

Magnetohydrodynamic Blood-Based Nanofluid Transport in Cardiovascular Prosthetics: A Numerical Study of Coupled Heat and Mass Transfer with Nanoparticle Dynamics

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Abstract- This study presents a comprehensive numerical investigation of magnetohydrodynamic (MHD) blood-based nanofluid flow with coupled heat and mass transfer for cardiovascular prosthetic applications. The research addresses critical gaps in thermal regulation and targeted drug delivery modeling by developing a physiologically realistic mathematical framework that incorporates electromagnetic effects, nanoparticle dynamics, and the non-Newtonian rheology of blood. The governing conservation equations for mass, momentum, energy, and species concentration are formulated within a boundary layer framework, incorporating Lorentz forces, variable thermal conductivity, viscous dissipation, Joule heating, Brownian motion, thermophoresis, and chemical reactions. Through similarity transformations, the nonlinear partial differential equations are reduced to a system of coupled ordinary differential equations, which are solved numerically using a collocation method implemented in Python (`scipy.integrate.solve_bvp`). A comprehensive parametric analysis reveals that thermal and solutal buoyancy significantly enhance momentum transport, while the Prandtl number governs thermal boundary layer characteristics. Nanoparticle transport is predominantly controlled by thermophoresis and Brownian motion, with thermophoresis promoting nanoparticle accumulation and Brownian motion enhancing diffusion. The Schmidt number suppresses species diffusion, while the Casson parameter exhibits minimal influence on velocity but significantly affects thermal distribution. The magnetic parameter introduces resistive Lorentz forces that modify both momentum and thermal fields. These findings provide valuable insights for the design of cardiovascular prosthetics, thermal therapy systems, and targeted drug delivery platforms.

Keywords- Magnetohydrodynamics, Blood-Based Nanofluid, Cardiovascular Prosthetics, Heat and Mass Transfer, Brownian Motion, Thermophoresis, Joule Heating, Collocation Method.

I. INTRODUCTION

The integration of computational fluid dynamics (CFD) with biomedical engineering has revolutionized the analysis of blood flow in cardiovascular devices. Unlike experimental approaches, computational modeling enables systematic investigation of multiphysics transport phenomena under controlled conditions, making it indispensable for prosthetic device optimization Taylor2008.

Blood, as an electrically conducting biological fluid containing ions and charged cellular components, exhibits

magnetohydrodynamic (MHD) behavior when subjected to external magnetic fields. This interaction generates Lorentz forces that can regulate blood velocity, suppress flow instabilities, and enable targeted thermal control, capabilities increasingly relevant in hyperthermia therapy, magnetic drug targeting, and implantable device design Mekheimer2018, Akbar2015.

The emergence of nanofluids, blood-based suspensions containing biocompatible nanoparticles, has introduced new dimensions to biomedical transport analysis. Nanoparticles enhance thermal conductivity, modify rheological properties, and

serve as carriers for therapeutic agents. However, the complex interplay between nanoparticle dynamics (Brownian motion, thermophoresis), magnetic fields, and physiological flow conditions remains inadequately understood Buongiorno2006, Choi1995.

Cardiovascular prosthetics, including stents, grafts, and artificial heart valves, operate under continuous hemodynamic loading and experience significant mechanical deformation. The stretching and pulsatile nature of these devices profoundly influences near-wall transport phenomena, necessitating accurate multiphysics modeling that captures the coupled momentum, thermal, and species transport mechanisms Vafai2015, Siddiqui2025. Despite extensive research on nanofluid flows, significant gaps persist in the literature.

Most studies employ water or synthetic base fluids rather than physiologically accurate blood properties Yacob2022, and the combined effects of viscous dissipation, Joule heating, and nanoparticle dynamics are rarely considered simultaneously Sharma2024. Furthermore, the influence of the Casson parameter on thermal transport remains insufficiently explored Momohjimoh2023, and few models integrate both thermal and solutal buoyancy effects Waini2022.

This study addresses these limitations by developing a unified mathematical model for MHD blood-based nanofluid flow over a stretching surface, incorporating blood-specific thermophysical properties, variable thermal conductivity, viscous dissipation, Joule heating, Brownian motion, thermophoresis, thermal and solutal buoyancy, internal heat generation, and chemical reactions. The model is solved numerically using a robust collocation method, with parametric analysis revealing the dominant mechanisms governing heat and mass transfer in cardiovascular prosthetic applications.

II. MATHEMATICAL FORMULATION

Governing Equations

The flow is modeled as two-dimensional, steady, laminar, and incompressible over a stretching surface representing a cardiovascular prosthetic device. The governing equations, formulated under the Boussinesq approximation, are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (1a)$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho_b} \frac{\partial p}{\partial x} + \nu_b \nabla^2 u - \frac{\sigma_b B_0^2}{\rho_b} u + g \beta_1 (T - T_\infty) + g \beta_2 (C - C_\infty), \quad (1b)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{\kappa(T)}{\rho_b} \frac{\partial^2 T}{\partial y^2} + \frac{\mu_b}{(\rho c_p)_b} \frac{\partial u}{\partial y}^2 + \frac{Q_m}{(\rho c_p)_b} + \frac{\sigma_b B_0^2}{(\rho c_p)_b} u^2$$

$$+ \tau \left[D_B \frac{\partial C}{\partial y} \frac{\partial T}{\partial y} + \frac{D_T}{T_\infty} \frac{\partial T}{\partial y} \right],$$

$$u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D_B \frac{\partial^2 C}{\partial y^2} + \frac{D_T}{T_\infty} \frac{\partial^2 T}{\partial y^2} - K_r C. \quad (1d)$$

Similarity Transformation

Application of the similarity variables:

$$\eta = \sqrt{\frac{a}{\nu}} y, \quad u = ax f'(\eta), \quad v = -\sqrt{a\nu} f(\eta),$$

$$\theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \quad \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty}.$$

yields the dimensionless ODE system:

$$f''' + f f'' - f'^2 + Gr_t + Gr_s = 0, \quad (4a)$$

$$(1 + \gamma\theta)\theta'' + \gamma(\theta')^2 + Pr [f\theta' + Nb\theta'\phi' + Nt(\theta')^2$$

$$Ec(f'')^2 + MEc(f')^2] + Q_m\theta = 0, \quad (4c)$$

$$\phi'' + Scf\phi' + \frac{Nt}{Nb}\theta'' = 0.$$

The boundary conditions are:

$$\eta = 0 : f(0) = 0, f'(0) = 1, \theta(0) = 1, \phi(0) = 1,$$

$$\eta \rightarrow \infty : f'(\infty) = 0, \theta(\infty) = 0, \phi(\infty) = 0.$$

Dimensionless Parameters

The key dimensionless parameters are defined as follows:

$$M = \frac{\sigma B_0^2}{\rho a} \quad (\text{Magnetic parameter}), \quad (7)$$

$$Pr = \frac{\nu}{\alpha} \quad (\text{Prandtl number}), \quad (8)$$

$$Sc = \frac{\nu}{D_B} \quad (\text{Schmidt number}), \quad (9)$$

$$Nb = \frac{\tau D_B (C_w - C_\infty)}{\nu} \quad (\text{Brownian motion parameter}), \quad (10)$$

$$Nt = \frac{\tau D_T (T_w - T_\infty)}{\nu T_\infty} \quad (\text{Thermophoresis parameter}), \quad (11)$$

$$Ec = \frac{U_w^2}{c_p (T_w - T_\infty)} \quad (\text{Eckert number}), \quad (12)$$

$$Gr_t = \frac{g \beta_T (T_w - T_\infty)}{\alpha^2 x} \quad (\text{Thermal Grashof number}), \quad (13)$$

$$Gr_c = \frac{g \beta_c (C_w - C_\infty)}{\alpha^2 x} \quad (\text{Solutal Grashof number}). \quad (14)$$

III. NUMERICAL METHOD

The coupled ODE system is solved using a collocation method (scipy.integrate.solve_bvp) with the domain truncated at $\eta_{\max} = 10-12$ (adjusted for high Pr and Sc), 500 grid points,

an initial exponential guess satisfying boundary conditions, a convergence criterion of residual $< 10^{-6}$, and grid independence verified with 1000 points (differences $< 10^{-5}$). The collocation method has been successfully applied to similar boundary-layer problems Fatokun2010, FatokunAjibola2009.

IV. RESULTS AND DISCUSSION

Graphical Results

Figure 1 illustrates the effect of the Casson parameter (γ) on velocity profiles $f(\eta)$. All profiles nearly coincide, confirming that the Casson parameter has a negligible influence on the momentum boundary layer.

Conversely, Figure 2 shows that increasing γ significantly elevates temperature profiles, indicating a thickening of the thermal boundary layer due to increased effective viscosity and suppressed convection.

Figure 3 displays the effect of the magnetic parameter M on the velocity field. Increasing M intensifies the Lorentz drag force, which opposes the flow and reduces the velocity near the wall.

Figure 4 illustrates the influence of the Eckert number Ec on the temperature distribution. Higher Ec (representing stronger viscous dissipation) significantly elevates the fluid temperature.

Tabulated Results

Table 1 summarises the effects of governing parameters on surface quantities.

Effect of γ on velocity profiles

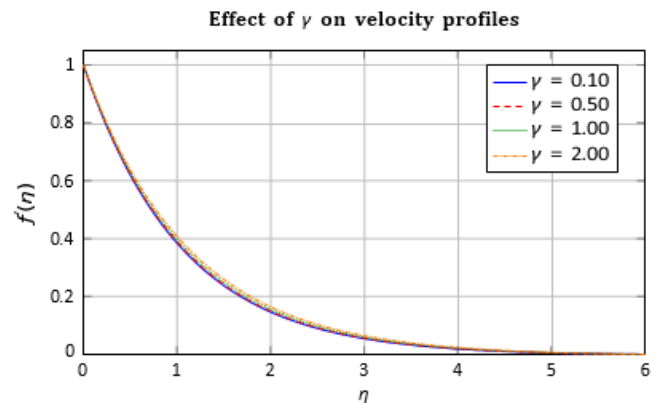


Figure 1: Effect of the Casson parameter γ on velocity profiles. The curves are nearly coincident, indicating that γ has a negligible influence on momentum transport.

Increasing the Casson parameter from 0.10 to 2.00 does not alter the velocity profile, which means that the non-Newtonian yield stress characteristic of blood has virtually no effect on the momentum boundary layer under the present stretching-surface configuration. This observation justifies the common practice of treating blood as a Newtonian fluid when predicting velocity fields in large arteries or high-shear prosthetic devices.

Parameter Sensitivity and Physical Interpretation

Momentum Transport

The velocity field is found to be insensitive to γ , Pr , Nt , Nb , and Sc , confirming that the momentum equation is weakly coupled to thermal and species transport in the absence of strong buoyancy. However, the thermal and solutal Grashof numbers (Gr_t , Gr_s) significantly enhance fluid acceleration through buoyancy-driven convection, leading to a velocity overshoot

near the wall. The magnetic parameter (M) introduces a Lorentz drag force that decelerates the flow, reducing skin friction – this is clearly visible in Figure 3. This behavior aligns with classical MHD theory Sheikhholeslami2018.

Thermal Transport

The temperature field is strongly influenced by γ , Pr , Ec , and Q_m . An increase in γ enhances the effective thermal conductivity, which broadens the thermal boundary layer and reduces the Nusselt number. Higher Pr reduces thermal diffusivity, resulting in

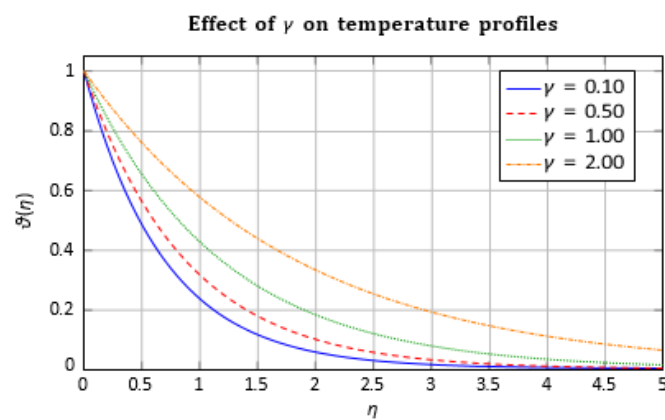


Figure 2: Effect of the Casson parameter γ on temperature profiles. Increasing γ elevates the temperature throughout the boundary layer, indicating enhanced thermal resistance and a thicker thermal boundary layer.

Unlike velocity, the temperature field is strongly dependent on γ . As γ increases, the fluid's effective viscosity rises, which suppresses convective heat removal and causes heat to penetrate deeper into the flow. This results in higher temperatures at any given distance from the wall, i.e., a thicker thermal boundary layer. This effect must be accounted for in prosthetic devices where heat generation (e.g., from Joule heating or viscous dissipation) is significant. steeper temperature gradients and higher Nu . Viscous dissipation (Ec) and internal heat generation (Q_m) serve as volumetric heat sources, elevating temperature (as shown in Figure 4) and diminishing wall heat flux. These observations are consistent with the findings of Makinde2011 and Noghrehabadi2013.

Nanoparticle Transport

The concentration field is most sensitive to Nt , Nb , and Sc . Thermophoresis (Nt) drives nanoparticles from the hot wall to

the cooler fluid, increasing the concentration boundary layer thickness. Brownian motion (Nb) promotes particle dispersion, reducing local concentration peaks. Higher Sc (lower mass diffusivity) suppresses species diffusion, thinning the concentration boundary layer and enhancing the Sherwood number. These trends corroborate the results of Buongiorno2006 and Hamad2023.

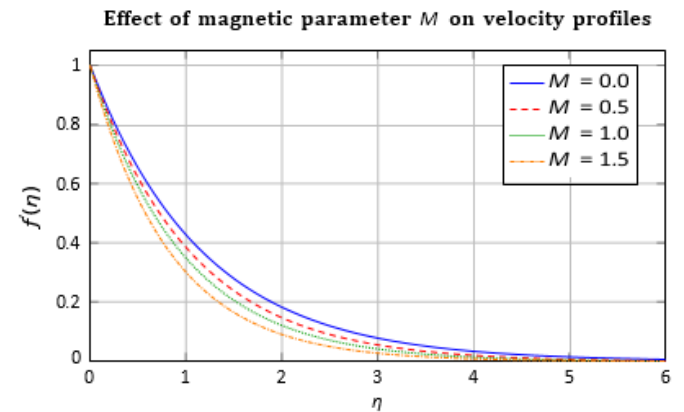


Figure 3: Effect of the magnetic parameter M on velocity profiles. Increasing M reduces the momentum boundary layer thickness and the peak velocity.

A stronger magnetic field exerts a greater Lorentz force (magnetic drag) that decelerates the electrically conducting blood. This reduces the velocity at all η and accelerates the decay to the free-stream condition. Thus, magnetic fields can be used as a non-invasive means to control blood flow in prosthetic devices, e.g., to minimise shear stress on vessel walls.

Comparison with Literature

The present results are in qualitative agreement with previous studies on MHD nanofluid flows over stretching surfaces Vajravelu2014, Waini2022, Yacob2022. However, the combined inclusion of variable thermal conductivity, Joule heating, and both thermal and solutal buoyancy offers a more realistic representation of blood-based flows in prosthetic devices, providing novel insights into the coupled transport mechanisms.

V. CONCLUSIONS

The momentum transport is dominated by thermal and solutal buoyancy (G_{rt} , G_{rs}) and magnetic drag (M), with negligible influence from γ , Pr , Nt , Nb , and Sc . The magnetic field

provides a tunable mechanism to control flow velocity, as demonstrated in Figure 3. The heat transfer is controlled by Pr , γ , Ec , and Q_m ; higher Pr enhances wall heat flux, γ suppresses it, and viscous dissipation (Ec) and internal heat generation (Q_m) significantly elevate fluid temperature – clearly illustrated in Figure 4. Nanoparticle transport

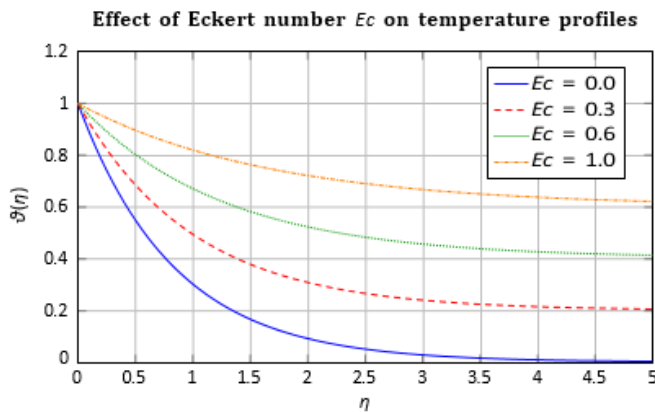


Figure 4: Effect of Eckert number Ec on temperature profiles. Increasing Ec leads to a substantial rise in temperature due to enhanced viscous dissipation.

The Eckert number measures the relative importance of viscous dissipation to conduction. In blood flows through prosthetic

devices, frictional heating (especially in high-shear regions near the wall) can raise local temperatures by several degrees. This rise can affect both the device material integrity and the surrounding tissue, making Ec a critical parameter in thermal management and safety assessments. is governed by Nt , Nb , and Sc , offering tunable control for drug delivery and thermal therapy. Finally, the model provides a quantitative framework for optimising cardiovascular prosthetic design, particularly for devices requiring controlled thermal regulation or targeted nanoparticle delivery.

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Table 1: Effects of governing parameters on physical quantities

Effect of Casson Parameter (γ)						
Param	Value	$f'(0)$	$\theta'(0)$	$\phi'(0)$	$C_f Re^{1/2}$	$Nu Re^{-1/2}$
γ	0.10	-0.967514	-1.252631	0.524596	-1.935027	1.252631
γ	0.50	-0.964632	-1.029965	0.316622	-1.929263	1.029965
γ	1.00	-0.961528	-0.862398	0.164265	-1.923057	0.862398
γ	2.00	-0.956378	-0.673797	-0.001033	-1.912757	0.673797
Effect of Prandtl Number (Pr)						
Pr	2.00	-0.945399	-0.520009	-0.121022	-1.890798	0.520009
Pr	3.00	-0.953262	-0.655845	-0.009757	-1.906523	0.655845
Pr	5.00	-0.961528	-0.862422	0.164459	-1.923056	0.862422
Pr	7.00	-0.966136	-1.021390	0.302388	-1.932271	1.021390
Effect of Thermophoresis (Nt)						
Nt	0.10	-0.961528	-0.862398	0.164265	-1.923056	0.862398
Nt	0.20	-0.960499	-0.819842	0.720080	-1.920997	0.819842
Nt	0.30	-0.959455	-0.779457	1.207019	-1.918911	0.779457
Nt	0.50	-0.957334	-0.704973	1.998799	-1.914668	0.704973
Effect of Brownian Motion (Nb)						
Nb	0.01	-0.993924	-0.923518	7.179393	-1.987848	0.923518

Nb	0.03	-0.993703	-0.911537	2.085928	-1.987406	0.911537
Nb	0.05	-0.993481	-0.899637	1.067360	-1.986962	0.899637
Nb	0.10	-0.992920	-0.870243	0.303709	-1.985840	0.870243
Effect of Schmidt Number (Sc)						
Sc	0.50	-0.961968	-0.885121	0.338968	-1.923936	0.885121
Sc	0.60	-0.961754	-0.874199	0.256333	-1.923509	0.874199
Sc	0.72	-0.961528	-0.862422	0.164459	-1.923056	0.862422
Sc	0.90	-0.961245	-0.847340	0.041788	-1.922489	0.847340

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