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Blood Flow Through Stenosed Arteries in the Presence of Silica (SiO_2) Nano Particles

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Abstract

The numerical investigation of blood flow through stenosed human arteries in the presence of Silica (SiO_2) nanoparticles (NPs) is carried out. The governing equations are discretized using the finite difference method, and the simulations are performed in MATLAB. The study focuses on analyzing the influence of Silica (SiO_2) nanoparticles on velocity distribution, volumetric flow rate, and resistive impedance. Results indicate that the inclusion of nanoparticles significantly alters these hemodynamic parameters, with a marked impact on velocity, flow rate, and impedance.

Keywords: Silica; Simulation; Finite difference scheme.

1. Introduction

Cardiovascular diseases remain one of the leading causes of mortality worldwide, with arterial stenosis serving as a major contributing factor. Stenosis refers to the narrowing of arteries due to deposition of fatty material, which disturbs normal blood circulation and increases vascular resistance, often resulting in severe clinical complications such as ischemia, hypertension, and myocardial infarction. A clear understanding of the hemodynamics of blood flow in stenosed arteries is therefore essential for accurate diagnosis and effective therapeutic interventions.

Nanotechnology has recently opened new avenues for enhancing blood flow behavior and enabling targeted drug delivery in stenosed arteries. Among the wide range of nanomaterials, Silica (SiO_2) nanoparticles (NPs) have gained attention due to their biocompatibility, chemical stability, tunable surface properties, and ease of functionalization. When introduced into the bloodstream, nanoparticles can alter the rheological properties of blood, thereby affecting velocity distribution, flow rate, and vascular impedance.

Previous studies have examined various nanoparticles for biomedical and hemodynamic applications. Gold and silver nanoparticles have been explored for their unique optical properties, particularly in

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targeted drug delivery and medical imaging. Magnetic nanoparticles have been widely investigated for controlled drug release and their impact on flow characteristics under external magnetic fields. Hybrid nanoparticles such as Cu–Ag and ZnO have also demonstrated the ability to modify blood flow resistance and improve therapeutic efficacy. Despite these advancements, comparatively limited attention has been directed toward Silica (SiO_2) nanoparticles, even though they are widely applied in drug delivery, biosensing, and tissue engineering. This highlights a research gap in exploring their direct influence on blood flow dynamics in stenosed arteries.

Mathematical and computational modeling provides a powerful tool for analyzing these complex interactions under pathological conditions. Numerical techniques such as the finite difference method offer reliable solutions for simulating blood flow through stenosed geometries, while MATLAB provides a robust computational platform for implementing such simulations. Recent research trends show increasing incorporation of nanoparticles into blood flow models, particularly due to their potential in therapeutic applications. Hybrid and metallic nanoparticles such as copper, alumina, and gold have been studied extensively for their effects on velocity, pressure drop, and flow resistance in stenosed arteries [1–3]. Silica (SiO_2) nanoparticles are of particular interest because of their strong biocompatibility and established applications in cardiovascular therapy and drug delivery [4]. Furthermore, their role in modifying blood rheology and enhancing drug transport efficiency within stenosed arteries has been reported in recent studies [5,6]. Computational fluid dynamics (CFD) has been widely applied in this context, providing valuable insight into blood flow alterations caused by stenosis [7].

However, only a few investigations have focused specifically on the influence of SiO2 nanoparticles on key hemodynamic parameters such as axial velocity, flow rate, and resistive impedance. Most existing studies emphasize hybrid nanofluids or generalized nanoparticle models, without isolating the distinct effects of SiO2 nanoparticles [1,8]. The study of [9] emphasizes magnetic drug delivery through tapered stenosed arteries, considering converging, diverging, and non-tapered geometries. The research of [10] examined the influence of metallic nanoparticles on blood flow velocity and flow resistance in arteries containing both stenosis and aneurysm. [11] analyzed the effect of copper nanoparticles on blood flow through a composite stenosed artery with permeable walls, where blood was mathematically modeled as a viscous nanofluid.

To address this gap, the present study simulates blood flow through a stenosed human artery in the presence of SiO2 nanoparticles using a finite difference framework in MATLAB. The work emphasizes the effects of nanoparticles on velocity distribution, flow rate, and resistive impedance, thereby highlighting their potential in modifying blood flow dynamics under stenotic conditions.

2. Governing Equations

The stenosed arterial segment illustrated in Figure 1 is modeled as a cylindrical tube carrying a Newtonian fluid to represent blood flow. The stenosis geometry is depicted in the same figure. The flow is assumed to be laminar, unsteady, two-dimensional, and axisymmetric. The mathematical formulation of the model is derived from the conservation laws of mass, momentum, and energy [12]

$$\frac{\partial u}{\partial r}+\frac{u}{r}+\frac{\partial w}{\partial z}=0 \tag{1}$$

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

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

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

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 [10],

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

3. The Stenosis Geometry

The stenosis geometry is time dependent. Multiple stenosis regions are overlapped. It is described from [13] by

$$\begin{aligned}R(z,t) &= a\{1-\}a_1(t)\frac{\tau_m}{5005al_0{}^6}\left[\frac{668662}{9}(z-d)l_0{}^5-370281(z-d)^2l_0{}^4+743344(z-d)^3l_0{}^3\right.\\ &\left.-698476(z-d)^4l_0{}^2+307584(z-d)^5l_0-51264(z-d)^6\right] \quad \ldots \quad d<z<d+2l_0\\ &= aa_1(t) \quad \ldots \quad \text{Otherwise}\end{aligned}$$

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.

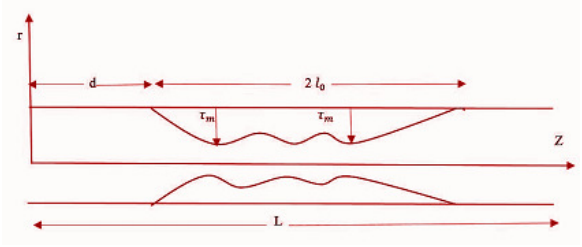

Figure 1: The Stenosis Geometry in an Artery

The thermal conductivity (k_{nf}),coefficient of thermal expansion (γ_{nf}) and density (ρ_{nf}) of nanofluids is given by [11]

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

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

$$\rho_{nf} = (1-\phi)\,\rho_f + \rho_s\phi$$

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.

Parameters	Blood	SiO_2
$C_p(J/Kg.K)$	3594	730
$\rho(Kg/m^3)$	1063	2650
$\gamma(1/K)$	0.18	0.06×10^{-5}
$K(W/m.K)$	0.492	1.5

Table 1: Physical Values of Blood and Nanoparticle are given by [12,14]

4. Boundary Conditions

The velocities at the inlet and outlet of an arterial segment of finite length are taken as [11,12]

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

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

It is assumed that initially radial and axial velocity both are zero. That is when system is at rest there is no flow through artery that is

$$u\,(r,z,0) = 0,\; w\,(r,z,0) = 0,\; T(r,z,0) = 0 \tag{7}$$

Axially, there is no radial flow, therefore the radial velocity is zero, the axial velocity gradient of the blood and temperature gradient may be assumed to be equal to zero. This may be stated as

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

On the artery wall the axial velocity is zero due to no slip condition, temperature of the fluid is zero and radial velocity is rate of change in shape of the stenosis, which can be written as

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

5. Results and Discussion

The governing equations are discretized using finite difference schemes, and the resulting system is solved with the aid of MATLAB software. Figure 2 presents the radial variation of axial velocity, where an increase in velocity is observed in the presence of silica nanoparticles. This behavior is associated with the altered rheological characteristics of the blood-nanoparticle mixture, which promote smoother flow through the narrowed region. Figure 3 illustrates the axial variation of axial velocity, which follows the profile of the stenosis and shows enhancement with nanoparticle inclusion. Figures 4 and 5 depict the axial distributions of flow rate and flow impedance, respectively. The results indicate that the presence of silica nanoparticles leads to an increase in flow rate and a reduction in resistive impedance.

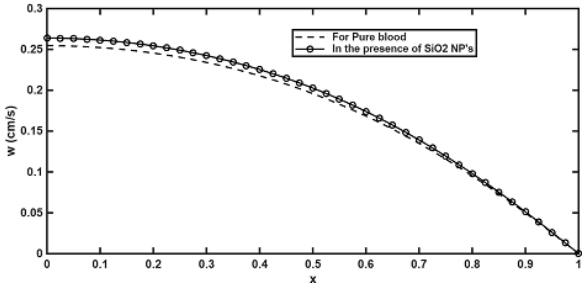

Figure 2: Radial variation of Axial Velocity

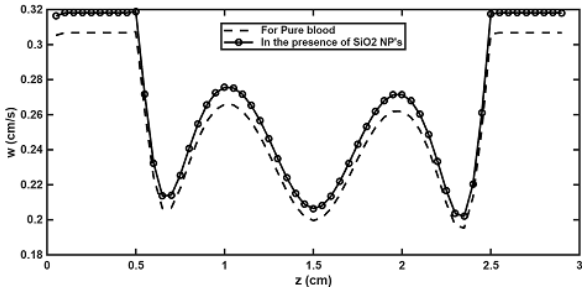

Figure 3: Axial Variation of Axial Velocity

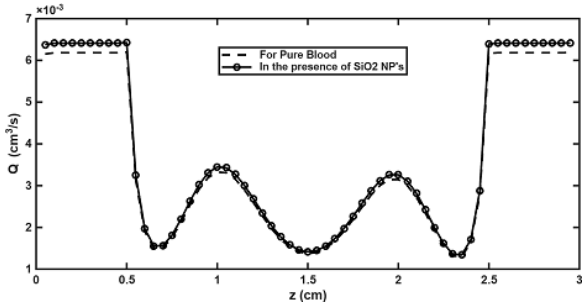

Figure 4: Flow rate along the axial direction

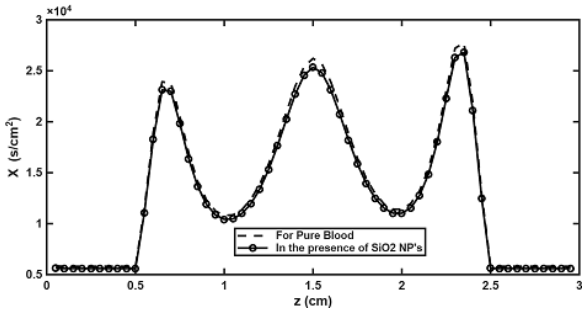

Figure 5: Impedance to flow along the axial direction

6. Conclusion

The simulation of blood flow in a stenosed human artery with 1% Silica (SiO_2) nanoparticles reveals the following key observations:

1. Axial velocity variation: The presence of nanoparticles slightly modifies the velocity magnitude.
2. Flow rate: Nanoparticles have an effect on flow rate. Insertion of nanoparticles increases the flow rate
3. Resistive impedance: The inclusion of 1% nanoparticles slightly decreases the resistance to flow.

The axial velocity, flow rate distribution, and resistive impedance are strongly influenced by the stenosis geometry, while low-concentration nanoparticles mainly affect flow resistance and velocity magnitude locally, demonstrating potential for controlling hemodynamic characteristics in stenosed arteries.

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