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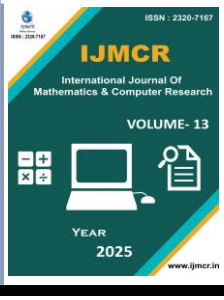

The Study of Hemodynamic Properties of Blood in the Presence of Gold (Au) Nanoparticles

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ABSTRACT

The present study investigates the behavior of blood flow in a stenosed human artery in the presence of gold (Au) nanoparticles (NPs). The governing equations describing the hemodynamic flow characteristics are discretized using a finite difference scheme to ensure accurate numerical representation of the system. These discretized equations are subsequently solved and simulated using MATLAB software to analyze the flow dynamics. The study focuses on evaluating key hemodynamic parameters, including axial velocity profiles, volumetric flow rate, and resistive impedance, both in the absence and presence of gold nanoparticles. The inclusion of Au nanoparticles is observed to cause notable alterations in these parameters, indicating a reduction in flow resistance and enhancement in flow uniformity. Such improvements suggest that nanoparticle-assisted blood flow modulation could play a beneficial role in developing advanced therapeutic strategies for cardiovascular diseases and the management of arterial stenosis.

KEYWORDS: Gold nanoparticles, Finite difference, Simulation.

INTRODUCTION

Cardiovascular diseases continue to rank among the leading causes of morbidity and mortality worldwide, posing a significant global health challenge. A major underlying factor contributing to these conditions is arterial stenosis — the abnormal narrowing of an artery — which disrupts the normal flow of blood and substantially increases vascular resistance. This alteration in flow dynamics can lead to reduced oxygen transport, elevated shear stress on arterial walls, and the progression of atherosclerotic plaque formation. Consequently, a detailed understanding of blood flow behavior within stenosed arteries is essential for improving diagnostic accuracy, optimizing treatment planning, and designing effective biomedical interventions for cardiovascular disorders.

In recent years, nanotechnology has emerged as a transformative field within biomedical engineering, offering innovative strategies for enhancing therapeutic efficiency, targeted drug delivery, molecular imaging, and the regulation of blood flow dynamics at the microscale. Over the past two decades, extensive research has been devoted to characterizing the hemodynamic behavior of blood in stenosed arterial geometries, driven by the need to elucidate how flow disturbances influence disease progression. Early studies employed simplified analytical and numerical models, treating blood either as a Newtonian or a non-Newtonian fluid to replicate essential flow mechanisms within constricted vessels [1], [2]. These foundational works established that key geometric parameters—such as the shape, degree, and location of stenosis—as well as flow pulsatility, significantly impact velocity distribution, wall shear stress, and pressure gradients, all of which are closely linked to endothelial dysfunction and arterial remodeling [3]. With the advent of computational fluid dynamics (CFD), more sophisticated and high-fidelity numerical frameworks have been developed to simulate these complex hemodynamic environments. Techniques such as the finite difference method (FDM), finite element method (FEM), and lattice Boltzmann method (LBM) have been widely applied to predict blood flow patterns within stenosed arteries, capturing transient flow behaviors with high spatial and temporal resolution [4], [5]. These advanced computational approaches have paved the way for integrating multiphysics effects, including nanoparticle interactions, magnetic fields, and thermal gradients, thereby offering a more comprehensive understanding of the biomechanical and therapeutic aspects of arterial flow under pathological conditions.

In recent years, the convergence of nanotechnology and biomedical fluid mechanics has opened new directions for enhancing therapeutic efficacy and precision drug delivery within the vascular system. Studies on nanofluid-based blood flow have demonstrated that the introduction of nanoparticles into the bloodstream can substantially modify its rheological properties, resulting in improved flow uniformity and a marked reduction in hydraulic resistance through stenosed regions [6]; [7]. Metallic nanoparticles, particularly gold (Au) and silver (Ag), have drawn significant attention due to their superior biocompatibility, stability, surface plasmon resonance, and tunable optical properties, which make them suitable for diagnostic and therapeutic biomedical applications [8]; [9]. Moreover, Investigations by [10] demonstrated that the incorporation of nanoparticles significantly modifies the effective viscosity, density, and thermal conductivity of blood, thereby influencing both momentum and energy transport mechanisms and ultimately enhancing hemodynamic performance.

Subsequent numerical studies have explored nanofluid flow through stenosed arteries containing hybrid nanoparticles such as Cu–Al_2O_3, Fe_3O_4–Au, and TiO_2–Ag, reporting notable improvements in velocity profiles, pressure recovery, and reduction in flow impedance [11], [12]. Furthermore, the integration of biocompatible nanoparticles into blood flow models has been examined for various biomedical applications, including targeted drug delivery, hyperthermia-induced therapy, and magnetically guided transport of therapeutic agents within diseased arterial regions [13], [14]. Collectively, these studies emphasize that nanoparticle-enhanced hemodynamic models not only provide a more comprehensive understanding of flow alterations caused by arterial constriction but also establish a promising foundation for optimizing therapeutic interventions and advancing vascular health management through nanotechnology-based approaches.

Among various metallic nanoparticles, gold (Au) nanoparticles have attracted considerable attention owing to their exceptional biocompatibility, chemical inertness, and facile surface functionalization. When dispersed in the bloodstream, these nanoparticles can modify the rheological characteristics of blood, thereby influencing its flow behavior, particularly within stenosed arterial segments. Understanding the extent to which gold nanoparticles affect critical hemodynamic parameters—such as velocity distribution, volumetric flow rate, and flow impedance—offers significant insights into their biomedical potential. In the present study, the governing equations describing blood flow through a stenosed artery are formulated and discretized using the finite difference method. Numerical simulations are subsequently conducted in MATLAB to examine the influence of gold nanoparticles on flow characteristics. By systematically comparing results with and without nanoparticle inclusion, the study elucidates the impact of Au nanoparticles on blood flow dynamics. The findings contribute to the growing body of research on nanoparticle-assisted cardiovascular therapy and may facilitate the design of advanced treatment strategies for enhancing blood circulation in narrowed arteries.

Governing Equations:

The stenosed arterial section shown in Figure 1 is represented as a cylindrical tube through which a Newtonian fluid flows, serving as an idealized model for blood movement within the artery. The geometric configuration of the stenosis (narrowed region) is also illustrated in the same figure to depict the extent and shape of the constriction. The flow within this segment is considered to be laminar, unsteady, two-dimensional, and axisymmetric, providing a realistic yet computationally manageable framework for analyzing hemodynamic behavior. The mathematical formulation of the problem is established based on the fundamental conservation principles of mass, momentum, and energy, which collectively govern the dynamics of blood flow and heat transfer within the stenosed arterial domain [15]

$$\frac{\partial u}{\partial r}+\frac{u}{r}+\frac{\partial w}{\partial z}=0 \qquad (1)$$

$$\rho_{nf}\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial r}+\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}-\frac{u^2}{r^2}+\frac{\partial^2 u}{\partial z^2}\right) \qquad (2)$$

$$\rho_{nf}\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial r}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu_{nf}\left(\frac{\partial^2 w}{\partial r^2}+\frac{1}{r}\frac{\partial w}{\partial r}+\frac{\partial^2 w}{\partial z^2}\right)+g(\rho\gamma)_{nf}(T-T_1) \qquad (3)$$

$$\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial r}+w\frac{\partial T}{\partial z}\right)=\left(\frac{k_{nf}}{(\rho C_p)_{nf}}\right)\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right)+\frac{Q_0}{(\rho C_p)_{nf}} \qquad (4)$$

Where u and w are radial and axial velocities respectively. μ_{nf}, ρ_{nf}, k_{nf} and γ_{nf} are viscosity, density, thermal conductivity, coefficient of thermal expansion of nanofluids. T is temperature of fluid, Q_0 is constant of heat absorption or heat generation.

The dynamic viscosity μ_{nf} of the nanofluid is given by [16],

$\mu_{nf}=\frac{\mu_f}{(1-\emptyset)^{2.5}}$.

The Stenosis Geometry:

The stenosis geometry is time dependent. Multiple stenosis regions are overlapped. It is described from [17] by

$$R(z,t) = a\{1 - a_1(t)\frac{\tau_m}{5005\, a\, {l_0}^6}\left[\frac{668662}{9}(z-d)\,{l_0}^5 - 370281(z-d)^2\,{l_0}^4 + 743344(z-d)^3\,{l_0}^3 - 698476(z-d)^4\,{l_0}^2 + 307584(z-d)^5 l_0 - 51264(z-d)^6\right]\}$$

$\ldots\ldots d < z < d + 2l_0$

$= aa_1(t)$ ……Otherwise

Where $a_1(t) = 1 - cos\, cos\,(\omega t - 1)\,\beta e^{\beta\omega t}$ in which ω is angular frequency and β is the constant parameter.

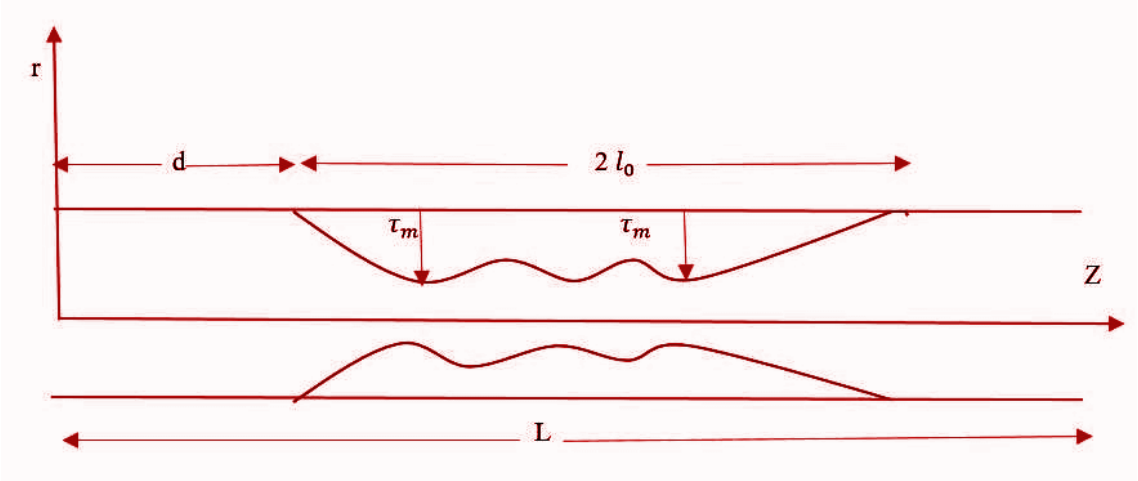

Figure. 1. The Stenosis Geometry in an Artery

The thermal conductivity (k_{nf}),coefficient of thermal expansion (γ_{nf}) and density (ρ_{nf}) of nanofluids is given by [18]

$k_{nf} = k_f\left[\frac{2k_f + k_s - 2\phi(k_f - k_s)}{2k_f + k_s + \phi(k_f - k_s)}\right]$.

$$\gamma_{nf} = (1-\phi)\gamma_f + \rho\gamma_s$$
$$\rho_{nf} = (1-\phi)\rho_f + \rho_s\phi$$

Where ϕ is the concentration of nanoparticles, k_s, ρ_s and γ_s are thermal conductivity, density and coefficient of thermal expansion of nanoparticles.

Table 1. Physical Values of Blood and Nanoparticle are given by [19]

Parameters	Blood	Gold (Au)
C_p(J/Kg.K)	3594	128.8
ρ (Kg/m^3)	1063	19320
γ (1/K)	0.18	1.4×10^{-5}
K (W/m.K)	0.492	314.4

Boundary conditions:

The velocities at the inlet and outlet of an arterial segment of finite length are taken as [20] and [15]

$u(r,z,t) = 0$ and $w(r,z,t) = \frac{5}{3}\left(1 - \left(\frac{r}{R(z,t)}\right)^3\right)$ at z = 0 (5)

$\frac{\partial w(r,z,t)}{\partial z} = 0 = \frac{\partial u(r,z,t)}{\partial z}$ at z = L (6)

It is presumed that both radial and axial velocities are initially zero. This means that when the system is at rest, there is no flow through the artery.

$u(r,z,0) = 0, w(r,z,0) = 0, T(r,z,0) = 0$ (7)

Axially, there is an absence of radial flow, leading to a radial velocity of zero. The gradients of axial velocity, blood temperature, and temperature gradient can be considered to be zero. This can be expressed as

$\frac{\partial w}{\partial r} = 0$, $u(r,z,t) = 0$, $\frac{\partial T}{\partial r} = 0$ on r = 0 (8)

At the artery wall, the axial velocity is zero, following the no-slip condition. The fluid temperature is zero, and the radial velocity corresponds to the rate of change in the shape of the stenosis. This relationship can be expressed as

$$w(r,z,t) = 0, u(r,z,t) = \frac{\partial R}{\partial t}, T(r,z,t) = 0 \text{ on } r = R(z,t) \quad (9)$$

RESULTS AND DISCUSSION

The governing equations governing nanofluid motion are discretized using finite difference schemes, which transform the coupled partial differential equations into a set of algebraic expressions that can be efficiently solved using numerical computation. This discretization enables the approximation of spatial and temporal derivatives with high accuracy, facilitating stable and precise simulations of complex flow behavior. The resulting algebraic system is implemented and solved in MATLAB, a robust computational platform that efficiently manages large-scale numerical data and performs iterative solutions with superior precision and convergence reliability.

Figure 2 presents the radial variation of axial velocity, illustrating a pronounced enhancement in velocity magnitude upon the introduction of gold (Au) nanoparticles into the blood flow. This behavior is primarily attributed to the altered rheological characteristics of the blood–nanoparticle suspension. The inclusion of nanoparticles reduces the effective viscosity of the fluid and enhances its shear-thinning response, thereby promoting smoother and more uniform flow through the stenosed arterial region. Additionally, the nanoparticles help diminish boundary layer resistance, further accelerating flow along the central axis and improving overall hemodynamic efficiency.

Figure 3 depicts the axial variation of the axial velocity along the arterial length, reflecting how the flow profile evolves in accordance with the geometry of the stenosis. A noticeable increase in axial velocity is observed in nanoparticle-laden regions, indicating improved momentum transfer and more streamlined flow behavior. The presence of Au nanoparticles thus contributes to mitigating flow separation and disturbances typically induced by arterial constriction, enhancing the continuity and steadiness of blood movement through the narrowed passage.

Furthermore, Figures 4 and 5 illustrate the axial distributions of flow rate and flow impedance, respectively. The results demonstrate a substantial increase in volumetric flow rate accompanied by a marked reduction in resistive impedance when gold nanoparticles are incorporated into the fluid. This inverse relationship underscores the capability of metallic nanoparticles to minimize hydrodynamic resistance and optimize flow conditions within stenosed arteries. Collectively, these findings emphasize the promising role of nanofluid-based modifications in improving circulatory performance and suggest potential biomedical applications for alleviating the adverse effects of arterial stenosis through nanoparticle-enhanced blood flow regulation.

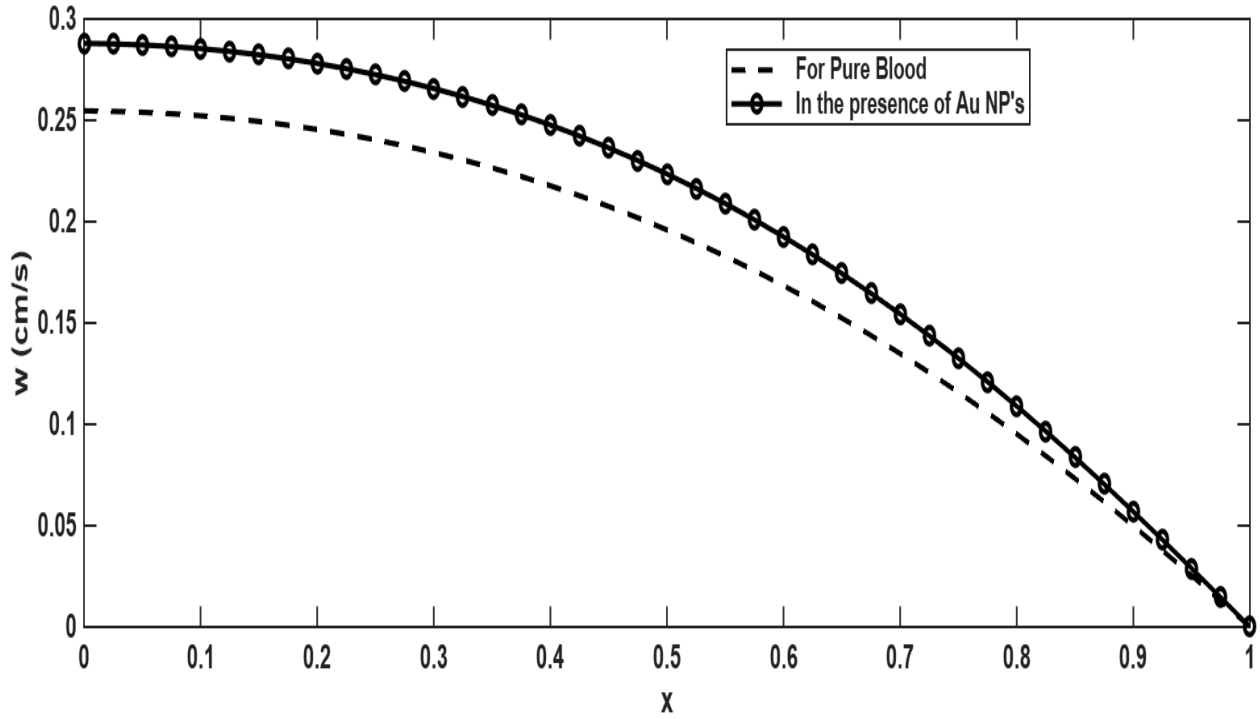

Figure 2. Radial variation of Axial Velocity

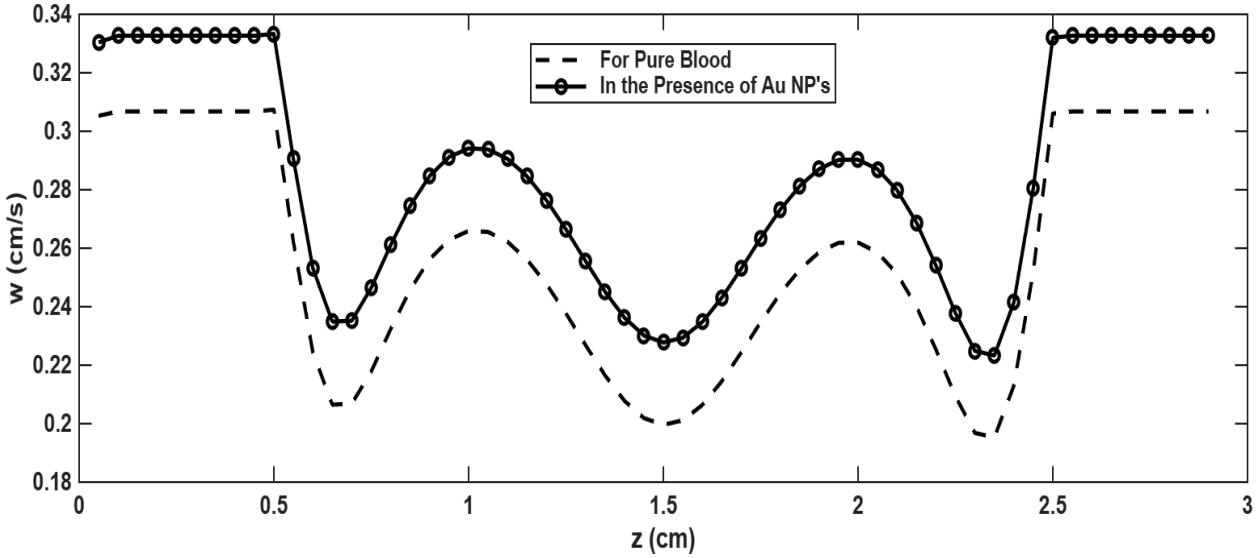

Figure 3. Axial Variation of Axial Velocity

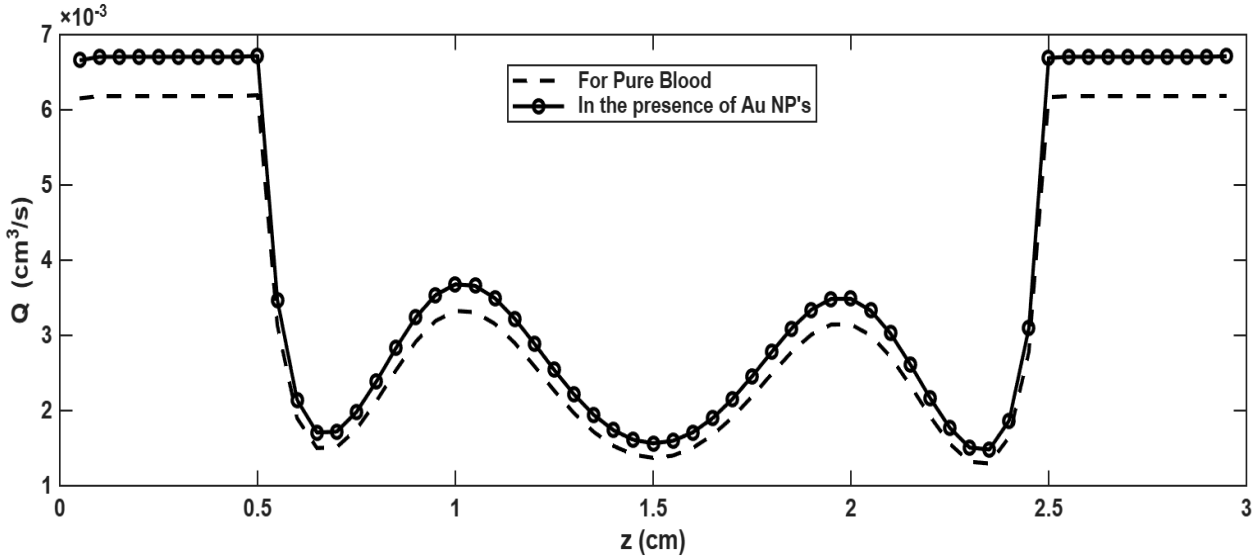

Figure 4. Flow rate along the axial direction

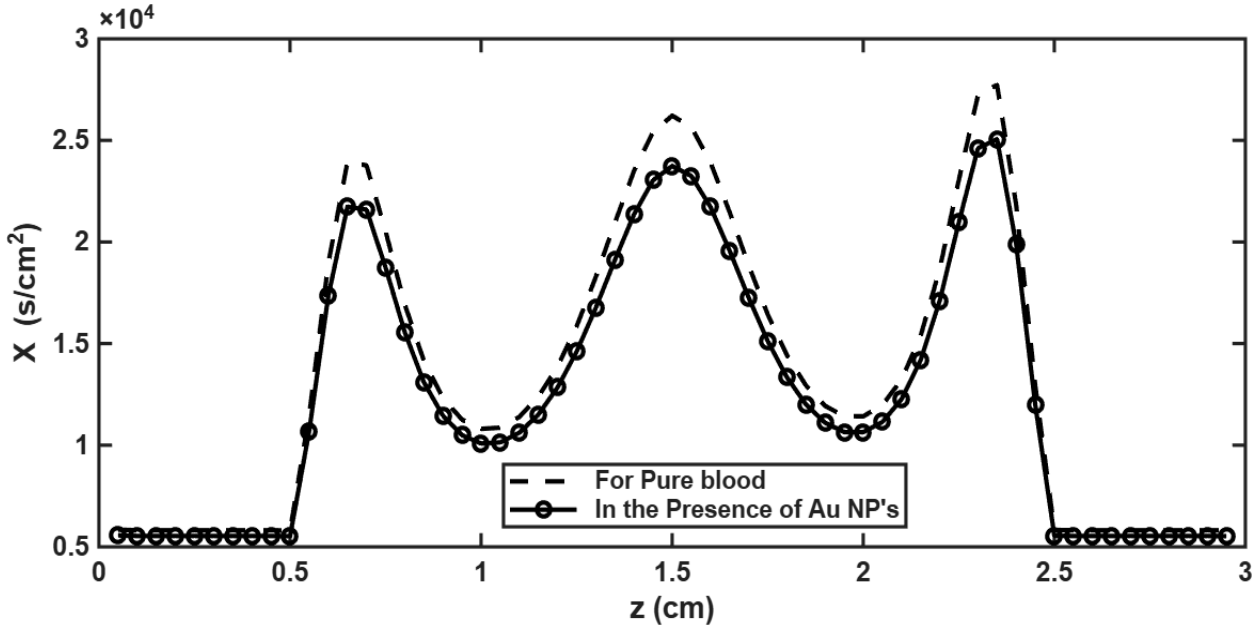

Figure 5. Impedance to flow along the axial direction

CONCLUSION

In conclusion, the present study delivers a comprehensive computational analysis of blood flow behavior through a stenosed arterial segment, idealized as a cylindrical conduit conveying a Newtonian fluid. By incorporating the geometric characteristics of the stenosis, the model effectively captures the influence of arterial constriction on fundamental flow parameters, including velocity distribution, volumetric flow rate, and flow impedance. The assumptions of laminar, unsteady, two-dimensional, and axisymmetric flow strike an optimal balance between physical accuracy and computational tractability, enabling a detailed assessment of the complex hemodynamic responses within narrowed arterial regions.

The governing equations, derived from the fundamental conservation laws of mass, momentum, and energy, were discretized using finite difference techniques and numerically implemented in MATLAB. The simulation results demonstrate that the introduction of gold (Au) nanoparticles significantly alters the rheological and dynamic characteristics of blood. The presence of nanoparticles enhances axial velocity and volumetric flow rate while reducing resistive impedance, collectively indicating improved flow performance within the stenosed domain. These improvements can be attributed to the decreased effective viscosity and enhanced shear-thinning behavior of the blood–nanoparticle suspension, leading to smoother and more stable flow patterns.

Overall, this research highlights the potential of nanoparticle-augmented hemodynamic modeling as a powerful approach for understanding and mitigating the detrimental effects of arterial stenosis. The integration of biocompatible metallic nanoparticles, such as Au, offers promising prospects for enhancing blood flow uniformity, optimizing oxygen transport, and improving targeted drug delivery efficiency in cardiovascular treatments. Moreover, the developed computational framework lays the foundation for future extensions that could incorporate non-Newtonian blood models, pulsatile pressure variations, and external magnetic or thermal influences—thereby providing a versatile and predictive tool for biomedical research, clinical diagnosis, and therapeutic design in arterial disease management.

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