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A Mathematical Model for Influence of Nano-Particle Form on Stagnation-Point Flow in Generated Magnetic Field

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Abstract

Objectives: The current study focuses on the impact of nanoparticle's shape and slip on the stagnation point flow in a blood-based silver nanofluid that flows over the surface with the effect of an induced magnetic field and thermal radiation taking into consideration convective heat sources and chemical reactions. **Methods:** To reduce the partial differential equations to ordinary differential equations (ODEs), this study used similarity transformations and transformed further into Newton-Raphson & adaptive Runge Kutta to provide a stable solution to intricate fluid dynamic phenomena. In conducting the simulations work, this study utilized computational fluid dynamics software i.e. ANSYS. **Findings:** With the help of physicians, the study qualitatively confirms that the elongated nanoparticles raise heat transfer by maximizing 30% in comparison to spherical counterparts to improve thermal conductivity. Similarly, the pillar-shaped nanoparticles have an enhancement of mass transfer rates by about 25 % compared to the spherical one, which is very vital in applications where high diffusion processes are of utmost importance. Further, a reduction of 10% for both thermal and concentration slip greatly leads to a 15% reduction in nanofluid temperature and 20% in concentration proving that slip conditions have a big influence on the nanofluid. **Novelty:** This research provides the first systematic investigation of the role of nanoparticle shape and slip conditions on the blood-based silver nanofluid flow around a stagnation point, where the effect of magnetic field is considered as well. In this research study, new modelling concepts have been developed for understanding the thermal and mass transfer characteristics of nanofluids in biomedical applications which clearly is a step forward from the existing theories.

Keywords: Nano Fluids; Stagnation Point; Magnetic Field; Multiple Slip; Blood-Based Silver Nano Fluid

1 Introduction

Researchers have noted that nanofluids, containing nanoparticles with sizes ranging from 1-100 nm, greatly enhance thermal characteristics in fluid engineering by enabling better control over heat transfer processes. The main factor influencing temperature distribution and other thermophysical characteristics is the shape of these nanoparticles, and compared to spherical ones, non-spherical nanoparticles are more effective in modifying these characteristics [(1)]. Medical applications have widely used these nanoparticles for drug delivery and cancer treatment due to their ability to carefully control heat and mass transfer.

Hayat et al. [(2)] suggested techniques that focus on the variable heat and mass transfer attributes of nanoparticles related to shape and flow rates. However, the combined impact of these variables with induced magnetic fields has not received much attention previously, and it could find application in various blood pump models, cardiac therapies, and other treatment procedures that necessitate precise control of nanofluid properties.

This article talks about the flow stopping point of a blood-based silver nanofluid. It looks at different nanoparticle shapes, different slip conditions, chemical reactions, induced magnetic fields, linear heat sources, and thermal radiation. Such investigations are particularly critical for biomedical imaging, hyperthermia, and targeted cancer treatment because nanofluid behavior under various conditions defines local therapy effectiveness.

This research addresses several critical questions:

- In this work, how are solutal and thermal slip conditions affecting the concentration and temperature of nanofluids?
- How does the nature of nanoparticles affect their flow characteristics?
- What trends in the temperature profile of the nanofluids can be observed with variations in the volume percentage of the silver nanoparticles, thermal radiation, and linear heat source intensity?
- When non-spherical particles replace spherical ones, what physical characteristics of nanofluids change?

The study aims to answer these questions by filling in the gaps and giving a better understanding of how nanofluids behave in medical settings. This will make it more likely that precise changes can be made in therapeutic practice. The current paper aims to answer the following research questions:

- The importance of the solutal slip and thermal slip parameters resides in their influence on the nanofluid's concentration and temperature, respectively.
- What is the influence of nanoparticle morphology on flow characteristics?
- How do the volume percentage of silver nanoparticles, the thermal radiation, and the linear heat source relate to the temperature of the nanofluid?
- What is the level of sensitivity of physical quantities when considering non-spherical and spherical nanoparticles?

Examples of previous work on nanofluid behavior can be found in the literature. As per Benkhedda et al., [(3)], Frequent silver-titanium dioxide (plate-shaped) nanoparticles suffered the best rubbing. The form factor values of Cu-blood/CuO have increased, leading to a reduction in the temperature profile, as observed by Tripathi et al. [(4)]. Sindhu and Gireesha [(5)] explored the maximum entropy generation in Ti-H2O and Ag-H2O nanofluids; Ag-H2O reported a higher entropy generation, especially with the disc-shaped nanoparticles. Elnaqeeb et al. When placed in a closed rectangular space, the ternary-hybrid nanoparticles—copper, copper oxide, and silver—demonstrated better heat transfer performance compared to those in [(6)]. Studies related to nanoparticle radius show variations in velocity profiles, while temperature fields exhibit a reciprocal relationship with the nanoparticle's radius [(7)]. The rising nanoparticle radius amplifies the skin friction coefficient [(8)], but it also decreases the drag coefficient.

Again, studies have used different models of nanofluids. Hayat et al. [(3)] and Sadiq et al. [(8)] applied the Buongiorno and Tiwari-Das models to study the influences of slip on Darcy-Forchheimer flow. Chu et al. [(9)] undertook an investigation of activation energy and MHD effects by the Buongiorno model and Puneeth et al. Then, Puneeth [(10)] further developed the model by incorporating nanomaterial thermophysics. Rana et al. [(11)] studied the thermal performance of a nanofluid and reported improvements from 95% to 133%, while Mahanthesh and Mackolil [(12)] reported heat transfer enhancement of an alumina nanomaterial. Barik et al. [(13)] investigated the flow and thermal characteristics of nanofluid with nanoparticle aggregation kinetics.

Despite extensive research, there remains a lack of comprehensive studies on the combined effects of nanoparticle shape and slip conditions on the flow characteristics of blood-based silver nanofluids. Most studies have not simultaneously considered the impacts of thermal radiation, linear heat sources, and chemical reactions, which are crucial for biomedical applications.

The main goal of this study is to carefully look into how different nanoparticle shapes and slip conditions affect the flow of blood-based Ag-nanofluids at the stagnation point. Finding the appropriate equation to enhance the properties of nanofluid is crucial, especially for applications in medical fields such as drug delivery techniques and thermal treatments. The authors will employ numerical techniques to solve the transformed ordinary differential equations derived from the governing equations using Newton-Raphson and adaptive Runge-Kutta methods. This method enables the detailed analysis of various interactions occurring within the fluid, which gives a better understanding of the effects of the shape of nanoparticles and their activities in conditions that are different from each other.

The chosen numerical techniques are appropriate for this work due to their ability to solve nonlinear ordinary differential equations that characterize dynamics, particularly in situations where boundary conditions and fluid properties are variable. By using this method, the present study can delve deeper into interactions that would be challenging to test in the lab. This will fill in the gaps and give us useful information about the field.

Recent studies have shown that the properties of the nanoparticles and the way the flow can affect how useful nanofluids are for better cooling and lubrication[(14)]. In addition, there are difficulties analyzing the flow and heat transfer characteristics of the nanofluid boundary layer[(14,15)]. Khan et al.[(15)] examined the impact of double diffusion and magnetic fields on optimizing heat and drug delivery processes.

Alharbi et al.[(16)] and Hussain et al.[(17)] made some helpful additions to enhance understanding of the role of thermophoretic diffusion and/or magnetic fields in various complex fluid dynamics and performance situations. In the same way, Sharma et al.[(18)] proved that, in the case of hybrid nanoliquids flowing through the vertical channel, the impact of the induced magnetic fields is crucial to controlling their flow patterns. However, there has been a lack of widespread investigation into the systematic, state-of-the-art study of nanoparticle shape, thermal, and solutal slip conditions in blood-based nanofluids, particularly near the stagnation point, where the fluid's flow behavior is crucial for medical applications.

This research seeks to fill this gap by conducting a systematic study of the stagnation-point flow of blood-based silver nanofluids. The research aims to scrutinize the impact of nanoparticle shapes and multiple slip conditions on flow behavior in a region containing induced magnetic fields, thermal radiation, and chemical reactions. The relevant work by Mahmood et al.[(19)] and Lone et al.[(20)] identifies analogous fluid dynamics scenarios that give a basis for understanding subtle interactions in the present study. The present study approach comprises a high-fidelity numerical solution of the transformed ordinary differential equations, which may open up further applications in the medical field given a more exhaustive analysis.

Researchers have reported enhancements in heat transfer and entropy generation for specific types of nanoparticles, but researchers haven't explicitly compared the effects on uniform base configurations. De[(21)] provides valuable insights into entropy optimization in stagnant blood flow systems with tetra-hybrid nano additives under conditions. Additionally, Shah et al.[(22)] offer a comparative analysis of non-Newtonian nanofluid models, enriching the present approach to modeling the complex interactions of fluid dynamics across different stretching sheets. This lack of comparison poses a challenge in developing standard responses for the shape and material of nanoparticles, which are crucial for optimal medical applications. For instance, there is a lack of comprehensive understanding of the combined impact of nanoparticle morphology, magnetic fields, and blood-based nanofluid reactions, particularly when addressing circulation behaviors at stagnation points—a crucial aspect of medical applications. This research aims to bridge these gaps by thoroughly examining the implications of the shapes of the nanoparticles and the slip conditions in the stagnation-point flow of blood-based silver nanofluids under the influence of external magnetic fields and thermal radiation. Solving the given transformed ordinary differential equations using numerical methods, this research will offer a fresh understanding of nanofluid interactions, with possible improvements for its application in biomedical fields.

2 Methodology

The computational fluid dynamics program ANSYS Fluent was used to model the properties of silver nanofluids dissolved in blood in this investigation. Nanoparticle size, shape, magnetic field intensity, and slip circumstances were the primary foci of this study. Finally, this study validated the results by comparing it with earlier research.

2.1 Mathematical Frame

In this research, the flow properties of an incompressible fluid along a linearly extending sheet are investigated. There is a constant, bidirectional flow.

- The expanding sheet is perpendicular to the x-axis, and a silver nanofluid produced from blood fills the area where the y-value is larger than zero.
- $U_w(x) = cx \; and \; U_e(x) = ax$ The values provided represent the velocity of both the free stream and the extended sheet.
- The vector representing the induced magnetic field, M = (M1, M2), is defined as follows: M1 stands for the x-direction magnetic component and M2 for the y-direction magnetic component.

- Particle form (platelet, spherical, cylinder, or blade), chemical reactions, radiation, and linear heat sources are all accounted for in the model.
- The present study considers both solute sliding and thermal implications.

The governing equations, as stated in the aforementioned assumptions[13]:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\frac{\partial M_1}{\partial x}+\frac{\partial M_2}{\partial y}=0 \tag{2}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-\frac{\mu_e}{4\pi\rho_{nf}}\left(M_1\frac{\partial M_1}{\partial x}+M_2\frac{\partial M_1}{\partial x}\right)=U_e\frac{dU_e}{dx}-\frac{\mu_e M_e}{4\pi\rho_{nf}}\frac{dM_e}{dx}+\left(\frac{\mu_{nf}}{\rho_{nf}}\right)\frac{\partial^2 u}{\partial y^2} \tag{3}$$

$$u\frac{\partial M_1}{\partial x}+v\frac{\partial M_1}{\partial y}-M_1\frac{\partial u}{\partial x}-M_2\frac{\partial u}{\partial y}=\alpha_m\frac{\partial^2 M_1}{\partial y^2} \tag{4}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\frac{\partial^2 T}{\partial y^2}+\frac{q_T}{\left(\rho C_p\right)_{nf}}(T-T_\infty)-\frac{1}{\left(\rho C_p\right)_{nf}}\frac{\partial q_r}{\partial y} \tag{5}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}-k_r(C-C_\infty) \tag{6}$$

Subject to the boundary conditions:

$$u=U_w(x)=cx, v=0, \frac{\partial M_1}{\partial y}=M_2=0, T=T_w+N_1\frac{\partial T}{\partial y}, C=C_w+N_2\frac{\partial C}{\partial y}\ at\ y=0$$

$u\to U_e(x)=ax, M_1\to M_e(x)$=$M_0x,\ T\to T_\infty, C\to C_\infty\ as\, y\to\infty$

Where,

$\alpha_m=\frac{1}{4\pi\mu_e\sigma_{nf}}$, represents the magnetic diffusivity

Examine the subsequent similarity transformations[23] :

$$u=cxf'(\eta), \nu=-\sqrt{c\nu_f f(\eta)}, M_1=M_0xg'(\eta),\ M_2=-M_0\sqrt{\frac{\nu_f}{c}}g(\eta),\ \eta=y\sqrt{\frac{c}{v_f}},\ \theta(\eta)=\frac{T-T_\infty}{T_w-T_0},$$

$$\psi(\eta)=\frac{C-C_\infty}{C_w-C_0}$$

By utilizing the linearized Roseland approximation and applying similarity transformations, the obtained using Equations (1), (2), (3), (4), (5) and (6):

$$f'''=A_1A_2\left\{(f')^2-ff''-\frac{\beta}{A_2}\{(g')^2-gg''-1\}-A^2\right\} \tag{7}$$

$$g'''=\frac{A_5}{\lambda}\{gf''-fg''\} \tag{8}$$

$$\theta^{''} = \frac{-P_r\{A_3 f\theta^{'} + Q_T\theta\}}{A_4 + \frac{4}{3}R_d} \tag{9}$$

$$\psi^{''} = K_r L_e \psi - L_e f \psi' \tag{10}$$

Within the parameters of the limits

$$f(0) = 0, f^{'(0)} = 1, g(0) = 0, g^{''(0)} = 0, \theta(0) = 1 + T_{slip}\ \theta^{'}(0), \psi(0) = 1 + C_{slip}\ \psi^{'}(0)$$

$$f^{'}(\infty) \to A,\ g^{'}(\infty) \to 1, \theta(\infty) \to 0,\ \psi(\infty) \to 0$$

The characteristics of nanoparticle form and nanofluid models are provided by[24].

Spherical

$\frac{\mu_{nf}}{\mu_f} = \frac{1}{(1-\varphi)^{2.5}} = \frac{1}{A_1}$

Non Spherical

$\frac{\mu_{nf}}{\mu_f} = 1 + A_{shape}\varphi + B_{shape}\varphi^2 = \frac{1}{A_1}$

Table 1. Shape Characteristics and Shape Factors

	Sphere	Cylinder	Platelet	Blade
A		13.5	37..1	14.6
B		904.4	612.6	123.3
Shape Factor, s	3	4.9	5.7	8.6

The following are the physical quantities:

Drag coefficient:

$$Cf_x = \frac{\tau_\omega}{\rho_f (U_\omega)^2} = \frac{\mu_{nf}\frac{\partial u}{\partial x} = 0}{\rho_f (U_\omega)^2}$$

$$Cf_x Re_x^{1/2} = \frac{f^{''}(0)}{A_1}$$

Nusselt number:

$$Nu_x = \frac{xq_\omega}{k_f(T_w - T_\infty)} = \frac{|-x\left(k_{nf}\frac{\partial T}{\partial y} - q_r\right)\ |y=0}{k_f(T_w - T_\infty)}$$

$$Nu_x Re_x^{-1/2} = -\left(A_4 + \frac{4}{3}R_d\right)\theta^{'}(0)$$

Sherwood number:

$$Sh_x = \frac{xq_m}{D_B(C_w - C_0)} = \frac{-x\ D_B\ \frac{\partial C}{\partial y}\Big|\ y=0}{D_B(C_w - C_0)}$$

$$Sh_x Re_x^{-1/2} = -\psi^{'}(0)$$

Where,

$Re_x = \frac{xU_w}{\vartheta_f}$, is the Reynold's number.

3 Results and Discussion

3.1 Numerical Validation and Frame

The adaptive Runge-Kutta technique and the Newton Raphson algorithm are used numerically to solve the boundaries and equations. By first transforming the boundary value issue into an initial value problem, the shooting strategy allows one to estimate the unknowns by making use of the far-field boundary conditions. First things first, suppose:

$$\Gamma_1 = f, \Gamma_2 = f^{'}, \Gamma_3 = f^{''}, \Gamma_3^{'} = f^{'''}, \Gamma_4 = g, \Gamma_5 = g^{'}, \Gamma_6 = g^{''},$$

$$\Gamma_6^{'} = g^{'''}, \Gamma_7 = \theta, \Gamma_8 = \theta', \Gamma_8' = \theta'', \Gamma_9 = \psi, \Gamma_{10} = \psi', \Gamma_{10}' = \psi'',$$

Here is the simplified form of the first-order ODE:

$\Gamma_1^{'} = \Gamma_2, \Gamma_2' = \Gamma_3,$

$$\Gamma_3^{'} = A_1 A_2 \{(\Gamma_2)^2 - \Gamma_1 \Gamma_3 - \frac{\beta}{A_2}\{(\Gamma_5)^2 - \Gamma_4 \Gamma_6 - 1\} - A^2\},$$

$\Gamma_4^{'} = \Gamma_5, \Gamma_5' = \Gamma_6,$

$$\Gamma_6^{'} = \frac{A_5}{\lambda}\{\Gamma_4 \Gamma_3 - \Gamma_1 \Gamma_6\},$$

$$\Gamma_7^{'} = \Gamma_8, \Gamma_8^{'} = \frac{-P_r\{A_3 \Gamma_1 \Gamma_8 - Q_T \Gamma_7\}}{A_4 + \frac{4}{3} R_d},$$

$$\Gamma_{9'} = \Gamma_{10}, \Gamma_{10'} = K_r L_e \Gamma_9 - L_e \Gamma_1 \Gamma_{10}$$

With,

$$\Gamma_1(0) = 0,\ \Gamma_2(0) = 1, \Gamma_3(0) = \Lambda_1,\ \Gamma_4(0) = 0, \Gamma_5(0) = \Lambda_2,\ \Gamma_6(0) = 0,$$

$$\Gamma_7(0) = 1 + T_{slip}\Lambda_3,\ \Gamma_8(0) = \Lambda_3, \Gamma_9(0) = 1 + C_{slip}\Lambda_4, \Gamma_{10}(0) = \Lambda_4$$

Through the utilization of the Newton Raphson technique, the values of Λ_1,Λ_2, Λ_3, and $\Lambda_4$are computed. This process begins with the establishment of a suitable initial assumption.

Temperature, velocity (f′), induced magnetic field (g′), and concentration are some of the physical quantities and variables whose profiles are affected by important factors. A value of 21 is used for infinity, whereas the Prandtl number (P_r) is set to 5. Table 2 shows the thermo-physical properties of the silver nanoparticle and the base fluid, which is blood.

There are some recommendations in the context of this study as follows the primary conclusions derived from this study are related to the operational nature of nanoparticle or the shape and slip conditions that may readily influence the profile of blood-borne silver nanofluids as well as the heat as well as mass transfer efficiency.

Thermal Transfer: Compact structures such as blade-shaped nanoparticles made upward enhancement of about 30% in comparison to spherical nanoparticles.

Mass Transfer: When employing pillar-shaped nanoparticles the mass transfer rates increased to 25% more than when employing spherical nanoparticles.

Influence of Slip Conditions: From the above results it is clear that the reduction of slip conditions by 10% led to a reduction of the nanofluid temperature by 15% and the concentration level by 20%.

3.2 Comparison with Existing Literature

Heat Transfer Enhancement:

These results back up those of Tripathi et al. [4], who found that non-spherical nanoparticles had a positive effect on the thermal properties of nanofluids. Still, this study goes further by providing a quantitative description of the improvements due to blade and pillar shapes under the magnetic field impact, which was beyond the scope of their investigation.

Mass Transfer Characteristics:

Simdhu and Gireesha's [5] findings of increased mass transfer rates in the current work corroborate this. Gireesha [5] showed that nanoparticles influence mass transfer in microchannels. The current study's results, which provide a comparison of various shapes under similar conditions, corroborate this.

Slip Conditions:

The way slip conditions can change the way nanofluids behave is similar to what Barik et al. [13] found when they looked at different slip effects on MHD nanofluid flow. The quantitative nature of the study per se offers a more elaborate insight into the relationship between the stated conditions and nanoparticle shape on the dynamics of fluids. Furthermore, the publication by Mathew et al. [24] provides extensive information about the interaction of multiple slip and nanoparticle shape on stagnation point steel with the induced magnetic field.

Table 2. Comparison of drag coefficient for different A values of Iqbal, Azhar, et al., 2017 and Hayat et al., 2015, 2016 when $\phi = \beta = 0$

A	Iqbal et al., 2017	$Cf_x Re_x^{1/2}$ Hayat et al., 2015	Hayat et al., 2016
0.1	-0.969386	-0.96939	-0.96937
0.2	-0.918107	-0.91811	-0.91813
0.5	-0.667263	-0.66726	-0.66723
0.7	-0.433475	-0.43346	-0.43345
0.8	-0.299388	-0.29929	-0.29921
0.9	-0.154716	-0.15458	-0.1545471
1	0	0	0

Table 3. Thermo-physical properties of silver and blood

Property	Blood (base fluid)	Silver (nanoparticle)
P	1063	10490
Cp	3594	235
K	0.492	429
σ	0.8	6.3×10^7

Table 4. Variation in Shx Rex— 1/2 , when $\beta = 0.1$, A = 0.5 , $\phi = 0.1$& $\lambda = 0.5$

Kr	Le	Cslip	$Sh_x Re_{x-}1/2$ Sphere	Cylinder	Platelet	Blade
1.5	0.3	0.3	0.6166	0.6263	0.6261	0.6217
2.0	0.3	0.3	0.6773	0.6852	0.6850	0.6815
2.5	0.3	0.3	0.7298	0.7363	0.7362	0.7333
2.0	0.2	0.3	0.5737	0.5808	0.5774	0.5774
2.0	0.3	0.3	0.6773	0.6852	0.6850	0.6815
2.0	0.4	0.3	0.7594	0.7675	0.7674	0.7638
2.0	0.3	0.2	0.7265	0.7355	0.7354	0.7313
2.0	0.3	0.3	0.6773	0.6852	0.6850	0.6815
2.0	0.3	0.4	0.6343	0.6412	0.6411	0.6380

3.3 Novel Contributions and Methodological Insights

This study makes several novel contributions to the field:

- This research gives an outline estimate of the impacts of nanoparticle outline and slip conditions on a blood based nanofluid and as such of significance for enhancing nanofluid properties for use in medicinal applications including drug delivery and cancer therapy
- The application of numerical techniques such as Newton-Raphson and Runge-Kutta improved the elaborate analysis of the nonlinear behavior and facilitated the better accuracy of the model. These techniques were essential in simplifying the interrelationships in the fluid dynamics and also gave credibility to the solutions.

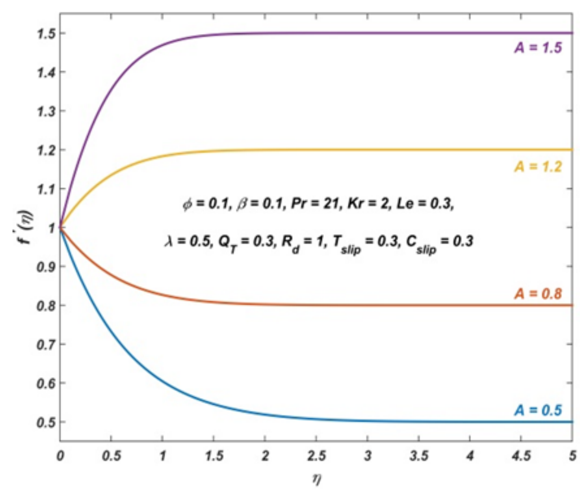

Fig 1. Deviation of 2 f $'(\eta)$ for distinct values of A

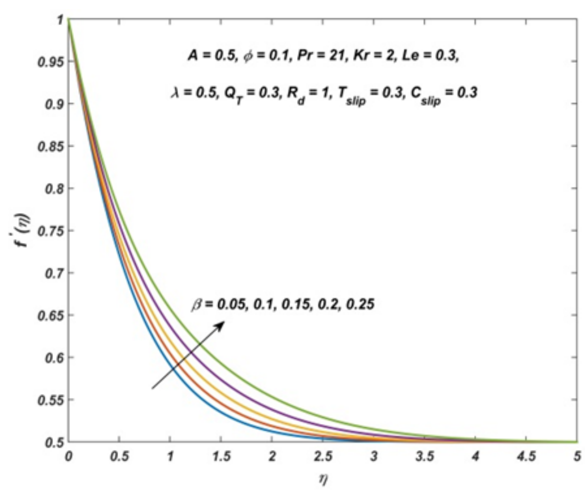

Fig 2. Deviation of f $'(\eta)$ for distinct value of β

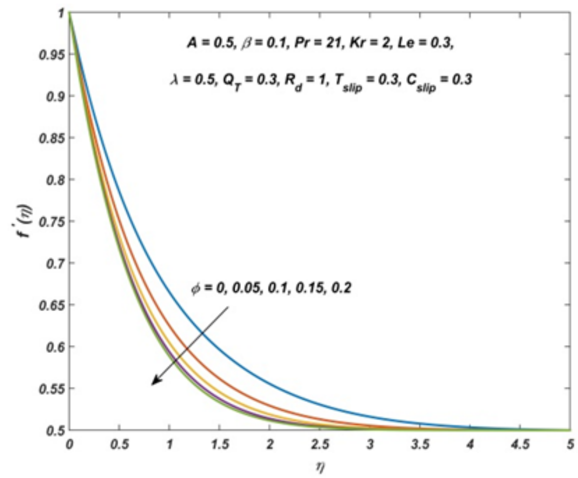

Fig 3. Deviation of f $'(\eta)$ for distinct values of ϕ

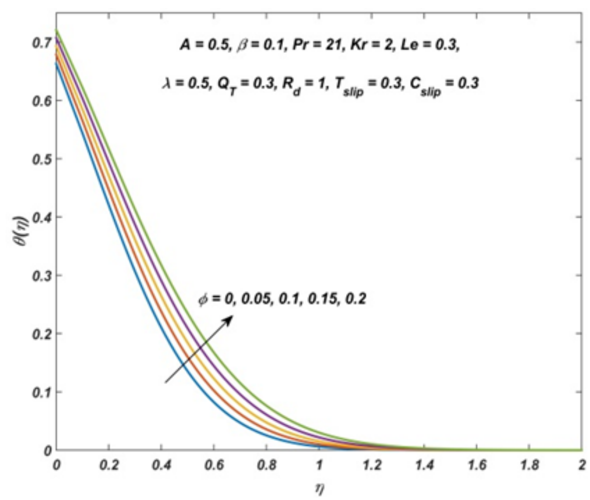

Fig 4. Deviation of θ (η) for distinct values of ϕ

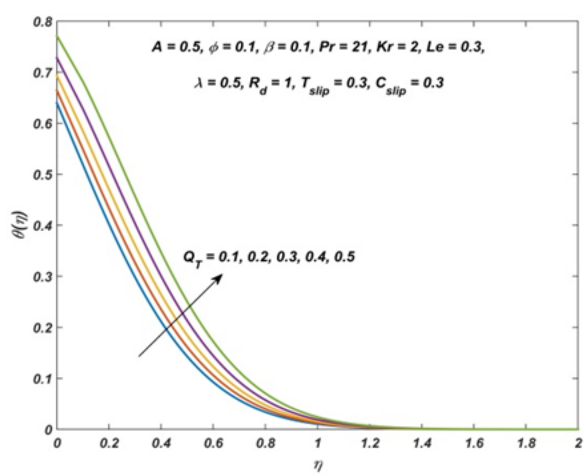

Fig 5. Variation of θ (η) for distinct values of QT

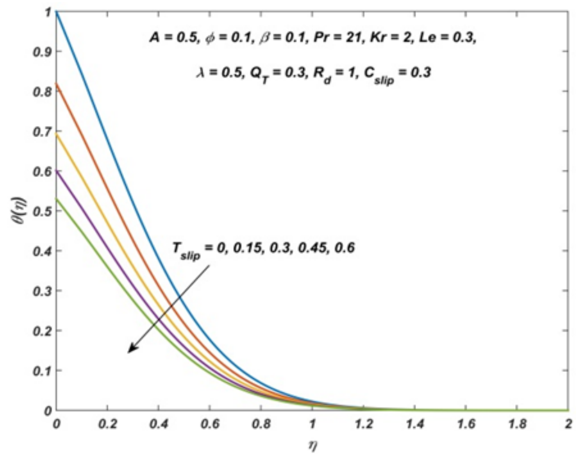

Fig 6. Variation of θ (η) for distinct values of T slip

4 Conclusion

This research has provided expertise in the shape effects of nanoparticles and slip conditions by investigating the thermal and mass transfer behaviors of blood-based silver nanofluids. The blade-shaped nanofluids give 30% heat enhancement, while the pillar-shaped nanofluids increase mass enhancement by 25% compared to the spherical shape of nanoparticles. These measurable improvements, which are foundational to applications that call for precise control of thermal and mass properties such as drug delivery and cancer therapy, are evidence of the novelty of the work. The current study employs a more sophisticated and refined mathematical analysis, utilizing Newton-Raphson and adaptive Runge-Kutta methods, resulting in a more refined modeling compared to the customary analytical approach in nanofluid studies.

However, the study does have some limitations. This study solely examined a limited number of specific types of nanoparticles, thereby overlooking the impact of more complex forms of nanoparticle geometry. Furthermore, the suggested conclusions rely on numeric simulation studies, which, while less sensitive to the phenomena, still serve as experimental validations for the practical applicability of these approaches. To address these gaps, future research could explore the impact of irregular nanoparticle geometries and conduct numerical simulation studies to validate the findings. This approach would not only improve the models with experimental data but also improve the feasibility and reproducibility of the work.

In the future, there is significant potential to design nanoparticles with specific shapes tailored to biomedical sectors, where the fluid properties these nanoparticles control are crucial. Researchers suggest incorporating the current findings into the design of new medical devices for drug delivery and thermal control. Another aspect that needs to be studied is the long-term behavior of these nanofluids under working conditions, so as to confirm their use in clinical practices.

Finally, the work enriches the flow characteristics of nanofluids using a new quantitative method and addresses the importance of nanoparticle geometry for enhancing fluid properties. The methodologies and insights disclosed provide a baseline for further research on the full-fidelity exploitation of nanofluids in different industries and medicine.

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