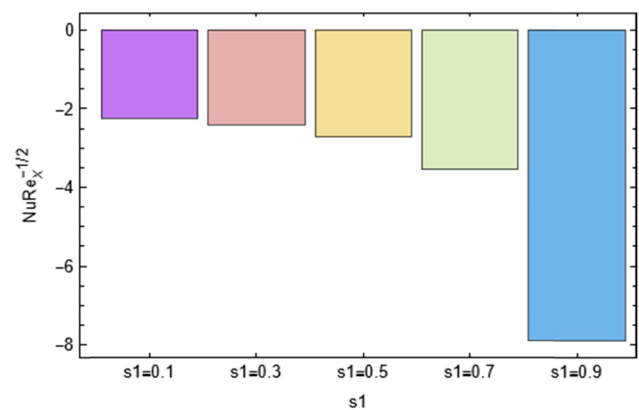
Figure 12: Temperature field for various values of ϕ .Figure 13: Temperature field for various values of s_1 .

Figure 15 shows that as the ratio parameter increases, the skin friction also increases. Figure 16 shows that as the melting parameter increases, the skin friction coefficient decreases. Figure 17 shows that as the stratification parameter increases,

Figure 14: Temperature field for various values of δ .Figure 15: Skin friction for ratio parameter A .

the local Nusselt number decreases. Figure 18 shows that as the Eckert number increases, the local Nusselt number increases. Figures 19 and 20 demonstrate the comparison of present work with the existing literature of Rehman *et al.*'s [3] velocity and temperature fields. In the absence of volume fraction parameter, porosity, and permeability parameters, one can get

Figure 16: Skin friction for melting parameter M .Figure 17: Local Nusselt number for stratification parameter s_1 .

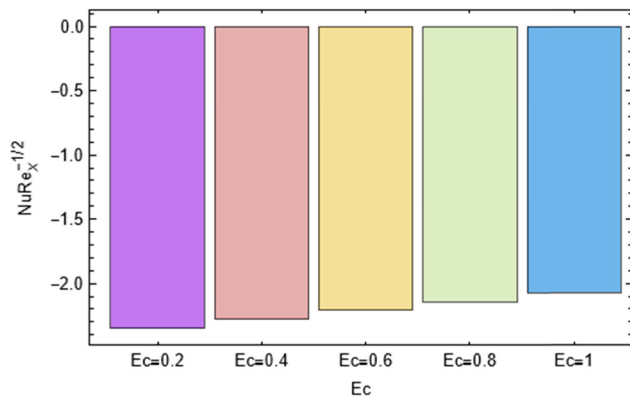


Figure 18: Local Nusselt number for Eckert number Ec .

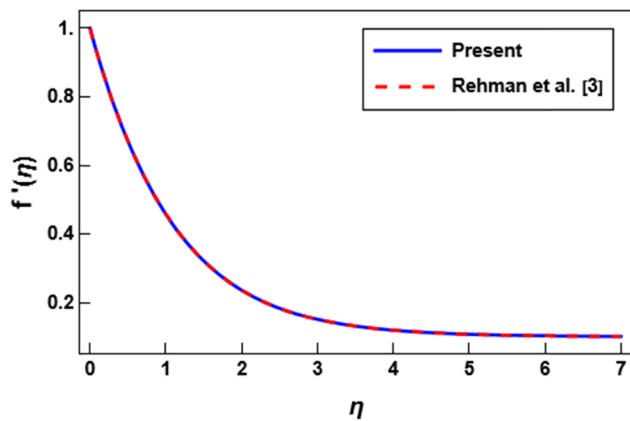


Figure 19: Velocity field of present work and that of Rehman *et al.* [3].

solution of velocity and temperature fields similar to that of Rehman *et al.* [3].

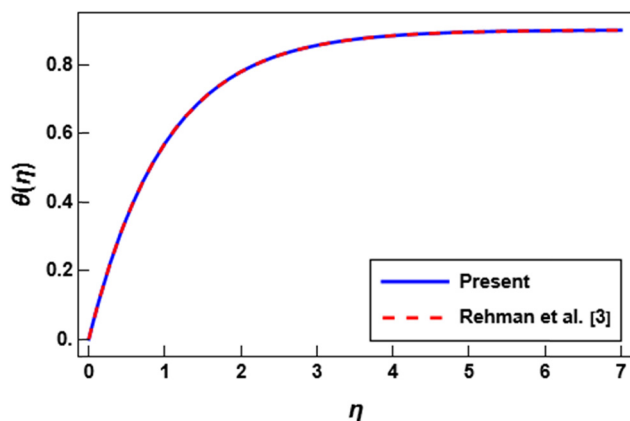


Figure 20: Temperature field of present work and that of Rehman *et al.* [3].

5 Conclusion

This research demonstrates the impact of melting phenomena and heat transport characteristics under more practical boundary conditions. In the modeled scenario, magnesium nanoparticles are uniformly suspended within a base fluid blood to address deficiencies in the human body and promote recovery. The unique material properties of these nanoparticles, including their thermal conductivity and interaction with the magnetic field, play a critical role in enhancing the treatment efficiency. Their precise engineering aids in achieving a desired thermal equilibrium between the fluid phase and the nanoparticles, thereby optimizing the medical outcome. In our analysis, the Powell–Eyring nanofluid flow at the stagnation point is subjected to an inclined magnetic field, emphasizing the interaction between magnetic responsiveness and nanoparticle dynamics. The given PDEs are adeptly transformed into a more manageable ODE system through the application of the correct similarity transformation. The efficacy of the HAM in this context confirms its suitability for complex simulations in material and medical sciences. The following are the final observations:

- 1) The fluid velocity decreases as the values of inclination angle α and porosity d increases, because when α increases, then the Lorentz forces increase while when the d accelerates, the fluid particles have more paths to follow through the material, this increases the resistance and tortuosity. Similarly, fluid velocity increases as the value of inertial parameters β , melting parameter M and uniform/variable porosity d_1 increase. Due to less resistance between the fluid particles because of the increase in the above parameters, the fluid velocity increases.
- 2) Temperature distribution shows an increasing influence, as the values of Eckert number Ec and magnetic factor Ha increases, because more heat is transferred due to the increase in Ec while due to high resistance force it produces more heat because of the enhancement of Ha . While the temperature distribution shows a decreasing influence, as the values of melting parameter M and thermal stratification s_1 increases.

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