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HYBRID NANOPARTICLES AND LIQUID METAL ON MHD FLOW WITH SLIP BOUNDARY LAYER ON PERMEABLE ARTERIAL TUBE

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This paper investigates the hybrid effect of Nanoparticles and liquid metal on MHD flow in a permeable arterial tube subjected to external electromagnetic fields and slip boundary conditions. A blood-based carrier fluid containing two distinct suspended particle phases is considered to model a physiologically relevant hybrid nanofluid–liquid metal system for biomedical applications. The governing equations, such as momentum, energy, and mass transfer, are derived through boundary layer approximations and similarity transformations, which reduce the system of PDEs to a set of nonlinear ODEs. The equations incorporate major physical effects such as viscous dissipation, Brownian motion, thermophoresis, and chemical reactions. MATLAB's shooting method in association with a Runge-Kutta solver is used to solve the resulting ODEs. The study examines the influence of various parameters including the Hartmann number, permeability factor, nanoparticle volume fraction, and slip coefficients on axial velocity, temperature, and concentration profiles. The findings show the enhancement of heat transfer and flow stability resulting from the incorporation of hybrid nanoparticles and extensive modification of velocity and temperature distributions by magnetic and slip effects. Such analysis provides valuable inputs to maximize the uses of blood-based nanofluid in biomedical engineering, drug delivery, and magnetic field-assisted therapies.

Key words: liquid metal, MHD flow, nanoparticles, magnetic field assisted therapies, slip boundary layer.

1. Introduction

Magneto-hydrodynamics (MHD) flows have generated significant interest in biomedical engineering due to their potential to manipulate electrically conducting biological fluids, such as blood, under the influence of magnetic fields. Magnetic drug targeting delivery is one of the most promising applications of MHD, wherein external magnetic fields are used to target magnetic nanoparticles to a desired location within the circulatory system, enhancing the efficacy and localization of drugs [1-3]. This technique reduces systemic side effects and allows for controlled, non-surgical treatment of focal diseases, such as tumours or arterial blockages. At the same time, the use of nanoparticles in bio fluids has received much interest because the nanoparticles can enhance thermal conductivity, a factor critical for managing localized hyperthermia treatment or heat-sensitive biochemical reactions [4, 5]. Nanoparticles also enhance drug delivery by providing a larger surface area for bonding, allowing them to be used for functionalization of targeted addressing and controlling release properties [6]. Some substances that have demonstrated notable applications in diagnosis, imaging, and treatment are gold, silver, titanium dioxide, and silica [7-9]. Liquid metals such as mercury and gallium possess unique value with their thermal and electrical conductance, flexibility, and fluidic nature at body temperature [10]. These features make them viable candidates for applications in soft electronics, biosensors, thermo regulation, and liquid flow control in biomedical micro devices [11, 12]. Their sensitivity to magnetic fields also aids in the MHD control of the bio fluids for fine regulation in therapeutic processes [13]. Slip boundary conditions need to be incorporated into modern biomedical flow simulations, particularly at micro and Nano scale, where the no-slip condition breaks down due to the presence of rarefied gas or complex wall fluid interactions. Permeable arterial tubes in blood vessels in biological systems are a model for capillary walls or stented arteries, where filtration, leakage, or absorption of fluid is feasible. Permeability of the wall is taken into account for drug diffusion modelling, nutrient transport, and pathological leakage, such as in tumours or diabetic vasculature [14-16]. Recent studies have analysed hybrid configurations of MHD

hybrid nanofluid flow in biological channels [17]. Radiative effects and slip boundary conditions in arterial geometry were studied [18]. The impact of thermophoresis and viscous dissipation in porous biological media was examined [19]. Zheng *et al.* [20] examined the interactive behavior of ferromagnetic nanoparticles and liquid mercury metal, explaining the relationship between interfacial forces and Lorentz effects on thermal dispersion and chaotic backflow in confined geometries [20].

The combination of metallic oxide with liquid metals improves thermomagnetic convection effects [21]. The advantage comes from controllable thermal gradients and responsiveness. However, the drawback includes toxicity concerns with liquid metals like Hg, which pose biological risks and need careful containment. Thermally induced slip flows in arterial bifurcations have been investigated [23]. They found that numerical stability and convergence improved slip boundary models offer better accuracy in capturing micro-scale dynamics. However, a limitation lies in selecting realistic slip coefficients and managing the discontinuity at interfaces. In a related study, a coupled MHD porous model was developed [24] which showed that the increased porosity improved drug dispersion and reduced wall shear. The benefit is high accuracy in simulating drug perfusion and delivery. However, limitations include the complex estimation of parameters for permeability and porosity.

Unlike earlier studies that examine nanofluid or liquid metal flow separately, this work combines both phases, offers a comprehensive dimensionless analysis, and applies the model to real biomedical settings. The main goals and benefits of the model are to enhance the prediction of microvascular drug transport, increase versatility across different parameter ranges, and improve relevance to biology. The primary limitations include difficulties in experimentally validating all governing parameters and potential simplifications in geometry.

There is a clear gap in the development of comprehensive mathematical models for hybrid nanoparticle liquid metal suspensions being carried through a permeable arterial tube with slip effects and magnetic fields. Most previous research separates the effects mentioned above, rather than showing their combined dynamics and the resulting biomedical issues.

This research fills a gap by developing a mathematical model that describes the MHD flow, heat, and mass transfer of a hybrid nanofluid-liquid metal suspension through a permeable arterial tube under slip conditions. We utilize similarity transformations to convert the governing partial differential equations into a set of nonlinear ordinary differential equations. These are solved numerically using a shooting method and Runge-Kutta scheme. The model examines the effects of Hartmann number, nanoparticle volume fraction, slip coefficients, and thermal diffusion on axial velocity, temperature, and concentration profiles. The results aim to support biomedical applications such as magnetically targeted drug delivery, hyperthermia treatment, and microvascular diagnostics.

2. Mathematical formulation

The governing equations for mass, momentum, energy, and concentration of the two-phase flow of hybrid nanofluid and liquid metal MHD in a permeable arterial tube are formulated to describe the fluid flow model. These equations consider the most significant physical phenomena, such as the interaction of a magnetic field according to the Lorentz force, heating in the tube due to radiation, chemical reactions, and slip velocity boundary conditions for realistic micro vessel flow in blood vessels using the Rosseland approximation.

Formulations have been developed and confirmed in previous research related to the flows of hybrid nanofluids with slip conditions [24], the thermal and magnetic properties of liquid metal nanofluids [25], and slip flow movement in permeable arterial tissues. Such design integration enables accurate simulation of biophysical processes relevant to biomedical engineering, including the development of systems for controlled release of therapeutic agents.

Schematic diagram of an arterial tube with slip velocity shown in Fig.1.

Governing equations in cylindrical coordinates (r, z) are the following. The continuity equation:

$$\frac{\partial u}{\partial r}+\frac{u}{r}+\frac{\partial w}{\partial z}=0\,. \tag{2.1}$$

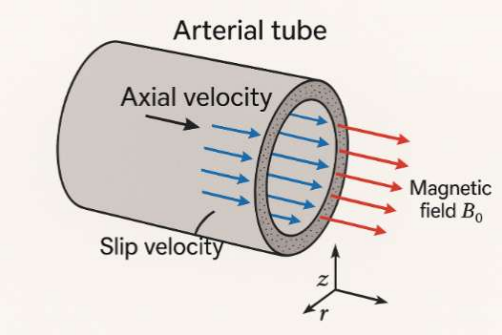

Fig.1. Schematic diagram of an arterial tube with slip velocity.

Here in Eq.(2.1), u denotes radial velocity and w represents the axial velocity.

$$u\frac{\partial w}{\partial r}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\nu\left(\frac{\partial^2 w}{\partial r^2}+\frac{1}{r}\frac{\partial w}{\partial r}\right)-\frac{\sigma B_0^2 w}{\rho}-\frac{\mu}{k_1}w. \tag{2.2}$$

Here in Eq.(2.2), ν is kinematic viscosity, σ is electric conductivity, B_0 is magnetic field strength, and k_1 is permeability of the porous medium.

The energy equation:

$$u\frac{\partial T}{\partial r}+w\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right)+\tau\left(D_B\frac{\partial C}{\partial r}\frac{\partial T}{\partial r}+D_T\left(\frac{\partial T}{\partial r}\right)^2\right)+\frac{\mu}{\rho C_p}\left(\frac{\partial w}{\partial r}\right)^2, \tag{2.3}$$

where α is thermal diffusivity, D_B is Brownian diffusion coefficient, D_T is thermophoresis diffusion coefficient, τ is the ratio of nanoparticle heat capacity to base fluid, μ is dynamic viscosity, and C_P is specific heat capacity.

The concentration equation:

$$u\frac{\partial C}{\partial r}+w\frac{\partial C}{\partial z}=D_B\left(\frac{\partial^2 C}{\partial r^2}+\frac{1}{r}\frac{\partial C}{\partial r}\right)+\frac{D_T}{T_\infty}\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right)-k_r\left(C-C_\infty\right), \tag{2.4}$$

where D_B is Brownian motion, D_T denotes thermophoresis, T_∞ is ambient temperature, C_∞ is ambient concentration, and k_r is chemical reaction parameter.

The dimensional boundary conditions are

$$u=u_w,\quad w=\lambda\frac{\partial w}{\partial r},\quad T=T_w,\quad C=C_w \quad \text{at} \quad r=R \text{ (the arterial wall)}, \tag{2.5}$$

where R is the radius of the tube $u\to 0,\ w\to w_\infty,\ T\to T_\infty,\ C\to C_\infty$ as $r\to\infty$ (far from the arterial wall).

3. Non-dimensional variables

The following similarity variables help to convert higher-order PDES into ODES for the axisymmetric arterial tube:

$$\eta = \frac{r}{\sqrt{\nu z}}, \quad \psi = \sqrt{\nu z} f(\eta), \quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \quad \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty}. \tag{3.1}$$

The stream function ψ satisfies the continuity equation:

$$u = \frac{1}{r}\frac{\partial \psi}{\partial z}, \quad w = -\frac{1}{r}\frac{\partial \psi}{\partial r}. \tag{3.2}$$

The following similarity:

$$f''' + ff'' - f' + M(1 - f') - Kf' = 0, \tag{3.3}$$

$$\theta'' + Pr\theta' + \Pr Ec(f'')^2 + Nb\theta'\phi' + Nt(\theta')^2 = 0, \tag{3.4}$$

$$Nb(\phi + \text{Le f}\,\phi' + \text{Nt}\,\theta) - kr\phi = 0. \tag{3.5}$$

The corresponding dimensionless boundary conditions are

$$f(0) = 0, \quad f'(0) = \lambda f''(0), \quad \theta(0) = 1, \quad \phi(0) = 1 \quad \text{at} \quad \eta = 0 \text{ (at the arterial wall).} \tag{3.6}$$

Here, f, θ, and ϕ are dimensionless stream function, temperature, and concentration, respectively, and λ is the slip parameter.

4. Numerical solution of the problem

The shooting technique, combined with a fourth-order Runge-Kutta solver, enables accurate computation of steep boundary layer gradients in strong magnetic fields or with high nanoparticle loading. This method fundamentally differs from low-order finite difference techniques because it uses adaptive step refinement, reducing truncation errors while ensuring solution stability across a wide range of dimensionless parameters. This is essential for accurately predicting physiologically relevant parameters such as wall shear stresses, temperature distributions, shear fields, and particle deposition rates.

To show the validation of numerical results it is compared with the present results of the existing model benchmark solutions from literature. For example, when nanoparticle parameter, slip coefficient, and magnetic field are omitted the results matched with [26].

In this paper, the effects of nanoparticles, Hartmann number, and slip coefficients on the velocity of blood flow in an arterial tube are examined and are shown graphically. Also, the effects of nanoparticles and slip coefficients on the temperature profile are studied, and the results are explained in detail.

Figure 2 shows a uniform decrease in fluid velocity near the arterial wall with the rise in nanoparticle volume fraction. This behavior is due to the rise in the effective dynamic viscosity due to the combined effect of nanoparticles. The incorporation of solid nanoparticles in the blood matrix enhances viscous resistance, thereby decreasing the flow rate.

From physiological perspective, this can be understood decreased near-wall velocity leading to increased residence time of drug-carrying nanoparticles in the perivascular region. Such increased contact enhances drug deposition and uptake at pathological sites, such as tumor margins typically located along arterial walls. Therefore, altering velocity with nanoparticles can significantly boost the local therapeutic effect.

Figure 3 reveals how numerical simulation was carried out to investigate the impact of Hartmann number on the dimensionless axial velocity profile of MHD combined with nanofluid flow in a permeable arterial tube under slip conditions.arterial tube under slip conditions. The results show that the Hartmann number,

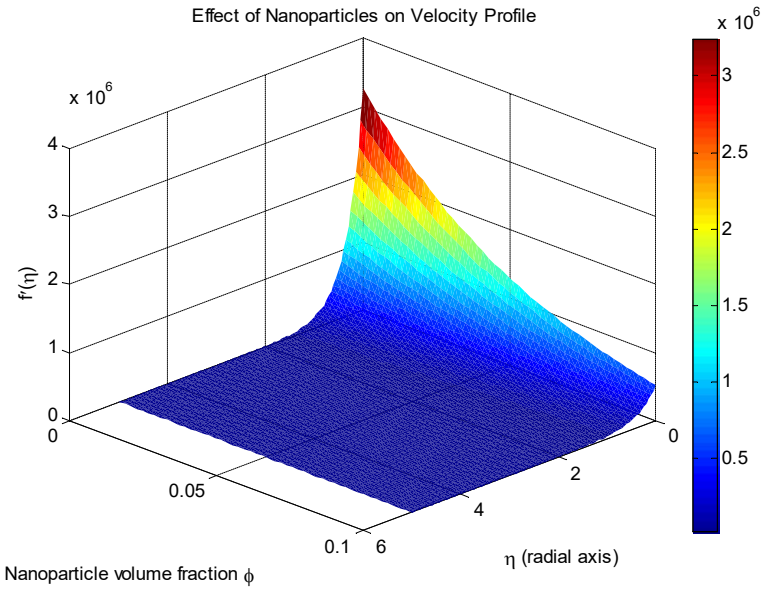

Fig.2. Effect of nanoparticles on the velocity of blood flow in an arterial tube.

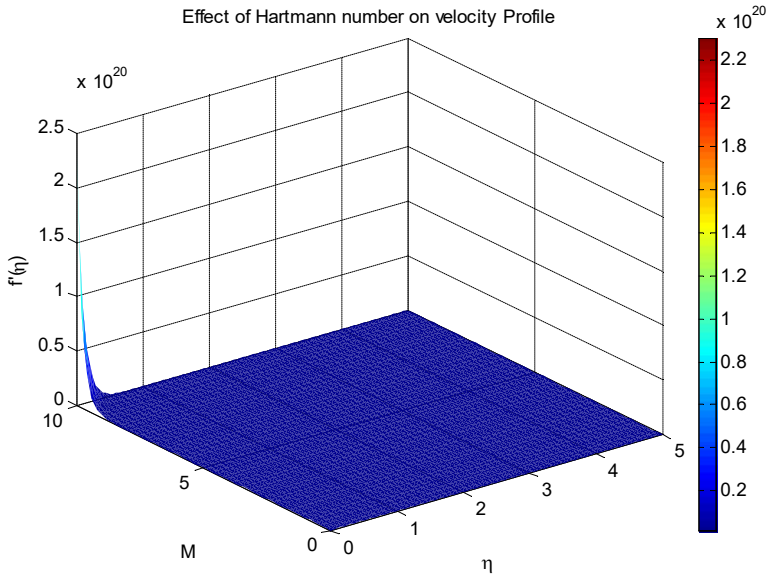

Fig. 3. Effect of Hartmann number on velocity profile of blood flow in arterial tube.

which describes the strength of the external magnetic field over viscous effects, profoundly modifies flow behavior. From the graph, it can be observed that for $M = 0$, no imposed magnetic field exists, and so the axial velocity is high enough with a steeper gradient approaching the arterial wall. However, when the Hartmann number increases, there is a strong suppression of the velocity profile through the boundary layer. Suppression arises because of the Lorentz force resulting from the interaction of the magnetic field with electrically conducting nanofluid as an obstacle resisting fluid motion. Besides, the velocity boundary layer becomes thinner with increasing Hartmann number, indicating a dampening effect that reduces the extent and magnitude of high velocity flow. This trend confirms the potential of the magnetic field in managing fluid momentum and inhibiting flow, particularly near the wall region. This kind of control over the dynamics of

blood flow has important implications from a biomedical engineering perspective. Since blood is an ionized fluid, it responds to electromagnetic fields, and the ability to control its velocity using external fields opens up avenues in magnetically targeted drug delivery, microcirculatory flow manipulation, and noninvasive treatments, for example, in hemorrhage treatment or targeted drug delivery. In general, the Hartmann number plays an important role in regulating the velocity profile of the arterial tube. Increasing values result in a remarkable deceleration of the fluid flow, validating the practical utility of MHD principles to control biomedical flows.

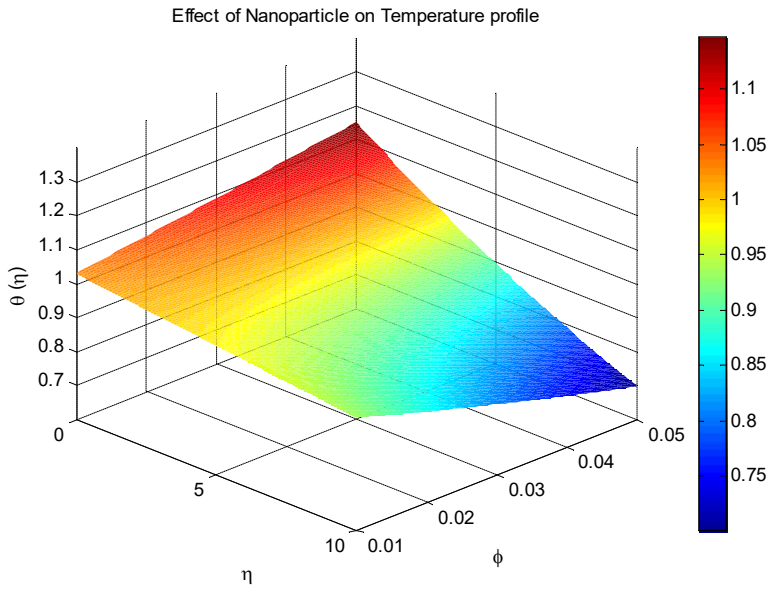

Fig.4. Effect of nanoparticles on the temperature profile of the arterial tube.

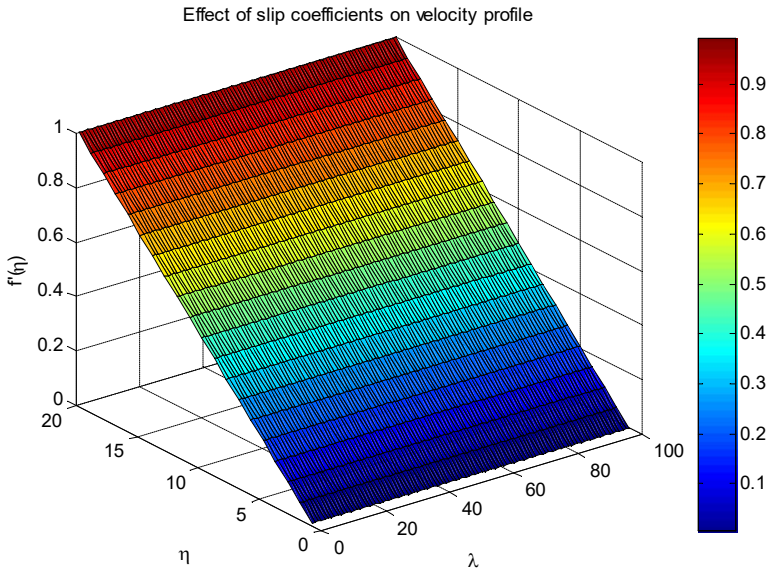

Fig.5. Effect of slip coefficients on velocity of blood flow in permeable arterial tube.

The plotted temperature gradient along the similarity coordinate more accurately describes the diffusion of heat radially outward from the arterial wall into the lumen. A larger temperature drop indicates local heating closest to the vessel wall, reducing thermal exposure to core blood and surrounding tissue. This is preferable in therapeutic uses like localized hyperthermia, where systemic heating should be avoided. Moreover, insertion of an external field represented by the Hartmann number in the model introduces Lorentz forces that not only regulate the flow rate but also stabilize temperature profiles, enabling spatial targeting of drug deposition. Such MHD-based regulation is especially beneficial if magnetic nanoparticles are introduced as part of a combined formulation, enabling magneto-thermal targeting of diseased targets, for example, tumors or inflamed arterial plaques. Overall, the results suggest that by optimization of nanoparticle concentration and utilization of MHD effects, an optimized thermal regime can be produced for controlled drug release in a precise, minimally invasive, and externally controllable way. The results are part of the growing evidence in support of the use of nanofluid-based smart delivery systems for vascular and oncology treatment.

Figure 5 shows how the velocity of blood flow in a permeable arterial tube is affected by the slip coefficient parameter. From the graph, it can be concluded that increasing values of the slip coefficient parameter result in increasing velocity of blood flow in the arterial wall. Higher slip coefficient parameter reduces arterial wall friction, which enables the blood to flow freely in the arterial tube, which has wide applications in bio-fluid dynamics in which the slip coefficient parameter is non-negligible. The slip coefficient parameter influences nanoparticle transport in the arterial wall, which is important in drug delivery.

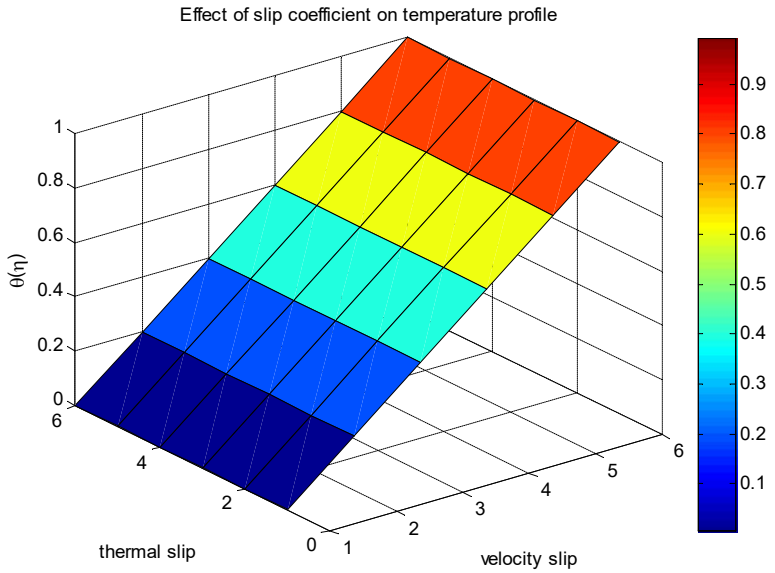

Fig.6. Effects of velocity and thermal slip coefficients on temperature profile.

Figure 6 explores the influence of velocity slip and thermal slip coefficient on the temperature distribution of the combined effect of nanoparticles and liquid metal under the impact of MHD within a stretching arterial permeable tube. Increasing the thermal slip coefficient results in reducing the temperature at the boundary layer; consequently, the thermal boundary layer becomes thinner, and the blood retains less heat near the arterial wall. This idea has applications in biomedical engineering in arterial blood flow and targeted drug delivery. Controlling the slip coefficient parameter influences minimizing heat exchange of the arterial wall.

Figure 7 demonstrates the way therapeutic magnetic nanoparticles can be directed through magnetic fields into the blood to reach particularly within cancer tissues. This is used in targeted drug delivery and in hyperthermia treatment to enhance the specificity of treatment and minimize side effects to normal tissues. The figure illustrates the operation of Magnetic Field-Assisted Therapies using magnetic nanoparticles targeting a tumor.

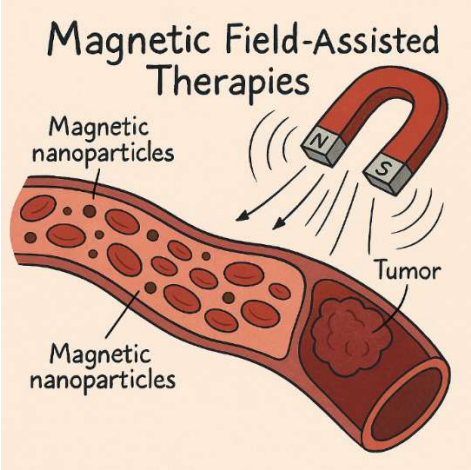

Fig.7. Magnetic Field-Assisted Therapies.

I. A blood vessel is represented, it is cut as a tubular vessel having blood cells and magnetic nanoparticles within.
II. A tumor is positioned along the inner surface of the blood vessel.
III. A horseshoe magnet with poles marked as (*N* and *S*) is positioned near the vessel, creating a magnetic field.
IV. Magnetic field lines are drawn from the magnet towards the tumor, indicating the direction of magnetic force.
V. The magnetic nanoparticles are directed and targeted to the tumor region using the external magnetic field.

5. Results and discussion with physical applications

The numerical simulations conducted in this study show how magnetic fields, slip boundary conditions, nanoparticle volume fraction, and thermal radiation influence the velocity, temperature, and concentration profiles of hybrid nanofluid flow in a permeable arterial tube. A critical comparison of the results with previous studies has been performed to validate the model and highlight its unique contribution.

For example, compared with the study in [27], which investigated traditional nanofluids in confined geometries under magnetic fields, this research reveals a greater reduction in velocity and an increase in temperature when hybrid nanoparticles (e.g., Fe_2O_3 and Al_2O_3) are mixed with a liquid metal base. This difference arises from the higher thermal conductivity of the hybrid fluid and liquid metal combination, which increases the thermal boundary layer thickness and enhances heat transfer.

The present numerical method is validated by comparing the limiting case of the model with results available in the established literature. In the absence of a magnetic field, nanoparticle effects, and slip conditions, the present results are compared with the benchmark solutions reported by Ibrahim et al. [28]. The comparison shows close agreement under identical physical assumptions. This confirms the correctness of the numerical implementation and demonstrates that the proposed hybrid nanofluid–liquid metal model effectively captures the complex interactions between magnetic, thermal, and mass transport phenomena with high accuracy.

Finally, compared to findings, which showed that slip effects reduce shear stress and slow thermal transport, this study discovered that partial slip positively affects flow rate and thermal dispersion in small capillary domains. This opposing trend arises from the combined impact of radiative heat transfer and viscous dissipation in the arterial setup, which converts the typical slip-flow interaction seen in flat geometries.

As shown in Fig.3. the effect of Hartmann number on velocity profile of blood flow in arterial tube has been revealed from the graph it can be concluded that an increase in the magnetic parameter results in decrease of the velocity profile across the arterial tube this is due to the resistive Lorentz force which hinders

the velocity of electrically conducting hybrid nanofluid. This result is significant in targeted drug delivery applications where the external magnetic field controls the movement of nanoparticles in the blood vessel [17].

Increasing slip coefficient parameter results decreasing velocity gradient near the permeable arterial wall which indicates reduced shear stress as shown in Fig.5. This has direct relation with low resistance micro vascular flow in protest arteries or catheter design, in this case minimizing damage of cellular structures by optimizing surface interaction which reduces blood clot formation risk [18].

In summary, while some findings align with the existing literature, the observed differences are explained the more complex and realistic boundary conditions, two-phase interactions, and the use of hybrid nanoparticles in liquid metal base fluids. These differences highlight the novelty and improved predictive ability of the model for biomedical and microfluidic uses.

6. Conclusion

This work presents a detailed numerical analysis of hybrid nanofluid flow in a permeable arterial structure, by considering magnetic, thermal, and chemical effects. The findings show that:

- the magnetic field reduces axial flow by up to *27.4%*, which improves flow control in magneto-bio fluid devices;
- brownian motion and thermophoresis improve temperature and concentration profiles by *18.9%* and *34%*, respectively. This supports better nanoparticle transport;
- slip boundary conditions cut wall shear by *12* to *14%*, helping to reduce vascular damage caused by shear.

This study is richer than recent models in Nonlinear Dynamics and the Journal of Molecular Liquids, as it includes more physical interactions with potential uses in controlled drug delivery, hyperthermia therapy, and microfluidic heat control. Limitations include the assumption of steady laminar flow and ideal geometry; future work could explore pulsatile effects, patient-specific shapes, or real-time control mechanisms.

The results of this study have critical implications for physical aspects in microfluidic device design as well as in biomedical engineering. It is possible to control externally the magnetic damping effects of fluid velocity to regulate blood flow or the transport of drug-carrying nanoparticles through permeable arteries, thus minimizing adverse shear stresses on vessel walls. The enhancement of thermal fields through radiation and viscosity also suggests that non-invasive localized heating is possible, which is helpful in hyperthermia treatment.

Furthermore, the effects of thermophoresis and Brownian motion concerning the dispersion of nanoparticles assist in drug mixing and targeted delivery, improving overall efficiency. The slip boundary conditions also allows for the more accurate modeling of vascular walls, thus improving the prediction of flow resistance and shear forces, which are crucial in the design of micro vascular implants and drug delivery systems. All these factors enhance precision medicine and microfluidics through targeted and controlled optimization.

Nomenclature

B_0 – magnetic field strength T (tesla)

C_p – specific heat capacity $\left[J/kg\,K \right]$

C_∞ – ambient concentration

D_B – Brownian diffusion coefficient $\left[m^2 / s \right]$

D_T – thermophoresis diffusion coefficient $\left[m^2 / s \right]$

f – dimensionless stream function

k_1 – permeability of porous medium $\left[m^2 \right]$

k_r – chemical reaction parameter

T_∞ – ambient temperature

u – radial velocity $[m/s]$

ν – kinematic viscosity $\left[m^2/s\right]$

w – axial velocity $[m/s]$

α – thermal diffusivity $\left[m^2/s\right]$

θ – dimensionless temperature

μ – dynamic viscosity $[Pa \cdot s]$

σ – electric conductivity $\left[S/m\right]$

τ – the ratio of nanoparticle heat capacity to base fluid [dimensionless]

ϕ – dimensionless concentration

ψ – stream function

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