
Cover Page

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ANALYTICAL STUDY OF MHD BLOOD NANOFLUID FLOW IN AN INCLINED ARTERY WITH MULTIPLE STENOSES VIA HOMOTOPY PERTURBATION METHOD

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Abstract

This paper presents an analytical investigation of magnetohydrodynamic (MHD) blood nanofluid flow through an inclined artery with multiple stenoses, modeled as an axisymmetric cylindrical conduit. A single-phase approach is employed to describe the flow of electrically conducting Newtonian blood containing gold nanoparticles under the influence of an externally applied magnetic field. The governing nonlinear equations of motion and energy balance, formulated from the Navier–Stokes and energy equations, are solved analytically using the Homotopy Perturbation Method (HPM). The effects of key dimensionless parameters—such as the Hartmann number, nanoparticle volume fraction, Grash of number, and heat source parameter—on velocity, temperature distribution, wall shear stress, pressure gradient, and stream function are examined. The results reveal that the presence of magnetic fields significantly reduces the velocity and wall shear stress of the blood nanofluid, while increasing nanoparticle concentration mitigates the hemodynamic impact of stenosis. Moreover, the inclusion of gold nanoparticles enhances the thermal characteristics of the fluid, offering insights into magnetic nanoparticle-assisted drug delivery and hyperthermia applications. The developed analytical model provides a valuable theoretical framework for understanding MHD-controlled blood flow behavior in stenosed arteries and can serve as a basis for biomedical applications in targeted therapy and cardiovascular diagnostics.

Keywords— Magnetohydrodynamics, Blood Nanofluid, Gold Nanoparticles, Multiple Stenoses, Homotopy Perturbation Method, Biomedical Applications.

1. Introduction

Cardiovascular diseases (CVDs), such as coronary artery disease, myocardial infarction, and stroke, continue to be the leading cause of morbidity and mortality worldwide. A major underlying cause of these conditions is atherosclerosis, which is characterized by the accumulation of low-density lipoproteins (LDL) and fatty deposits along the arterial walls, leading to the formation of stenoses and progressive narrowing of the lumen [1]. Such geometric constrictions alter the hemodynamic behavior of blood, disrupt the shear stress distribution, and may result in severe clinical complications, including ischemia and thrombosis [2]. Understanding the fluid mechanical aspects of blood flow through stenosed arteries has therefore been a subject of extensive analytical and numerical studies, providing valuable insights into the development and progression of vascular diseases [3], [4].

In recent years, magnetohydrodynamics (MHD) has emerged as a key mechanism in controlling and manipulating blood flow in biomedical applications. Blood, being an electrically conducting fluid due to the presence of ionized plasma and hemoglobin, exhibits distinct flow behavior under the influence of a transverse magnetic field. The interaction between the magnetic field and the conducting fluid generates a Lorentz force, which acts as a resistive drag, thereby suppressing the velocity profile and influencing the pressure and wall shear stress characteristics [5]. Such magnetic field effects have found promising applications in bio-magnetic drug targeting, magnetic resonance imaging (MRI), and magnetically induced hyperthermia therapy [6].

Parallel to these developments, the rapid growth of nanotechnology has led to the introduction of nanofluids—a new class of engineered fluids formed by dispersing nanoparticles (metals, oxides, carbides, or carbon nanotubes) in conventional base fluids such as water, oil, or biological fluids [7]. The pioneering work of Choi [8] demonstrated that the inclusion of nanoparticles significantly enhances the thermal conductivity and heat transfer characteristics of the fluid. In biomedical engineering, such nanofluidic suspensions have opened new avenues for targeted drug delivery, thermal therapy, and

Cover Page

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diagnostic imaging [9],[10]. Among various metallic nanoparticles, gold (Au) nanoparticles (AuNPs) are particularly attractive due to their biocompatibility, tunable optical properties, chemical stability, and superior photothermal conversion efficiency [11]. These unique properties make AuNPs highly suitable for use in localized hyperthermia and magnetically guided therapeutic applications.

Mathematical modeling of MHD nanofluid flow through stenosed arteries provides a powerful theoretical framework for analyzing the interplay between magnetic field strength, nanoparticle concentration, and arterial geometry. A number of studies have explored MHD blood flow characteristics under different physiological conditions [12],[13]. However, most of the existing models either consider simplified geometries or rely on purely numerical approaches, often neglecting the coupling between magnetic and thermal effects in nanoparticle-laden blood flow. Analytical models, by contrast, offer explicit relations among physical parameters, facilitating a more detailed understanding of the underlying mechanisms influencing flow resistance, shear stress, and thermal distribution.

In the present investigation, an analytical study has been carried out to examine the MHD flow of a gold-based blood nanofluid through an inclined artery with multiple stenoses under the influence of an externally applied magnetic field. Blood is modeled as a Newtonian, viscous, incompressible, and electrically conducting fluid, while the gold nanoparticles are assumed to be uniformly dispersed, forming a homogeneous nanofluid under the single-phase approximation. The governing nonlinear momentum and energy equations, derived from the Navier–Stokes and energy balance laws, are solved analytically using the Homotopy Perturbation Method (HPM) [14], [15]. The effects of the Hartmann number (M), nanoparticle volume fraction (ϕ), Grashof number (Gr) and heat source parameter (α_1) on the velocity distribution, temperature profile, wall shear stress, pressure gradient, and stream function are systematically investigated.

The results reveal that the application of a magnetic field suppresses the axial velocity of the nanofluid due to the induced Lorentz force, thereby increasing flow resistance. Conversely, an increase in nanoparticle concentration enhances the thermal conductivity of the fluid and mitigates the adverse effects of stenosis by improving the temperature uniformity and flow stability. The analytical expressions derived in this study provide significant insight into magnetically controlled blood nanofluid dynamics, with direct implications for magnetic nanoparticle-assisted drug delivery, controlled hyperthermia, and cardiovascular diagnostic modeling.

2. Physical Assumptions of MHD Nanofluid and Single-Phase Mathematical Model

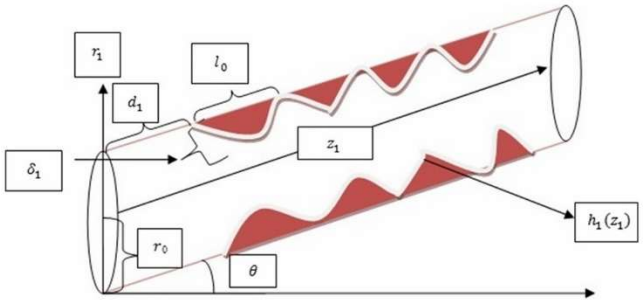

Fig.1: The geometry of stenosed artery along the axial direction which makes an angle θ with horizontal, and d = distance of stenosis from the radial axis.

In the present investigation, the arterial segment is modeled as an axi-symmetric cylindrical tube of radius r_0, inclined at an angle θ with the horizontal axis, as illustrated in Fig. 1. Blood is considered as a steady, homogeneous, incompressible, viscous, and electrically conducting Newtonian fluid of density ρ and kinematic viscosity ν. The flow field is governed by the Navier–Stokes and energy equations expressed in cylindrical coordinates (r_1, θ_1, z_1) where r_1 and θ_1 denote the radial and circumferential directions respectively, and the z_1 −axis is taken along the axial direction of the artery [2], [16].

Cover Page

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The velocity components along the axial and radial directions are represented by u_z and v_r, respectively, while $T_1(r_1, z_1)$ denotes the temperature of the nanofluid. A single-phase model is employed to describe the electrically conducting nanofluid flow in the presence of an externally applied magnetic field, neglecting the induced magnetic effects due to the low magnetic Reynolds number [17]. The motion and energy balance for a steady, viscous, and incompressible MHD nanofluid can thus be represented as

$$\rho_{nf}\left(u_r\frac{\partial u_r}{\partial r_1}+u_z\frac{\partial u_r}{\partial z_1}\right)=-\frac{\partial p_1}{\partial r_1}+\mu_{nf}\left(\frac{\partial^2 u_r}{\partial {r_1}^2}+\frac{1}{r_1}\frac{\partial u_r}{\partial r_1}+\frac{\partial^2 u_r}{\partial z_1^2}-\frac{u_r}{r_1^2}\right)+g(\rho B)_{nf}(T_1-T_\infty)\cos\theta \tag{1}$$

$$\rho_{nf}\left(u_r\frac{\partial u_z}{\partial r_1}+u_z\frac{\partial u_z}{\partial z_1}\right)=-\frac{\partial p_1}{\partial z_1}+\mu_{nf}\left(\frac{\partial^2 u_z}{\partial {r_1}^2}+\frac{1}{r_1}\frac{\partial u_z}{\partial r_1}+\frac{\partial^2 u_z}{\partial z_1^2}\right)+g(\rho B)_{nf}(T_1-T_\infty)\sin\theta-\sigma B_0^2 u_z \tag{2}$$

$$\rho_{nf}c_{p,nf}\left(u_r\frac{\partial T_1}{\partial r_1}+u_z\frac{\partial T_1}{\partial z_1}\right)=k_{nf}\left(\frac{\partial^2 T_1}{\partial {r_1}^2}+\frac{1}{r_1}\frac{\partial T_1}{\partial r_1}+\frac{\partial^2 T_1}{\partial z_1^2}\right)+Q_0 \tag{3}$$

Here, B_0 denotes the applied magnetic field strength, Q_0 represents the volumetric heat source, and the subscript "nf" indicates nanofluid properties.

The effective thermophysical properties of the nanofluid—density ρ_{nf}, heat capacity $(\rho c_p)_{nf}$, viscosity μ_{nf}, thermal expansion coefficient $(\rho\beta)_{nf}$, and thermal conductivity k_{nf}—are evaluated using the classical mixture relations [7],[8],[9],[10]:

$$\rho_{nf}=(1-\phi)\rho_{bf}+\phi\rho_p\,,\qquad (\rho c_p)_{nf}=(1-\phi)(\rho c_p)_{bf}+\phi(\rho c_p)_p\,,$$

$$\mu_{nf}=\mu_{bf}(1+7.3\phi+123\phi^2)\,,\qquad (\rho\beta)_{nf}=(1-\phi)(\rho\beta)_{bf}+\phi(\rho\beta)_p\,,$$

$$k_{nf}=k_{bf}\frac{k_p+2k_{bf}-2\phi(k_{bf}-k_p)}{k_p+2k_{bf}+\phi(k_{bf}-k_p)}\,, \tag{4}$$

where ϕ denotes the volume fraction of nanoparticles, and subscripts "bf" and "p" correspond to base fluid (blood) and nanoparticle phases, respectively.

The axial geometry of the stenosed artery is defined as

$$h_1(z_1)=\begin{cases} r_0-\dfrac{\delta_1}{2}\left(1+\cos\dfrac{2\pi}{l_0}\left(z_1-d_1-\dfrac{l_0}{2}\right)\right), & d_1+l_0\le z_1\le d_1+5l_0 \\ r_0\,, & \text{otherwise}\end{cases} \tag{5}$$

where δ_1 denotes the maximum height of stenosis, d_1 is the location of stenosis onset, and l_0 represents its length.

To nondimensionalize the governing equations, the following transformations are introduced:

$$r=\frac{r_1}{r_0}\,,\qquad z=\frac{z_1}{l_0}\,,\qquad u=\frac{u_z l_0}{u_0}\,,\qquad T=\frac{T_1-T_\infty}{T_0-T_\infty}\,,\qquad p=\frac{{r_0}^2 p_1}{u_0 l_0 \mu_{bf}}\,, \tag{6}$$

where $u_0$denotes the average axial velocity. The dimensionless parameters are defined as follows:

$$Re=\frac{l_0 u_0 \rho_{bf}}{\mu_{bf}}\,,\qquad G_r=\frac{g\rho_{bf}\beta_{bf}{r_0}^2(T_0-T_\infty)}{u_0\mu_{bf}}\,,\qquad M=B_0 l_0\sqrt{\frac{\sigma}{\mu_{bf}}}\,, \tag{7}$$

Cover Page

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representing the Reynolds number, Grashof number, and Hartmann number, respectively.

Under the assumption of mild stenosis ($\delta_1 \ll 1$) and low Reynolds number flow, inertia terms can be neglected, allowing the flow to be approximated as creeping MHD nanofluid motion [15]. Thus, the dimensionless momentum and energy equations reduce to

$$\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}-\frac{\mu_{bf}}{\mu_{nf}}\left(\frac{(\rho\beta)_{nf}}{(\rho\beta)_{bf}}Gr\sin\theta+\frac{dp}{dz}\right)-M^2u=0\,, \tag{8}$$

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}-\frac{k_{bf}}{k_{nf}}=0\,. \tag{9}$$

The heat source parameter and magnetic parameter are expressed as

$$\alpha_1=\frac{Q_0{r_0}^2}{T_0k_{bf}}\,,\qquad M=\frac{B_0L_0}{\sqrt{\sigma/\mu_f}}$$

and the dimensionless boundary conditions are applied as

$$\frac{\partial u}{\partial r}=0\,,\frac{\partial T}{\partial r}=0\ \text{ at } r=0\,;\ u=0,T=0\ \text{ at } r=h(z)\,. \tag{10}$$

The analytical solution of the temperature profile, derived under these assumptions, is obtained as

$$T=\frac{\alpha_1}{4}\frac{k_p+2k_{bf}-(k_p-k_{bf})\phi}{k_p+2k_{bf}+2(k_p-k_{bf})\phi}(h^2-r^2)\,, \tag{11}$$

which satisfies the prescribed thermal boundary conditions and captures the influence of nanoparticle concentration and magnetic field on the temperature distribution of the MHD nanofluid in a stenosed artery.

3. Homotopy Perturbation Method (HPM)

To obtain an analytical solution for the nonlinear governing equation describing MHD nanofluid flow through a stenosed artery, the Homotopy Perturbation Method (HPM), originally proposed by He [14], [18] is employed. This semi-analytical approach combines the concepts of classical perturbation and homotopy techniques, providing rapidly convergent series solutions without requiring small physical parameters [19], [20].

Consider the general nonlinear differential equation

$$A(u)-f(r)=0\,,r\in\Omega\,, \tag{12}$$

subject to the boundary condition

$$B\left(u,\frac{\partial u}{\partial n}\right)=0\,,r\in\Gamma\,, \tag{13}$$

where A and B denote differential and boundary operators respectively, $f(r)$ is an analytic function, and Γrepresents the boundary of the physical domain Ω . The operator Acan be decomposed into linear and nonlinear components as

$$A(u)=L(u)+N(u)\,, \tag{14}$$

Cover Page

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where L and N are the linear and nonlinear operators. Consequently, Eq. (12) can be expressed as

$$L(u) + N(u) - f(r) = 0\,. \tag{15}$$

A homotopy $H(v,q)$ is constructed as

$$H(v,q) = (1-q)[L(v) - L(u_0)] + q[A(v) - f(r)] = 0, \tag{16}$$

where $q \in [0,1]$ is the embedding parameter, and u_0 denotes an initial approximation satisfying the boundary conditions. As q varies from 0 to 1, the solution continuously deforms from $u_0(r)$ to $u(r)$.

The solution is expanded as a power series in q:

$$v = v_0 + qv_1 + q^2v_2 + \cdots \ldots\ldots\ldots\ldots\ldots, \tag{17}$$

and for $q = 1$, the approximate analytical solution becomes

$$u = \lim_{q\to 1} v = v_0 + v_1 + v_2 + \cdots \ldots\ldots\ldots\ . \tag{18}$$

The dimensionless governing equation for MHD nanofluid flow, derived earlier, can be written as

$$\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} - \alpha_2(h^2 - r^2) - M^2u - P_1 = 0\,, \tag{19}$$

where

$$\alpha_2 = \frac{\alpha_1 k_{bf}}{4k_{nf}}\frac{(\rho\gamma)_{nf}}{(\rho\gamma)_{bf}} Gr\sin\theta\,, \quad P_1 = \frac{dp/dz\ \mu_m}{\mu_{bf}}\,, \tag{20}$$

To solve Eq. (19), a suitable homotopy is formulated as

$$H(v,q) = (1-q)[L(v) - L(u_0)] + q[L(v) - \alpha_2(h^2 - r^2) - M^2v - P_1] = 0\,, \tag{21}$$

where $L(v) = \frac{\partial^2 v}{\partial r^2} + \frac{1}{r}\frac{\partial v}{\partial r}$, $u_0(r) = \frac{(r^2-h^2)}{4}$.

The approximate solution is expressed as

$$v(r) = v_0 + qv_1 + q^2v_2 + \cdots. \tag{22}$$

Substituting Eq. (22) into Eq. (21) and equating coefficients of identical powers of q yields the following equations:

For q^1:

$$\frac{\partial^2 v_1}{\partial r^2} + \frac{1}{r}\frac{\partial v_1}{\partial r} + \frac{1}{4}\frac{du_0}{dr} - M^2u_0 - P_1 - \alpha_2(h^2 - r^2) = 0\,, \tag{23}$$

and for q^2:

$$\frac{\partial^2 v_2}{\partial r^2} + \frac{1}{r}\frac{\partial v_2}{\partial r} - M^2v_1 = 0\,. \tag{24}$$

Solving Eq. (23) gives

$$v_1(r) = \left(\frac{P_1}{2} - 1\right)(r^2 - h^2) + (\alpha_2 - M^2)\left(\frac{h^2r^2}{16} - \frac{r^4}{4} + \frac{h^4}{4}\right), \tag{25}$$

Cover Page

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and substituting Eq. (25) into Eq. (24) yields

$$v_2(r) = M^2\left(\frac{P_1}{2}-1\right)\left(\frac{h^2r^2}{16}-\frac{r^4}{16}+\frac{3h^4}{16}\right)+M^2(\alpha_2-M^2)\left(\frac{h^2r^4}{32}-\frac{r^6}{144}+\frac{h^4r^2}{16}+\frac{11h^6}{288}\right). \quad (26)$$

Hence, for $q = 1$, the analytical expression for the axial velocity of MHD nanofluid flow is obtained as

$$u(r) = \frac{(r^2-h^2)}{4}+\left(\frac{P_1}{2}-1\right)(h^2-r^2)+(\alpha_2-M^2)\left(\frac{h^2r^2}{16}-\frac{r^4}{4}+\frac{h^4}{4}\right)+M^2\left(\frac{P_1}{2}-1\right)\left(\frac{h^2r^2}{16}-\frac{r^4}{16}+\frac{3h^4}{16}\right)$$
$$+M^2(\alpha_2-M^2)\left(\frac{h^2r^4}{32}-\frac{r^6}{144}+\frac{h^4r^2}{16}\right.$$
$$\left.+\frac{11h^6}{288}\right). \quad (27)$$

Equation (27) represents the axial velocity profile of MHD nanofluid flow through a stenosed artery obtained via HPM. The series solution exhibits rapid convergence, and the inclusion of higher-order terms yields more refined results, consistent with previous analytical works [19], [23].

The wall shear stress at the stenotic surface is expressed as

$$\tau = \frac{\mu_{nf}}{\mu_{bf}}\left(\frac{\partial u}{\partial r}\right)_{r=h} = -(1+7.3\phi+123\phi^2)\left[\frac{M^2(\alpha_2-M^2)h^5}{24}-\frac{M^2(P_1-2)h^3}{8}+h(2.5-P_1)\right], \quad (28)$$

where ϕ denotes the nanoparticle volume fraction.

The stream function $\psi(r)$ satisfying $u = \frac{1}{r}\frac{d\psi}{dr}$ is obtained by integrating with respect to $r$under the boundary condition $\psi = 0$ at $r = 0$:

$$\psi(r) = \frac{1}{4}(r^4-2r^2h^5)(5-2P_1)+(\alpha_2-M^2)\left(\frac{h^2r^6}{192}-\frac{r^8}{1152}+\frac{h^4r^4}{64}+\frac{11h^6r^2}{576}\right)$$
$$+M^2(\alpha_2-M^2)\left(\frac{h^2r^4}{32}-\frac{r^6}{144}+\frac{h^4r^2}{16}+\frac{11h^6}{288}\right)$$
$$+M^2\left(\frac{P_1}{2}-1\right)\left(\frac{h^2r^2}{16}-\frac{r^4}{16}+\frac{3h^4}{16}\right). \quad (29)$$

The volumetric flow rate through the artery is given by

$$F = \int_0^h r\,u\,dr\,, \quad (30)$$

and the axial pressure gradient for a fixed flow rate is derived as

$$\frac{dp}{dz} = \frac{M^2(\alpha_2-M^2)h^5}{384}+\frac{3h^4}{16}+\frac{h^6}{24}\Big/\left[48(6h^4+M^4h^6)\frac{\mu_{nf}}{\mu_{bf}}\right]. \quad (31)$$

Equation (31) illustrates that the pressure gradient increases with both the Hartmann number (M) and nanoparticle volume fraction (ϕ) , reflecting the combined influence of electromagnetic and viscous effects on the hemodynamic resistance of the nanofluid within the stenosed artery.

Cover Page

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4. Results and Discussion

The analytical expressions for the velocity, pressure gradient, wall shear stress, temperature, and stream function, obtained using the Homotopy Perturbation Method (HPM), are evaluated to investigate the combined influence of the Hartmann number (M), nanoparticle volume fraction (ϕ), and heat source parameter (α_1) on the magnetohydrodynamic (MHD) flow of a gold-based blood nanofluid through an inclined, multiple-stenosed artery. The results are graphically represented in Figs. 2–6, and the corresponding physical interpretations are discussed in this section.

4.1. *Effect of Hartmann Number on Pressure Gradient*

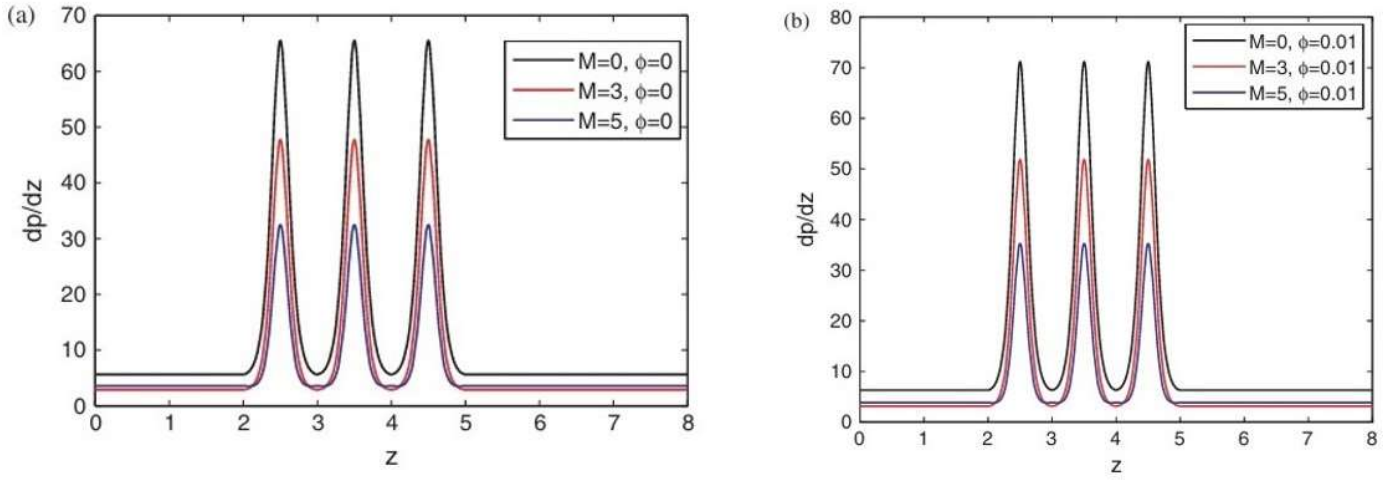

Fig.2: Pressure gradient for varying Hartmann number M (a) pure blood i.e., $\phi = 0$, and (b) gold nanoparticle with $\phi = 0.01$.

Fig. 2(a)–(b) demonstrates the variation of the axial pressure gradient (dp/dz) along the length of the stenosed artery for different values of the Hartmann number (M) and nanoparticle volume fraction (ϕ). The pressure gradient exhibits pronounced peaks in the regions of maximum constriction, indicating a sharp increase in flow resistance due to the geometric narrowing of the artery. For all values of M, three distinct peaks correspond to the positions of multiple stenoses.

As the Hartmann number increases, the magnitude of the pressure gradient decreases significantly. This reduction is attributed to the Lorentz force, which acts opposite to the direction of motion and suppresses the velocity of the conducting nanofluid, thereby damping pressure fluctuations along the axial direction. In Fig. 2(a), for pure blood $(\phi = 0)$, the reduction in the pressure gradient with increasing $M$is more prominent compared to the gold nanofluid case shown in Fig. 2(b). The presence of nanoparticles slightly enhances the effective viscosity and density of the fluid, which tends to stabilize the flow and smoothen pressure variations within the stenotic regions. These findings are in good agreement with the results of Nadeem and Ijaz [21] and Changdar and De [15], who reported similar damping effects of magnetic fields on blood flow in stenosed arteries.

Cover Page

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4.2. *Wall Shear Stress Behavior*

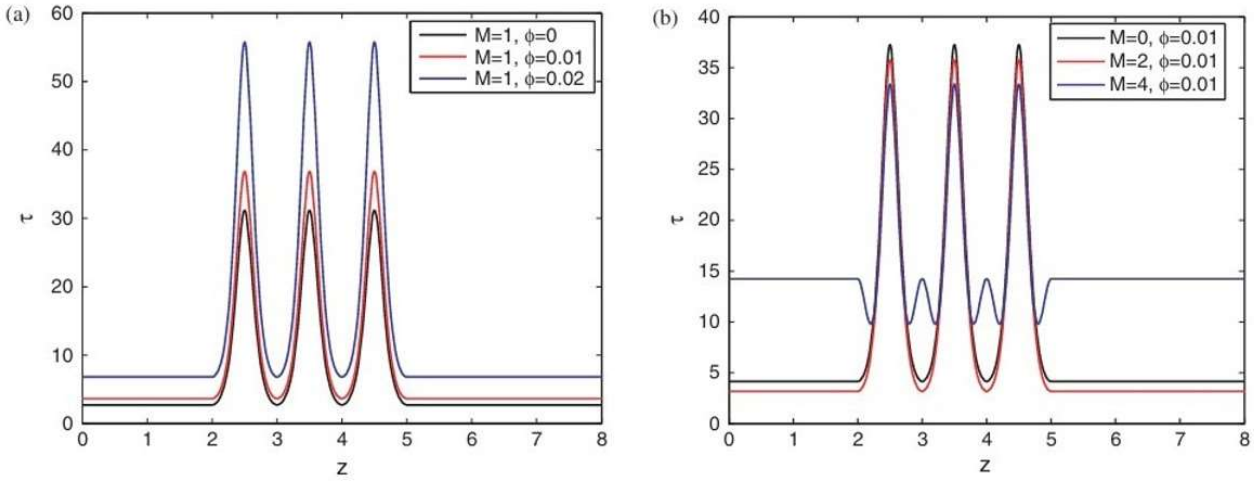

Fig.3: Wall shear stress for varying (a) gold nanoparticle volume fraction, (b) Hartmann number M .

Fig. 3(a)–(b) depicts the wall shear stress (τ) distribution along the axial coordinate z for varying nanoparticle volume fractions (ϕ) and Hartmann numbers (M). The wall shear stress follows a pattern analogous to the pressure gradient, with multiple peaks corresponding to the regions of maximum stenosis.

In Fig. 3(a), the wall shear stress increases noticeably with an increase in the nanoparticle volume fraction (ϕ). The presence of nanoparticles enhances the fluid's thermal conductivity and effective viscosity, resulting in higher shear resistance near the arterial wall. This rise in τ is more pronounced near the throat of each stenosis, where the velocity gradients are steepest. Conversely, Fig. 3(b) indicates that an increase in the Hartmann number reduces the wall shear stress, as the magnetic field generates a resistive Lorentz force that counteracts fluid motion and suppresses shear. The shear stress magnitude decreases from $M = 0$ to $M = 4$, confirming the retarding influence of the magnetic field on wall friction.

Physiologically, this reduction in τ with increasing M implies that the application of an external magnetic field can potentially reduce endothelial damage and enhance flow control in magnetically assisted biomedical devices. Similar observations have been reported by Ellahi et al. [5] and Akbar and Nadeem [22], validating the present analytical results.

Cover Page

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4.3. *Axial Velocity Distribution*

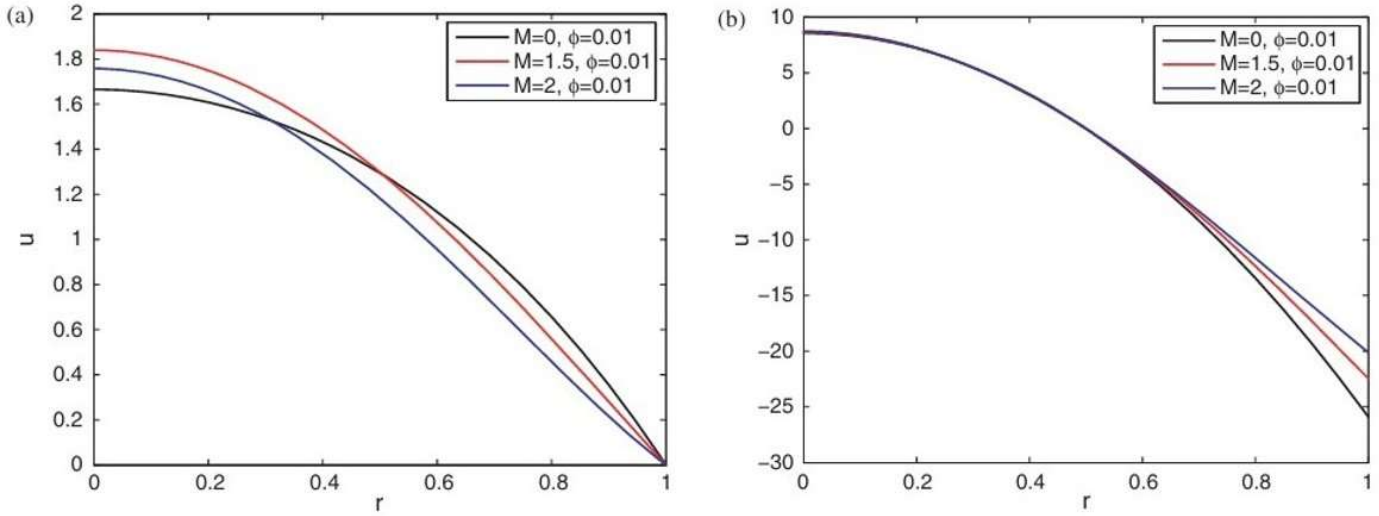

Fig.4: Axial velocity for varying Hartmann number M (a) at $z = 1$ and (b) at $z = 2.5$ of gold nanofluid with $\phi = 0.01$.

The effect of the Hartmann number on the axial velocity (u) distribution is presented in Fig. 4(a)–(b) for different positions along the artery. The velocity profiles exhibit a parabolic nature, attaining a maximum at the centerline and satisfying the no-slip boundary condition at the wall.

As illustrated in Fig. 4(a), for $z = 1$, an increase in M from 0 to 2 results in a marked decrease in the peak velocity, consistent with the Lorentz force's retarding action. However, the presence of gold nanoparticles ($\phi = 0.01$) enhances the effective conductivity of the fluid, which slightly offsets the magnetic damping, thereby preserving smoother velocity gradients across the cross-section. In Fig. 4(b), corresponding to $z = 2.5$, the velocity magnitude further decreases due to intensified stenotic constriction, showing a flattened profile near the center and steeper gradients near the wall.

These findings corroborate earlier analytical works [15], [23] which demonstrated that the combined effects of magnetic and viscous forces play a crucial role in flow regulation within stenotic arteries. The suppression of velocity is also physiologically relevant for magnetic nanoparticle-assisted drug targeting, where controlled deceleration of nanoparticle transport enhances drug localization efficiency.

Cover Page

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4.4. *Temperature Distribution*

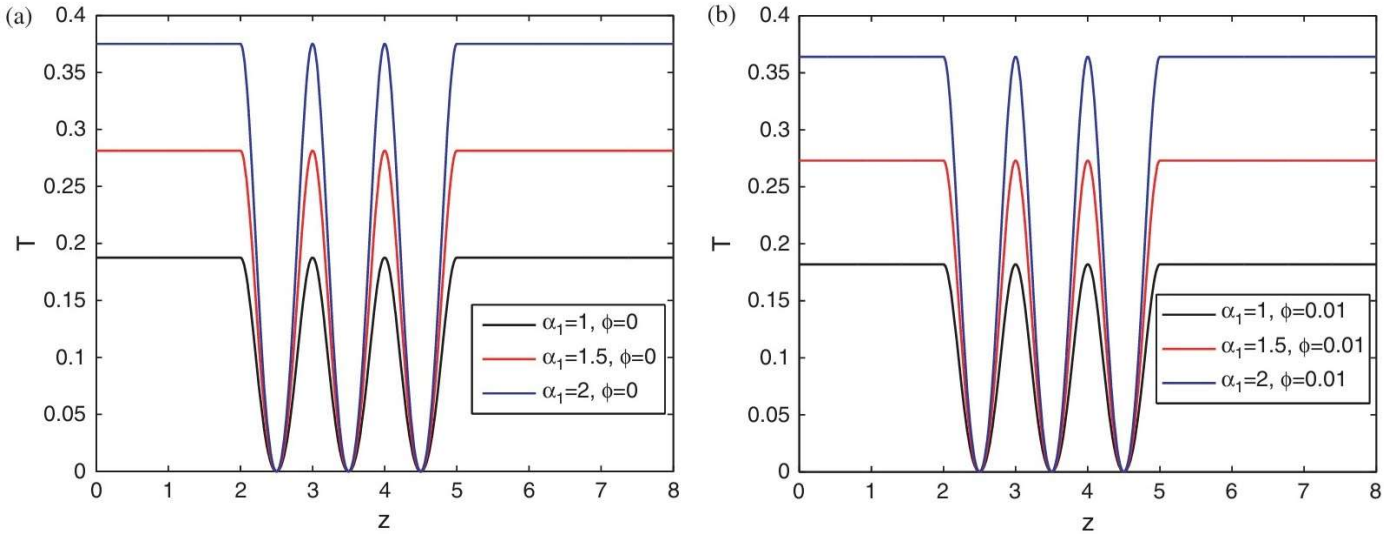

Fig.5: Temperature profile for (a) pure blood and (b) gold nanofluid with $\phi = 0.01$.

The temperature profiles for varying heat source parameter (α_1) are displayed in Fig. 5(a)–(b) for both pure blood and gold-based nanofluid ($\phi = 0.01$). The temperature shows a symmetric pattern along the stenosed region, with noticeable increases near constrictions where viscous and Joule heating effects are more prominent.

As seen in Fig. 5(a), the temperature rises with increasing values of α_1 due to enhanced internal heat generation, reflecting the direct proportionality between α_1 and the rate of heat source energy. When nanoparticles are introduced [Fig. 5(b)], the temperature distribution becomes more uniform, and the maximum temperature rises further owing to the improved thermal conductivity of the nanofluid. This enhancement facilitates better heat dispersion within the arterial wall, potentially beneficial for localized hyperthermia-based treatments in cancer therapy and vascular heating applications [11], [17]. Overall, the thermal enhancement due to gold nanoparticles is more significant in high magnetic field regimes, indicating a strong coupling between MHD and thermophysical effects in nanofluidic blood flow systems.

Cover Page

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4.5. *Stream Function and Flow Pattern*

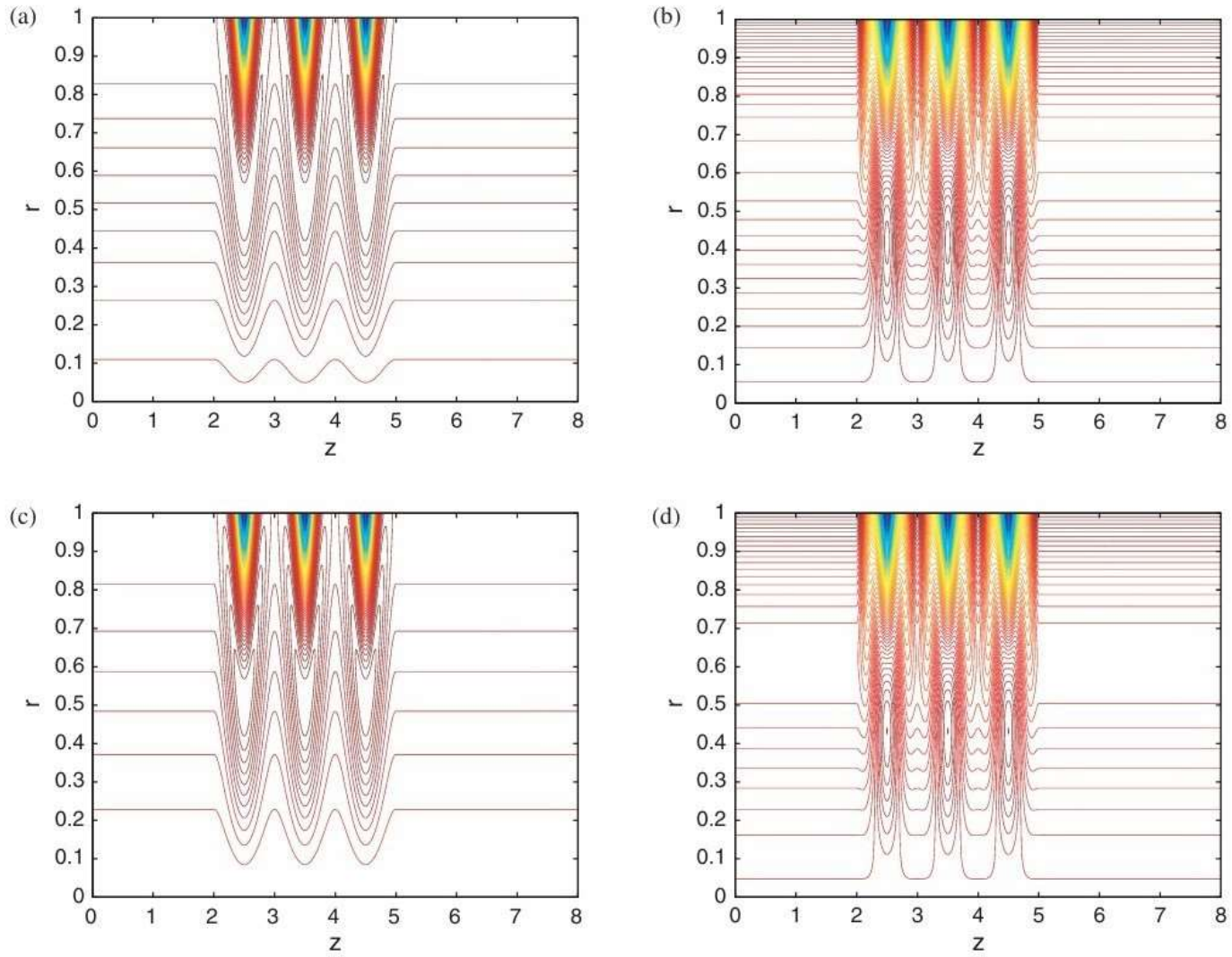

Fig.6: Stream lines profile for (a) $\phi = 0, M = 0$; (b) $\phi = 0, M = 5$; (c) $\phi = 0.01, M = 2$; (d) $\phi = 0.01, M = 5$.

Fig. 6(a)–(d) depicts the streamlines for different combinations of Hartmann number (M) and nanoparticle concentration (φ). The streamline plots clearly illustrate the hemodynamic behavior and recirculation zones near the stenotic regions.

For pure blood without magnetic influence [Fig. 6(a)], the flow remains nearly symmetrical, with strong acceleration at the throat and mild flow separation downstream. When the magnetic field is applied $(M = 5)$, as shown in Fig. 7(b), the streamlines become more uniform, and recirculation zones weaken, indicating that magnetic damping reduces secondary motion. The inclusion of nanoparticles $(\phi = 0.01)$ in Figs. 6(c)–(d) results in a smoother streamline curvature and reduced flow separation, reflecting the stabilizing role of nanoparticle loading on the flow field. With higher M, the streamlines elongate axially, and vortices diminish in intensity, demonstrating that the combined effect of magnetism and nanofluid viscosity suppresses flow instabilities. This controlled flow behavior is desirable for biomedical flow regulation and magnetically guided nanoparticle transport in arterial systems [24].

Cover Page

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The combined parametric analysis indicates that increasing magnetic field strength (M) reduces both velocity and wall shear stress, providing a protective effect on arterial walls under stenotic conditions. On the other hand, increasing nanoparticle volume fraction (ϕ) enhances the thermal performance of blood flow, making the system more efficient for hyperthermic drug delivery applications. The analytical results obtained using HPM are consistent with previous computational and experimental findings [5], [14], [15] confirming the method's reliability for nonlinear biofluid mechanics problems.

Conclusion:

In this study, a comprehensive analytical investigation has been conducted on the magnetohydrodynamic (MHD) flow of a blood–gold nanofluid through an inclined, multiple-stenosed artery subjected to an externally applied magnetic field. The nonlinear governing equations of motion and energy, derived from the Navier–Stokes and energy balance equations, were solved analytically using the Homotopy Perturbation Method (HPM). The proposed single-phase model provides detailed insight into the combined effects of magnetic field strength, nanoparticle concentration, and heat source parameters on the hemodynamic and thermal characteristics of blood flow in a stenosed arterial geometry. The application of a magnetic field significantly influences the flow behavior of the nanofluid. As the Hartmann number increases, the Lorentz force acts in opposition to the motion of the conducting fluid, resulting in a noticeable reduction in the axial velocity, wall shear stress, and pressure gradient. This electromagnetic damping stabilizes the flow by reducing recirculation and suppressing oscillations in the stenotic regions. The findings suggest that an external magnetic field can effectively regulate blood velocity and wall shear distribution, which has important implications for biomedical control mechanisms and magnetically guided therapies.

The inclusion of gold nanoparticles enhances the thermal conductivity and viscosity of the fluid, thereby improving heat transport characteristics and minimizing the adverse effects of stenosis on flow uniformity. With an increase in nanoparticle volume fraction, the hemodynamic disturbances within the constricted zones are reduced, and the flow exhibits smoother velocity and temperature profiles. Furthermore, the temperature field is highly sensitive to variations in the heat source parameter; an increase in this parameter amplifies the temperature gradient along the arterial wall. The combined effects of nanoparticle loading and magnetic influence lead to efficient thermal regulation and improved convective heat transfer, which are vital for biomedical processes such as hyperthermia treatment and targeted drug delivery. The analysis of the pressure distribution reveals that the pressure gradient exhibits sharp peaks near the throat of each stenosis, corresponding to regions of maximum constriction. However, these peaks diminish with increasing Hartmann number, indicating that the magnetic field alleviates pressure fluctuations and enhances the stability of the flow. The stream function profiles further confirm that magnetic and nanoparticle effects contribute to the suppression of secondary vortices, leading to a more streamlined and controlled flow field.

The study concludes that nanofluid-based MHD flow control offers a powerful mechanism for regulating hemodynamic parameters within stenosed arteries. By tuning the magnetic field intensity and nanoparticle concentration, it is possible to achieve desired flow characteristics, minimize wall shear stresses, and improve heat transport efficiency. These results have significant biomedical implications, particularly in the areas of magnetic nanoparticle-assisted drug delivery, bio-thermal therapy, and cardiovascular diagnostics. The developed analytical model provides a robust theoretical foundation for understanding magnetically controlled blood flow behavior in complex arterial geometries and may serve as a basis for future research involving non-Newtonian effects, pulsatile motion, and multi-phase flow conditions. This investigation highlights the potential of MHD nanofluid models to advance modern nanomedicine and offers valuable insights into the design of magnetically tunable therapeutic and diagnostic systems.

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