Bol. Soc. Paran. Mat.
©SPM – E-ISSN-2175-1188
SPM: www.spm.uem.br/bspm

(3s.) **v. 2026 (44) 4** : 1–11.
ISSN-0037-8712
doi:10.5269/bspm.80167

Mathematical Analysis of Blood Microcirculation Through an Overlapping Stenosis under the Influence of Magnetic Field with Hybrid Nanoparticles

Asha K. N.[1], Neetu Srivastava[2] and M. Kamal Kumar[3]

ABSTRACT: This study analyses the effect of hybrid nanoparticles on the flow of blood through an artery containing overlapped stenosis along with microcirculation phenomena. Copper and Silver nanoparticles are used with blood as the base fluid. The slip effects along with Newtonian nature of blood are also considered. This analysis is done under the proximity of an external magnetic field. Analytical solutions for velocity, temperature and wall shear stress are obtained. Effects of fluid and flow parameters such as Heat absorption parameter, slip velocity, volume fraction and shape of nanoparticles on velocity and wall shear stress are discussed through graphs. The effect of shape of nanoparticles on fluid velocity in case of hybrid nanoparticles is same as that in case of mono nanoparticles. This article provides an overview of the model with the solutions and graphs that furnish the researchers and medical practitioners helpful data generating expressions about the use of hybrid nanoparticles in flow through stenosis during microcirculation.

Keywords: Blood flow, microcirculation, stenosis, hybrid nanoparticles, magnetic field, wall shear stress.

Contents

1. Introduction

Microcirculation is the circulation of the blood in the small blood vessels. Microcirculation is responsible for exchange of oxygen and nutrients between blood and tissue. The study of blood flow in microcirculation has captivated many researchers in recent years because of its significance in appreciating rheological properties of the blood. Studies of exchange process between blood and tissue during microcirculation have also relied to a great extent. Study of regulations of blood flow by microcirculatory vessels is also benefited from study of flow characteristics in different organisms. During recent years, clinical practice of devices that allow the microcirculation is introduced. Patient's mental, physical health and general life style has an influence on microcirculation. Guven et al. [1] studied the physiology of microcirculation and analysed its applications. Different approaches and formulations for mathematical modelling of microcirculation is studied by Fletcher [2]. Arciero et al. [3] discussed different mathematical methods for modelling microcirculation.

In most of the flow problems, there is a problem of lower thermal conductivity of different liquids. While flowing through the arteries, blood carries a considerable quantity of heat to various parts of the body. Effectiveness of heat transfer rely on thermal conductivity. Usually, the thermal conductivity nature of most fluids is poor compared to that in solids. This issue is resolved by adding appropriate volume of nanoparticles having high thermal conductivity in the base fluid domain. This enhances the thermal conductivity and connective heat transfer of the fluid. Hybrid nanomaterials is one of the exhilarating research fields in the area of materials engineering during recent years. These materials have exceptional properties that they derived from their nanoscale size. They are multidisciplinary in nature

2020 *Mathematics Subject Classification:* 76Z05, 92C35, 80A19.
Submitted November 15, 2025. Published February 26, 2026

and multifunctional. Nanomaterials are mixture of two or more inorganic components. The obtained new material is not a simple mixture of its components but a symbiotic material new properties and functionalities. Synthesis, processing, applications, and challenges of hybrid nanomaterials is studied and documented by Khieu et al. [4]. Ullah [5] et al. examined the influence of nanomaterials over a revolving porous disk. The main inspiration behind hybrid nanofluids is to improve heat transfer ability, thermal conductivity and other thermophysical properties of the base fluid. Copper and silver nanoparticles are considered for the study of flow in a microchannel by Akbar et al. [6].

Stenosis is developed due to the cumulative accretion of lipids, cholesterol, fat, blood cells and other substances on the wall of the artery. Since this is such crucial issue, a lot of research is in progress to find out more about the artery diseases and their treatment. Several researchers [7,8,9,10,11,12] have studied the treatment of stenosed artery with nanoparticle. Cilla et al. [13] studied a mathematical model to represent stenosis formation in coronary arteries. Carvalho et al. [14] presented the present learnings on the pros and cons of blood viscosity models accessible. Impact of metallic nanoparticles on magneto hydrodynamics (MHD) in a stenosed vertical artery containing micro polar blood was studied by Ahmed and Nadeem [15]. An extensive study of computational simulations of flow of blood with hybrid-nanoparticles done by Tripathi et al. [16]. Maraj et al. [17] and Ghailan et al. [18] investigated on the related issues.

Shape of nanoparticles is important in sustained drug delivery. Usually, nanoparticles occur in spherical, cylindrical, brick, platelet, and few other shapes. Shape of nanoparticles regulates their uptake into cells. Asha and Srivastava Neetu [19] have analysed the effect of shape of the nanoparticles on flow properties of fluid. Thermal conductivity of various shaped nanoparticles and their effects on the peristaltic flow is made by Akbar et al [20].

According to author's knowledge, no work has been done on the treatment of stenosis using hybrid nanoparticles in a small artery with microcirculation. We have developed a mathematical model and examined how the nanoparticles addition in blood can be useful in arterial blood and in the speedy recovery of sclerotic patient. In this work, we have considered the effect of hybrid nanoparticles (Cu-Ag) on stenosis in the small arteries during microcirculation under external magnetic field. Six different shaped nanoparticles are used to see their effect on the blood flow. Blood is considered as a Newtonian fluid.

2. Formulation of the Problem

Let us consider the axisymmetric blood flow in a circular cylindrical tube-like artery presented in Fig.1. Let the radius of the artery be R_0. The flow is considered across an overlapping stenosis present in the artery having length larger than its radius R_0. Axisymmetric flow governing equations are represented in the cylindrical polar co-ordinates systems in which r represents the radial distance, z represents the axial distance, d is the location of the stenosis. The length of the artery is larger compared to its radius. The maximum height of the stenosis is δ which is seen at $z = d+L_0/6$ and at $z = d+5L_0/6$, whereas the axial distance for the arterial tube analysis is taken as 2d + L_0 and R(z) is the radius of the artery in the stenotic region.

$$\frac{R(z)}{R_0} = \begin{cases} 1 - \frac{3\delta}{2R_0 L_0^4}\left[11(z-d)L_0^3 - 47(z-d)^2L_0^2 + 72(z-d)^3L_0 - 36(z-d)^4\right], & d \leq z \leq d + L_0 \\ 1, & Otherwise \end{cases} \tag{2.1}$$

The flow governing equations [21] describing the flow are as follows:

$$\frac{1}{r}\frac{\partial}{\partial r}(rv) + \frac{\partial u}{\partial z} = 0, \tag{2.2}$$

$$\frac{\partial p}{\partial r} = \mu_{hnf}\left(\frac{\partial^2 v}{\partial r^2} + \frac{1}{r}\frac{\partial v}{\partial r} - \frac{v}{r^2} + \frac{\partial^2 v}{\partial z^2}\right), \tag{2.3}$$

$$\frac{\partial p}{\partial z} = \mu_{hnf}\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} - \frac{v}{r^2} + \frac{\partial^2 u}{\partial z^2}\right) + \rho_{hnf} g\alpha\,(T - T_0) - \sigma B_0^2\left(u + \frac{k}{R_0}\right), \tag{2.4}$$

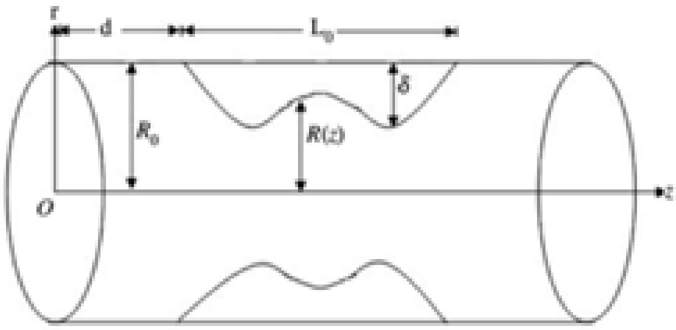

Figure 1: Geometry of the stenosis

$$(\rho_{cp})_{hnf}\left(v\frac{\partial T}{\partial r}+u\frac{\partial T}{\partial z}\right)=k_{hnf}\left[\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right]+Q_0. \tag{2.5}$$

Second term in the RHS of equation (4) represents the heat capacitance and last term in the RHS of equation (4) represents external magnetic field. Last term in the RHS of equation (5) represents heat dissipation.

Maxwell and Brinkman model [23,24] has given the heat conductivity and viscosity as:

For mono nanofluid,

$$k_{nf}=k_f\left\{\frac{k_{s1}+(q-1)k_f-(q-1)\varnothing_1\,(k_f-k_{s1})}{k_{s1}+(q-1)k_f+\varnothing_1\,(k_f-k_{s1})}\right\}. \tag{2.6}$$

For hybrid nanofluid,

$$k_{hnf}=k_{nf}\left\{\frac{k_{s2}+(q-1)k_{nf}-(q-1)\varnothing_2\,(k_{nf}-k_{s2})}{k_{s2}+(q-1)k_{nf}+\varnothing_2\,(k_{nf}-k_{s2})}\right\}. \tag{2.7}$$

$$\mu_{hnf}=\frac{\mu_f}{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}} \tag{2.8}$$

Let us non-dimensionalize the flow governing equations using non-dimensional terms:

$$\overline{r}=\frac{r}{R_0},\quad \overline{z}=\frac{z}{L_0},\quad \overline{v}=\frac{v}{\delta U},\quad \overline{u}=\frac{u}{U},\quad U=\frac{k}{R_0},\quad \overline{d}=\frac{d}{L_0},\quad \overline{R}=\frac{R}{R_0},\quad M^2=\frac{\sigma B_0^2 R_0^2}{\mu_f}, \tag{2.9}$$
$$\overline{p}=\frac{R_0^2}{UL_0\mu_f}p,\quad G_r=\frac{g\alpha R_0^2T_0\rho_{hnf}}{U\mu_f},\quad \theta=\frac{T-T_0}{T_0},\quad \beta=\frac{Q_0R_0^2}{k_fT_0}.$$

For the case of mild stenosis, we assumed $\frac{\delta}{R_0}\ll 1$. Due to the presence of mild stenosis, radial velocity term in the equation of motion is treated as negligible. Mathematically, $\frac{\partial v}{\partial r}$ will be ignored. Substituting (9) in equations (3) – (5) the equation will take the form:

$$\frac{1}{R_0}\frac{\partial}{\partial \overline{r}}\left(\frac{UL_0\mu}{R_0^2}\overline{p}\right)=\mu_{hnf}\left(\frac{1}{R_0}\frac{1}{R_0}\frac{\partial}{\partial \overline{r}}\left(\frac{\partial}{\partial \overline{r}}(\overline{v}\delta U)\right)+\frac{1}{\overline{r}R_0}\frac{1}{R_0}\frac{\partial}{\partial \overline{r}}(\overline{v}\delta U)-\frac{\overline{v}\delta U}{(\overline{r}R_0)^2}+\frac{1}{L_0}\frac{1}{L_0}\frac{\partial}{\partial \overline{z}}\left(\frac{\partial(\overline{v}\delta U)}{\partial \overline{z}}\right)\right), \tag{2.10}$$

$$\begin{aligned}\frac{1}{L_0}\frac{\partial}{\partial \overline{z}}\left(\frac{UL_0\mu}{R_0^2}\overline{p}\right)=\mu_{hnf}\Bigg(&\frac{1}{R_0}\frac{1}{R_0}\frac{\partial}{\partial \overline{r}}\left(\frac{\partial}{\partial \overline{r}}(\overline{u}U)\right)+\frac{1}{\overline{r}R_0}\frac{1}{R_0}\frac{\partial}{\partial \overline{r}}(\overline{u}U)+\\ &\frac{1}{L_0}\frac{1}{L_0}\frac{\partial}{\partial \overline{z}}\left(\frac{\partial(\overline{u}U)}{\partial \overline{z}}\right)\Bigg)+\left(\frac{U\mu_fG_r}{g\alpha R_0^2T_0\rho_{hnf}}\right)g\alpha(\theta T_0)-\frac{M^2\mu_f}{R_0^2}(\overline{u}U+U),\end{aligned} \tag{2.11}$$

$$(\rho_{cp})_{hnf}\left(\overline{v}\delta U\frac{1}{R_0}\frac{\partial}{\partial\overline{r}}(\theta T_0+T_0)+\overline{u}U\frac{1}{L_0}\frac{\partial}{\partial\overline{z}}(\theta T_0+T_0)\right)=$$
$$k_{hnf}\left(\frac{1}{R_0}\frac{1}{R_0}\frac{\partial}{\partial\overline{r}}\left(\frac{\partial}{\partial\overline{r}}(\theta T_0+T_0)\right)+\frac{1}{\overline{r}R_0}\frac{1}{R_0}\frac{\partial}{\partial\overline{r}}(\theta T_0+T_0)+\frac{1}{L_0}\frac{1}{L_0}\frac{\partial}{\partial\overline{z}}\left(\frac{\partial(\theta T_0+T_0)}{\partial\overline{z}}\right)+\frac{k_fT_0\beta}{R_0^2}\right). \tag{2.12}$$

Because of microcirculation, the inertia terms will be zero. After simplifying equations (10), (11) and (12) and dropping the dashes from them we obtain,

$$\frac{\partial p}{\partial r}=0, \tag{2.13}$$

$$\frac{\partial p}{\partial z}=\frac{1}{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}\frac{\partial^2 u}{\partial r^2}+G_r\theta-M^2(u+1), \tag{2.14}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\theta}{\partial r}\right)+\beta\frac{k_f}{k_{hnf}}=0. \tag{2.15}$$

Boundary conditions for the case of microcirculation [22] is given by:

$$\frac{\partial u}{\partial r}=0,\quad \frac{\partial\theta}{\partial r}=0 \qquad at \qquad r=0, \tag{2.16}$$

$$\frac{\partial u}{\partial r}=-\frac{\alpha}{\sqrt{c}}u,\quad \theta=0 \qquad at \qquad r=R(z).$$

The boundary condition at r=R(z) is the Beavers and Joseph slip condition. Here α is the slip parameter and c is the specific permeability of the porous medium.

Integrate equation (15) twice and then using boundary conditions (16), we get the solution as follows:

$$\theta(r,z)=\frac{k_f}{k_{hnf}}\ \beta\left(\frac{R^2-r^2}{4}\right). \tag{2.17}$$

Substituting equation (17) in equation (14), equation (14) takes a form as:

$$\frac{1}{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}\frac{\partial^2 u}{\partial r^2}-M^2u=\frac{\partial p}{\partial z}-G_r\beta\frac{k_f}{k_{hnf}}\left(\frac{R^2-r^2}{4}\right)+M^2.$$

This is a second order linear differential equation. Solving this analytically, the general solution can be written as follows:

$$u=C_1e^{M\sqrt{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}r}+C_2e^{-M\sqrt{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}r}+\frac{1}{M^2}\left(r^2-\frac{dp}{dz}+G_r\frac{k_f}{k_{hnf}}\ \beta-M^2+\frac{2}{M^2(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}\right).$$

Using the boundary conditions (16), the particular solution for velocity u is obtained as

$$u=\frac{-\left(\alpha M^2+2R\sqrt{c}\right)\left[e^{M\sqrt{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}r}+e^{-M\sqrt{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}r}\right]}{M^3\sqrt{c}\sqrt{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}\left[e^{M\sqrt{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}R}+e^{-M\sqrt{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}R}\right]}+\frac{1}{M^2}\left(r^2-\frac{dp}{dz}+G_r\frac{k_f}{k_{hnf}}\ \beta-M^2+\frac{2}{M^2(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}\right). \tag{2.18}$$

From equation (18), we get,

$$\tau = \frac{-\left(\alpha M^2 + 2R\sqrt{c}\right)\left[e^{M\sqrt{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}r} + e^{-M\sqrt{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}r}\right]}{M^2\sqrt{c}\left[e^{M\sqrt{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}R} + e^{-M\sqrt{(1-\varnothing_1)^{2.5}(1-\varnothing_2)^{2.5}}R}\right]} + \frac{2r}{M^2}. \tag{2.19}$$

Table 1: Thermophysical properties of blood and nanoparticle

Substance	$\rho\left(kg/m^3\right)$	$C_p\left(Jkg^{-1}k^{-1}\right)$	$k\left(Wm^{-1}k^{-1}\right)$
Blood	1050	3617	0.52
Silver (Ag)	10500	235	429
Copper (Cu)	8933	385	400

3. Results and Discussion

Velocity and wall shear stress are the two important variables that we come across in the current study. The analytical solutions for the same is shown in equations (18) and (19). Graphs have been plotted for velocity and wall shear stress with respect to crucial parameters like slip velocity, Hartmann number, Grashof number, Heat absorption number and volume fraction of nanoparticles.

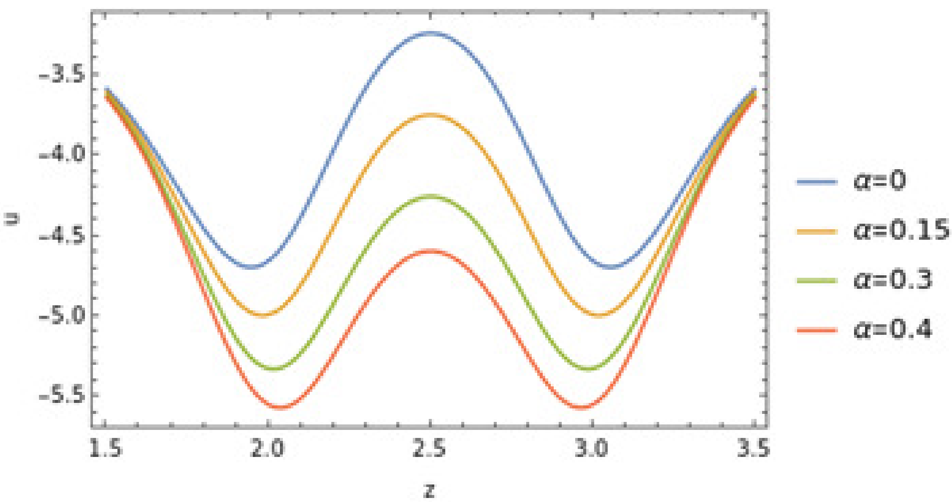

Figure 2: Variation in axial velocity for different values of slip parameter

3.1. Velocity Profile

In Fig.2 the influence of Hartmann number on velocity along axial axis is analysed. It is depicted from the graph that the velocity decreases with the onset of the stenosis height and then there is an increase in the velocity with the decrease in the stenosis height. Velocity decreases again when there is an increase in the stenosis height and becomes normal after the stenotic region. This shows the effect of stenosis on the velocity of the blood. The same nature is seen in Fig.3-Fig.8. From Fig.2, it is observed that there is a downfall in velocity with the increase in slip velocity α. In Fig.3, it is noticed that the velocity and Hartmann number M are inversely correlated. The change in velocity is prominent for lesser values of the Hartmann number and the changes are very minimal as the values of Hartmann number increases. Fig.4 shows the variation of velocity for different values of volume fraction $\varnothing = \varnothing_1 = \varnothing_2$ of nanoparticles. Increase in volume fraction offers higher resistance to fluid flow and thus decreases the velocity. Increase in volume fraction makes the fluid less flexible and decreases its velocity.

Graphs are also plotted to observe the behavior of radial velocity along the axis. As seen from the graph in Fig. 5., radial velocity decreases with the increase in slip velocity and from Fig.6, velocity falls as the value of Hartmann number increases along radial axis.

The variation in velocity is compared for different shaped nanoparticles in Fig.7. The graph indicates that the velocity is maximum in case of spherical nanoparticles, followed by brick, cylinder, platelet, blade shaped nanoparticles with laminar nanoparticles resulting in minimum velocity. This result matches with the result obtained by Asha and Srivastava Neetu [19].

3.2. Wall Shear Stress Profile

Fig.8-Fig.10 portrays the variation of wall shear stress corresponding to all emergent parameters. Graphs are plotted to analyze the correlation between significant parameters and Wall shear stress. Fig.8. reveals the change in wall shear stress along radial axis for different values of slip parameter. We can notice that the shear stress at the arterial wall and the slip parameter are inversely related to each other. Fig.9 represents wall shear stress in axial axis for different values of Hartmann number values, M=1,2,3,4. In the normal region, wall shear stress is highest for M=1 and least for M=4 whereas in the stenotic region where the stenosis height is maximum, this nature reverses i.e., velocity is minimum for M=1 and maximum for M=4. Hartmann number M=1 results in greater variations in wall shear stress. Fig.10 represents the behavior of shear stress at wall for different volume fraction of nanoparticles along axial axis. We may also find some negative shear stress seen at certain spots, which seems to suggest reversed flow.

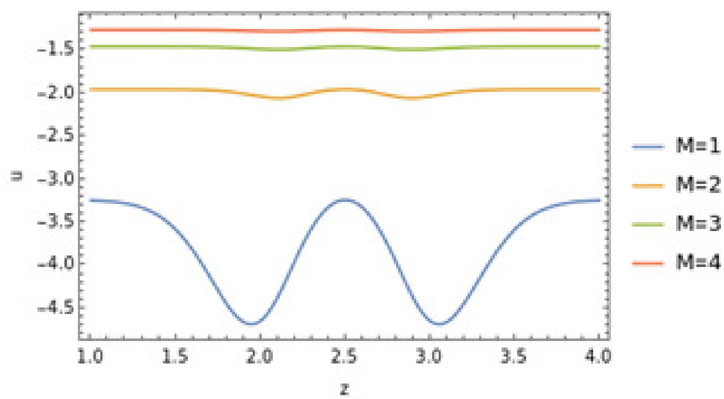

Figure 3: Axial velocity variation with Hartmann number M

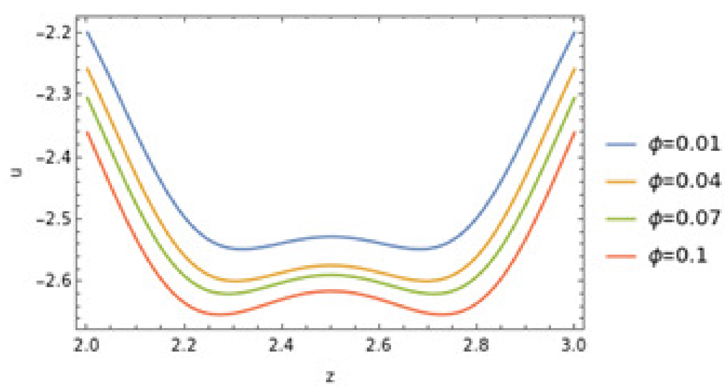

Figure 4: Axial velocity variation with volume fraction

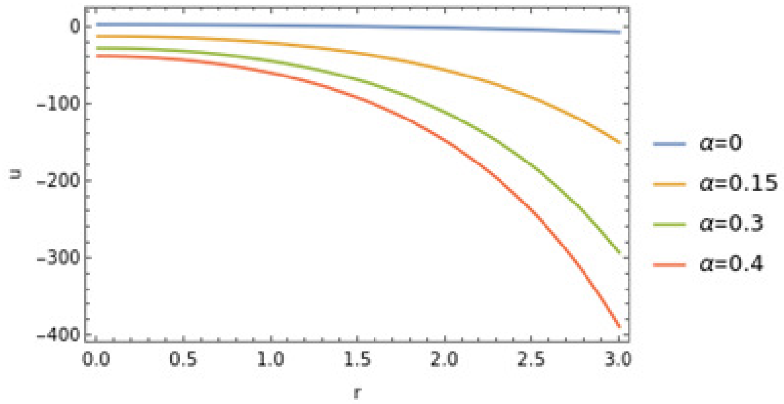

Figure 5: Radial velocity variation with slip velocity parameter

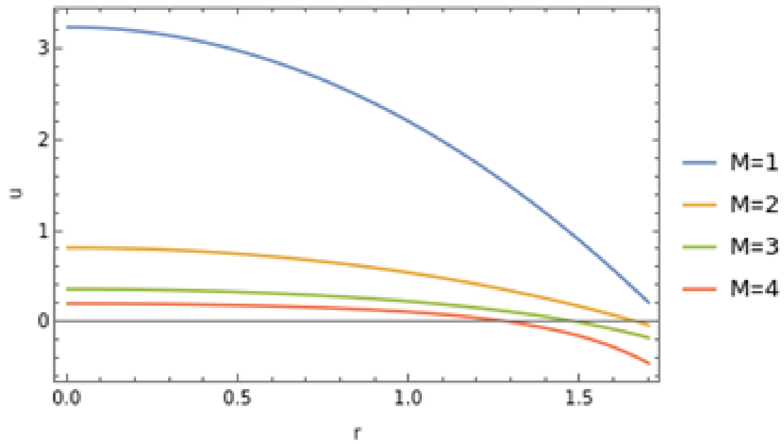

Figure 6: Radial velocity variation with Hartmann Number

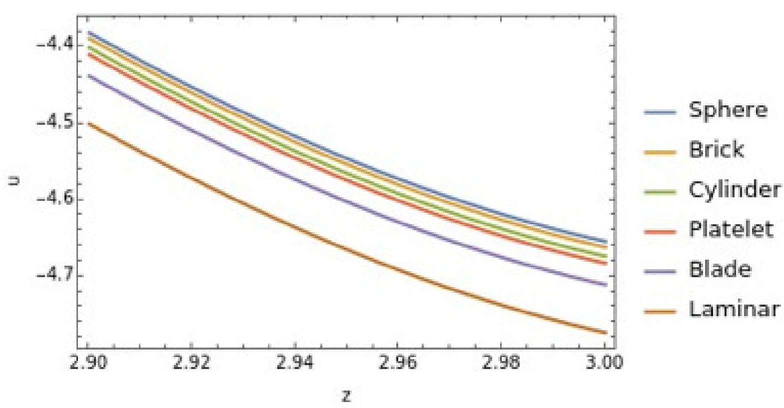

Figure 7: Axial velocity variation with different shaped nanoparticles

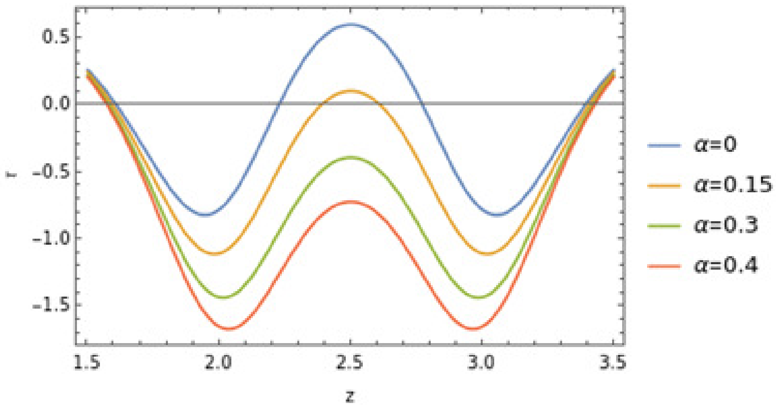

Figure 8: Wall shear stress along axial axis for different values of slip parameter

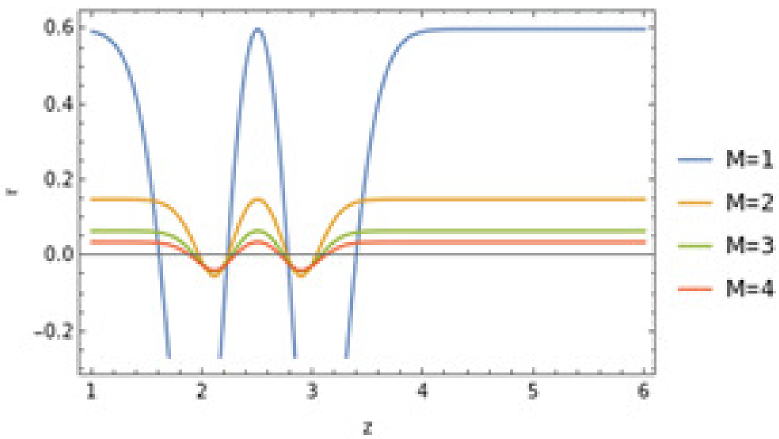

Figure 9: Wall shear stress along axial axis for different values of M

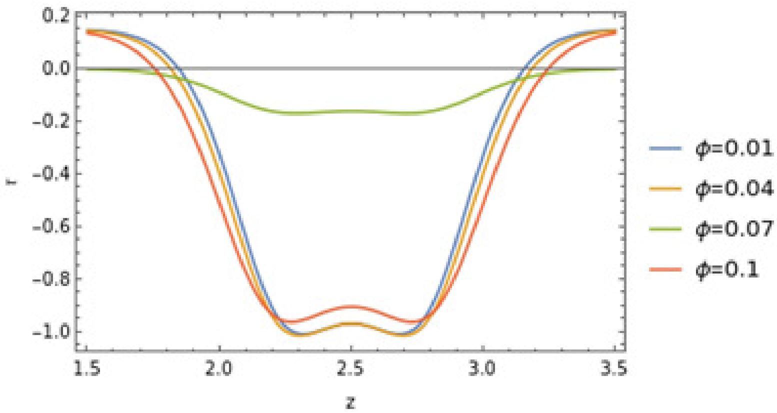

Figure 10: Wall shear stress along axial axis for different values of volume fraction

4. Conclusion

The present study reveals the impact of hybrid nanoparticles on the flow of blood in the presence of overlapped stenosis during microcirculation. Velocity and wall shear stress profiles are obtained by analytical method. This study is so relevant in the current situation where hybrid nanoparticles are used in many areas of the medical field as the characteristics of different nanoparticles when merged together suitably, produces a greater impact. As this technology is being applied more in the recent years, this study helps finding new results related to their impact on different flow parameters of a fluid. Hence, it provides numerous results that may be helpful for further research and applications in medical field and biomechanical engineering.

The main observations of the performed analysis are:

- Velocity is least at the peak of stenosis.
- Larger value of slip parameter causes less velocity.
- The Hartmann number enhances the velocity. Rising trend in velocity is detected due to the significant impact of the electromagnetic field.
- Larger the nanoparticles volume fraction, lesser the velocity.
- Effect of slip parameter on velocity is same along both axial axis and radial axis.
- Spherical shaped nanoparticles enhance the velocity of the fluid whereas laminar shaped nanoparticles diminish it.
- Nature of velocity for different shaped nanoparticles is same in case of both mono and hybrid nanoparticles.
- The effect of Hartmann number on wall shear stress is opposite in the stenotic and non-stenotic region.
- Wall shear stress is directly proportional to the value of slip parameter.
- Volume fraction of nanoparticles has greater influence on wall shear stress and this effect varies in stenotic region.

Nomenclature

L_0	length of overlapping stenosis.
ρ_{hnf}	Effective density of hybrid nanofluid
μ_{hnf}	Effective dynamic viscosity of hybrid nanofluid
$(\rho_{cp})_{hnf}$	Heat capacitance of hybrid nanofluid
α_{hnf}	Effective thermal diffusivity of hybrid nanofluid
k_{hnf}	Effective thermal conductivity of hybrid nanofluid
$k_{s1},\ k_{s2}$	Thermal conductivity of copper and silver solid nano particles
$\varnothing_1$, $\varnothing_2$	Volume fraction of copper and silver nanoparticles
M	Magnetic interaction parameter
β	Heat absorption parameter
G_r	Grashof number
δ	Stenosis height

Acknowledgments

We thank the anonymous referees for their valuable comments and suggestions.

References

1. Guven, G., Hilty, M. P., and Ince, C., *Microcirculation: Physiology, Pathophysiology, and Clinical Application*, Blood Purif., 49(1–2), 143–150, (2020).
2. Fletcher, J. E., *Mathematical modeling of the microcirculation*, Math. Biosci., 38(3–4), 159–202, (1978).
3. Arciero, J. C., Causin, P., and Malgaroli, F., *Mathematical methods for modeling the microcirculation*, AIMS Biophys., 4(3), 362–399, (2017).
4. Khieu, D. Q., Dinh, N. T., Mau, T. X., and Mai, H. D., *Synthesis and Application of Novel Hybrid Nanomaterials in Catalysis, Adsorption, and Electrochemistry*, Adv. Mater. Sci. Eng., 2019, 6182374, (2019).
5. Ullah, I., Alajlani, Y., Pasha, A. A., Adil, M., and Weera, W., *Theoretical investigation of hybrid nanomaterials transient flow through variable feature of Darcy–Forchheimer space with exponential heat source and slip condition*, Sci. Rep., 12, 15085, (2022).
6. Akbar, N. S., Rafiq, M., Muhammad, T., and Alghamdi, M., *Electro osmotically interactive biological study of thermally stratified micropolar nanofluid flow for Copper and Silver nanoparticles in a microchannel*, Sci. Rep., 14, 518, (2024).
7. Srivastava, N., *Analysis of Flow Characteristics of the Blood Flowing through an Inclined Tapered Porous Artery with Mild Stenosis under the Influence of an Inclined Magnetic Field*, J. Biophys., 2014, 797142, (2014).
8. Srivastava, N., *The Casson fluid model for blood flow through an inclined tapered artery of an accelerated body in the presence of magnetic field*, Int. J. Biomed. Eng. Technol., 15(3), 1–15, (2014).
9. Asha, K. N. and Srivastava, N., *Magnetic repercussion on the different shaped copper nanoparticles to improve vasodilatation effect in stenosed artery*, Mater. Today, 44, 2142–2146, (2021).
10. Asha, K. N. and Srivastava, N., *Geometry of stenosis and its effects on the blood flow through an artery – A theoretical study*, AIP Conf. Proc., 2375, 030006, (2021).
11. Gayathri, K. and Shailendhra, K., *MRI and Blood Flow in Human Arteries: Are There Any Adverse Effects?*, Cardiovasc. Eng. Technol., 10(2), 242–256, (2019).
12. Suresh, A. and Rajan, V., *Study of non-Newtonian blood flow through arteries using Open FOAM*, AIP Conf. Proc., 2134, 040003, (2019).
13. Cilla, M., Peña, E., and Martínez, M. A., *Mathematical modelling of atheroma plaque formation and development in coronary arteries*, J. R. Soc. Interface, 11(90), 20130866, (2014).
14. Carvalho, V., Pinho, D., Lima, R. A., Teixeira, J. C., and Teixeira, S. E., *Blood Flow Modeling in Coronary Arteries: A Review*, Fluids, 6(2), 53, (2021).
15. Ahmed, A. and Nadeem, S., *Effects of magnetohydrodynamics and hybrid nanoparticles on a micropolar fluid with 6-types of stenosis*, Results Phys., 7, 1–10, (2017).
16. Tripathi, J., Vasu, B., Gorla, R. S. R., Chamkha, A. J., Murthy, P. V. S. N., and Bég, O. A., *Blood Flow Mediated Hybrid Nanoparticles in Human Arterial System: Recent Research, Development and Applications*, J. Nanofluids, 10(1), 1–30, (2021).
17. Maraj, E. N., Shah, S. I., Akbar, N. S., and Muhammad, T., *Thermally progressive Particle-Cu/Blood peristaltic transport with mass transfer in a Non-Uniform Wavy Channel: Closed-form exact solutions*, Alex. Eng. J., 74, 453–466, (2023).
18. Ghailan, K. Y., Akbar, N. S., Albakri, A., and Alshehri, M. M., *Biological analysis of emerging nanoparticles with blood through propagating flow along a plumb porous canal in the occurrence of energy and heat transfer*, Surf. Interfaces, 40, 103013, (2023).
19. Asha, K. N. and Srivastava, N., *Homotopy Perturbation Analysis on Shape Effect of Vasodilators during Arterial Flow*, Nanoscience Technol., 14(1), 55–70, (2023).
20. Akbar, N. S., Mehrizi, A. A., Rafiq, M., Habib, M. B., and Muhammad, T., *Peristaltic flow analysis of thermal engineering nano model with effective thermal conductivity of different shape nanomaterials assessing variable fluid properties*, Alex. Eng. J., 81, 395–404, (2023).
21. Pal, D., Rudraiah, N., and Devanathan, R., *The effects of slip velocity at a membrane surface on blood flow in the microcirculation*, J. Math. Biol., 26, 705–712, (1988).
22. Beavers, G. S. and Joseph, D. D., *Boundary conditions at a naturally permeable wall*, J. Fluid Mech., 30, 197–207, (1967).
23. Brinkman, H., *The viscosity of concentrated suspensions and solutions*, J. Chem. Phys., 20, 571, (1952).
24. Maxwell, J. C., *A treatise on electricity and magnetism*, Vol. 1, Clarendon Press, (1881).

[1] *Assistant Professor, Department of Mathematics, CMR Institute of Technology, Bengaluru, Karnataka, India, 560037*
[2] *Associate Professor, Department of Mathematics, Amrita School of Engineering, Bengaluru, India, 560035*
[3] *Professor, Department of Science and Mathematics, University of Technology and Applied Sciences, Muscat, Sultanate of Oman*
E-mail address: asha.kn@cmrit.ac.in