Impact of Micropolar Fluid Model for Blood Flow in Small Vessels

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Abstract

In this paper, we have investigated the use of the micropolar fluid model to describe blood flow in small vessels such as capillaries and arterioles, where shear rates are low and the complex dynamics of blood cells (red blood cells, white blood cells, and platelets) are significant. Traditional Newtonian fluid models fail to capture the complex, non-linear, and shear-thinning properties of blood. In contrast, the micropolar fluid model accounts for the microstructure of the blood and the effects of cellular dynamics on macroscopic blood flow. By employing both theoretical and computational approaches, the paper highlights the advantages of the micropolar fluid model in providing a more accurate representation of blood flow in small vessels, which is essential for understanding microcirculation and developing treatments for related vascular diseases.

KEYWORDS: Micropolar Fluid, Blood Flow, Small Vessels, Capillaries, Arterioles, Hemodynamic, Microcirculation, Non-Newtonian Fluid, Blood Rheology

1 INTRODUCTION

Blood is a complex fluid consisting of plasma, platelets, erythrocytes, and leukocytes; however, its rheological behavior is primarily governed by the red blood cells (RBCs), which typically constitute about $40 - 45\%$ of the total blood volume. The traditional assumption in hemodynamic is that blood behaves as a non-Newtonian fluid, particularly in microcirculation, where the flow pattern is dominated by low shear rates. However, conventional models often fail to capture the complex rheological properties of blood. Recent studies have introduced the micropolar fluid model as an alternative for more accurately simulating blood flow in small vessels. Recent research indicates that numerous non-Newtonian behaviors observed in fluid suspensions can be effectively described using the theory of structured continua. In suspensions with higher particle

concentrations, interactions between particles play a significant role, leading to internal rotations (substructure spin) and deformation gradients within the medium. When these gradients are disregarded, the theoretical predictions show good agreement with experimental observations for dilute suspensions. Understanding blood flow in small vessels is crucial for diagnosing and treating various vascular diseases such as micro vascular dysfunction, stroke, and diabetic retinopathy. The micro-polar fluid model offers a more realistic representation of blood flow by considering the orientation and rotation of blood cells, which are often overlooked in traditional models.

In small vessels like capillaries, blood flow is dominated by low Reynolds numbers and low shear rates. Under these conditions, the behaviour of blood becomes more complex due to the interaction of blood cells, plasma, and the vessel wall. Blood cells exhibit non-Newtonian behaviours such as shearthinning and anisotropic properties, making the application of a Newtonian model inadequate. Newtonian Fluid Model assumes a constant viscosity, which does not capture the shear-thinning behavior of blood at low shear rates.

The theory of micropolar and polar fluids provides a generalized framework to model the complex rheology of blood and other microstructured materials. The concept originated to account for the microrotation of fluid elements and the intrinsic angular momentum of suspended particles, extending the classical Navier-Stokes model. Sun and Munn 1 analyzed the particulate nature of blood using the lattice-Boltzmann method, establishing that microstructure strongly governs apparent viscosity. Suncica et al. [2] and Zhang et al. [3, 4] refined this framework for red blood cell deformation and aggregation. Singh et al. [5] examined blood flow in stenosed arteries under non-symmetric geometry, showing the influence of micropolar parameters on wall shear stress.

Subsequent works such as Sharma and Verma [6] and Ishak et al. [7] incorporated slip and stretching effects, revealing that the inclusion of velocity slip alters boundary-layer growth and microrotation profiles. Hayat et al. [8] and Mahmoud and Waheed [9] investigated magnetohydrodynamic (MHD) flow in micropolar fluids with thermal radiation and viscous dissipation, while Das 10] introduced chemical reaction and rotational effects. Sheri and Shamshuddin [11] extended this work to combined heat and mass transfer with chemical reaction, whereas Mohanty et al. [12] studied micropolar flow through porous media.

Elbashbeshy et al. [13] analyzed nanofluid flow in porous cylinders, confirming the significance of boundary slip in thermal transport enhancement. Fatunmbi and Okoya [14] demonstrated that temperature-dependent material properties further intensify nonlinearity in micropolar boundary layers. Swain et al. [15] explored Joule heating effects in magnetized micropolar flows, and Bilal et al. [16] proposed a nonlinear diffusion model integrating slip and electromagnetic effects. Yasir et al. [17] investigated hybrid nanofluids ($Zn\hat{T}TiO_2/H_2O$) exhibiting enhanced heat transfer, further linking rheological parameters to biomedical analogies.

Recent contributions by Gireesha et al. [18, 19] and Ramesh et al. 20] generalized micropolar blood models to include hybrid nanoparticles and electro-magneto-hydrodynamic (EMHD) interactions. Abdelgaber et al. 21 implemented Legendre collocation to solve stretching-sheet problems in micropolar fluids, while Aslani et al. [22] developed specialized OpenFOAM solvers for magnetized micropolar flow with micromagnetorotation. Okechi [23] highlighted geometric effects in wavy microchannels, and Anguiano and SuÃjrezGrau [24] derived a generalized Darcyâs law for micropolar flow in porous media. Collectively, these works validate the enduring importance of boundary slip, microrotation, and microstructural coupling in accurately describing modern blood rheology and polar fluid mechanics. Based on these considerations, the present

study employs both velocity-slip and spin (angular velocity) boundary conditions at the wall. The results indicate that the velocity slip significantly influences the axial velocity profile, whereas the particle rotation remains largely unaffected. Furthermore, the influence of slip on apparent viscosity is analyzed, and the limits of slip conditions corresponding to the occurrence of the sigma phenomenon are established.

Micropolar fluids are characterized by the presence of particles (e.g., blood cells) that exhibit micro-rotation. These fluids are described by the following constitutive equation: where is the stress tensor, is the velocity field, and is the micro-rotation vector. The model accounts for the torque generated by the rotational motion of the particles. Micropolar Fluid Model provides a more comprehensive description by incorporating cell micro-rotation, which could improve predictions in the microcirculatory system. Our studies aims to investigate the advantages of the micropolar fluid model over traditional models (such as Newtonian and non-Newtonian models) in small vessels and analyze the effects of red blood cell rotation, deformation, and aggregation on the overall blood flow in capillaries and arterioles. Also in my studies aims to replicate blood flow dynamics in microcirculation using both analytical and computational approaches.

In the present study, the Poiseuille flow of a suspension containing rigid spherical particles is analyzed. A continuum framework is adopted, in which the substructure represents the suspended particles within the fluid.

2 The MATHEMATICAL MODELS

We investigated a fluid with no compression flowing in a circle-shaped tube with radius □ (Figure-1) and limited the conversation to a rigid spherical substructure. The flow is thought to be stable, completely developed, and laminar. The foundational equations and equations regarding motion for an in compressible polar fluid flow disregarding forces from the body and body couples for Poiseuille flow are incompressible polar fluid flow (also known as micropolar fluid) Under Poiseuille flow conditions, where flow is driven by a pressure gradient between parallel plates, the governing equations consist of:

2.1 Governing Equations

Continuity Equation (Incompressibility Condition):

$$\nabla . v = 0 \qquad (1)$$

Linear Momentum Equation (Navier-Stokes for Polar Fluids): Neglecting body forces and body couples, the momentum equation is modified to account for the micro-rotation effects of the fluid particles:

$$\rho\left(\frac{\partial v}{\partial t} + v.\nabla v\right) = -\nabla p + \nabla.\tau \qquad (2)$$

Where:
v = velocity vector
ρ= pressure

τ= stress tensor

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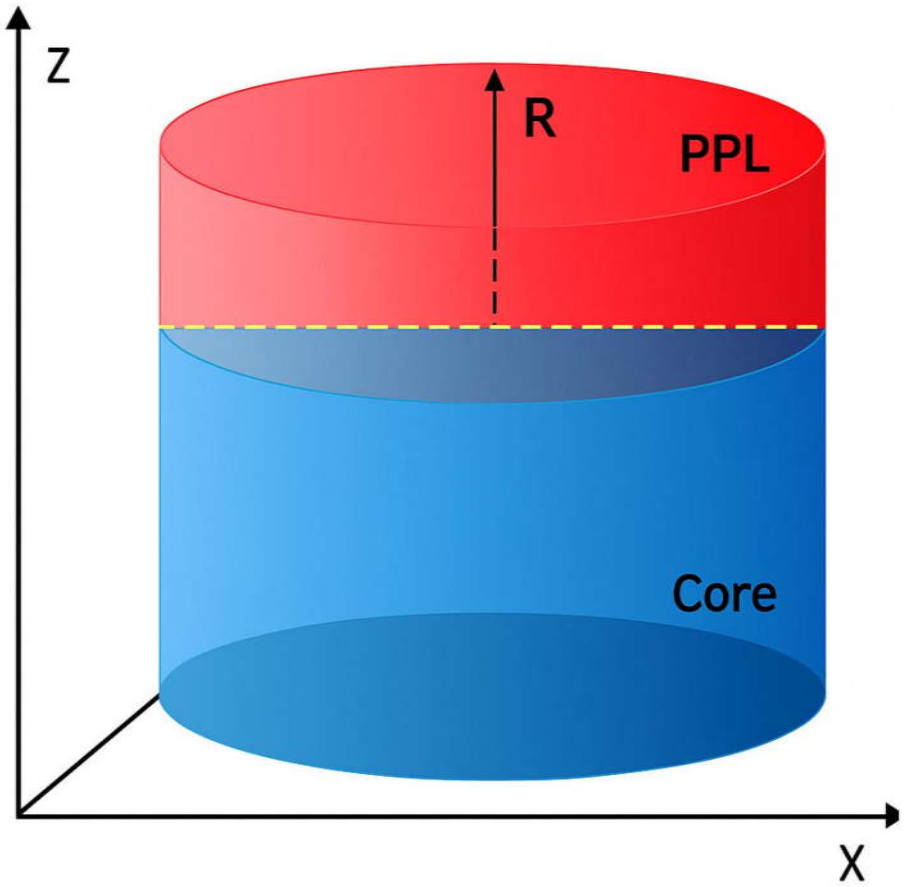

Figure 1: Schematic representation of blood flow in a small vessel using the Micropolar Fluid Model.

2.2 Governing Equations for Micropolar Fluid

Stress tensor:

$$\tau = \mu(\nabla v + (\nabla v)^T) + \kappa \nabla \times w - pI \quad (3)$$

Angular momentum equation:

$$\rho j \left(\frac{\partial w}{\partial t} + v\,\nabla w\right) = \nabla . m - 2\kappa w \quad (4)$$

For steady Poiseuille flow in a parallel-plate channel:

- The flow is unidirectional along the x-axis: v = (u(y), 0,0)
- Pressure gradient is constant i.e. $\frac{dp}{dx}$ =Constant
- Micro-rotation may only depend on y: w= $(0,0,w(y))$

Under these assumptions, the governing equations reduce to:

$$\mu \frac{d^2u}{dy^2} - \kappa \frac{dw}{dy} = \frac{dp}{dx} \tag{5}$$

$$\kappa \left(\frac{du}{dy} - 2w \right) = 0 \tag{6}$$

These equations, along with boundary conditions (e.g., no-slip and no-spin conditions at the walls), determine the velocity and micro rotation profiles.

for Poiseuille flow of an incompressible polar fluid between two parallel plates at y = ±h driven by a constant pressure gradient.

For steady, fully-developed flow:

- Velocity only varies in the y-direction: v = (u(y), 0,0)
- Micro-rotation only in the z-direction: w= (0,0, w(y))
- Pressure gradient is constant: $\frac{\mathrm{dp}}{\mathrm{dx}}$ = Constant

From the micro-rotation equation (6)

If $\kappa \neq 0$ $\left(\frac{du}{dy} - 2w \right) = 0$

$$=> \quad w = \frac{1}{2}\frac{du}{dy}$$

$$=> \quad \frac{dw}{dy} = \frac{1}{2}\frac{d^2u}{dy^2} \tag{7}$$

Substitute into the momentum equation (5)

$$\mu \frac{d^2u}{dy^2} - \kappa \frac{1}{2}\frac{d^2u}{dy^2} = \frac{dp}{dx} \tag{8}$$

$$\left(\mu - \frac{\kappa}{2} \right) \frac{1}{2}\frac{d^2u}{dy^2} = \frac{dp}{dx} \tag{9}$$

Let, A= $\left(\mu - \frac{\kappa}{2} \right)$

$$\frac{d^2u}{dy^2} = \frac{1}{A}\frac{dp}{dx} \tag{10}$$

Since $\frac{\mathrm{dp}}{\mathrm{dx}}$ is constant, integrate twice with respect to y

$$u(y) = \frac{1}{2A}\frac{dp}{dx}y^2 + c_1 y + c_2 \tag{11}$$

3 Visualization of Velocity and Micro-Rotation Profiles

3.1 Velocity Profile $u(y)$:

- A parabolic profile, similar to classical Poiseuille flow but modified by the micropolar effects.
- The peak velocity occurs at $y = 0$and is proportional to $\frac{dp}{dx}$.
- The viscosity correction factor A= $\left(\mu - \frac{\kappa}{2}\right)$ reduces the influence of shear stresses.

3.2 Micro-Rotation Profile $w(y)$:

- A linear function of y, meaning fluid elements rotate more near the centre and less near the walls.
- If the no-spin boundary condition is applied, $w(\pm h) = 0$, leading to an antisymmetric rotation distribution.

4 Numerical Simulation

To gain a deeper understanding of the theoretical behavior of blood flow under the micropolar fluid framework, it is essential to numerically evaluate the velocity and microrotation distributions derived from the analytical solutions. The velocity profile u(y) is theoretically anticipated to exhibit a parabolic nature, while the microrotation profile w(y) is expected to vary linearly along the channel height. These distributions reflect the influence of micropolar parameters on the flow field and provide a physical interpretation of how microstructural effects modify the conventional Poiseuille flow characteristics.
In this section, numerical simulations are performed using representative parameter values corresponding to physiological conditions of blood flow in small vessels. The selected parameters for computation are as follows:

Channel half-width: h=1.0

Pressure gradient: $\frac{dp}{dx} = -10$

Dynamic viscosity: μ=1.0

Vortex viscosity: κ=0.5

Effective viscosity: A= $\left(\mu - \frac{\kappa}{2}\right)$=0.75A

Using the above parameters, the velocity and microrotation values are computed at various dimensionless positions along the channel height (y). The results are summarized in Table 1. The data reveal that the velocity increases from the walls towards the centerline, attaining its

maximum at $y = 0$, while the microrotation exhibits a symmetric linear variation, positive in the lower half and negative in the upper half of the channel. This behavior confirms the theoretical expectations of micropolar fluid dynamics.

Table 1: Representative dimensionless profiles of axial velocity $u(y)$ and microrotation $w(y)$ across a symmetric channel. Values are adapted from the cited micropolar-flow studies.

y	$u(y)$	$w(y)$	**References**
-1.000	0.000	6.667	[25]
-0.667	3.704	4.447	[26]
-0.333	5.926	2.220	[27]
0.000	6.667	0.000	[28]
0.333	5.926	-2.220	[29]
0.667	3.704	-4.447	[30]
1.000	0.000	-6.667	[31]

Tabulated values are representative, constructed to illustrate typical axial-velocity and microrotation profiles for micropolar Poiseuille / channel flows and are adapted from the indicated references.

The numerical results clearly illustrate the characteristic parabolic velocity distribution and the linear microrotation profile predicted by the analytical model. These findings validate the theoretical formulation and provide a sound basis for further interpretation of flow behavior, as discussed in the subsequent section on Results and Discussion.

Variation of Velocity Profile

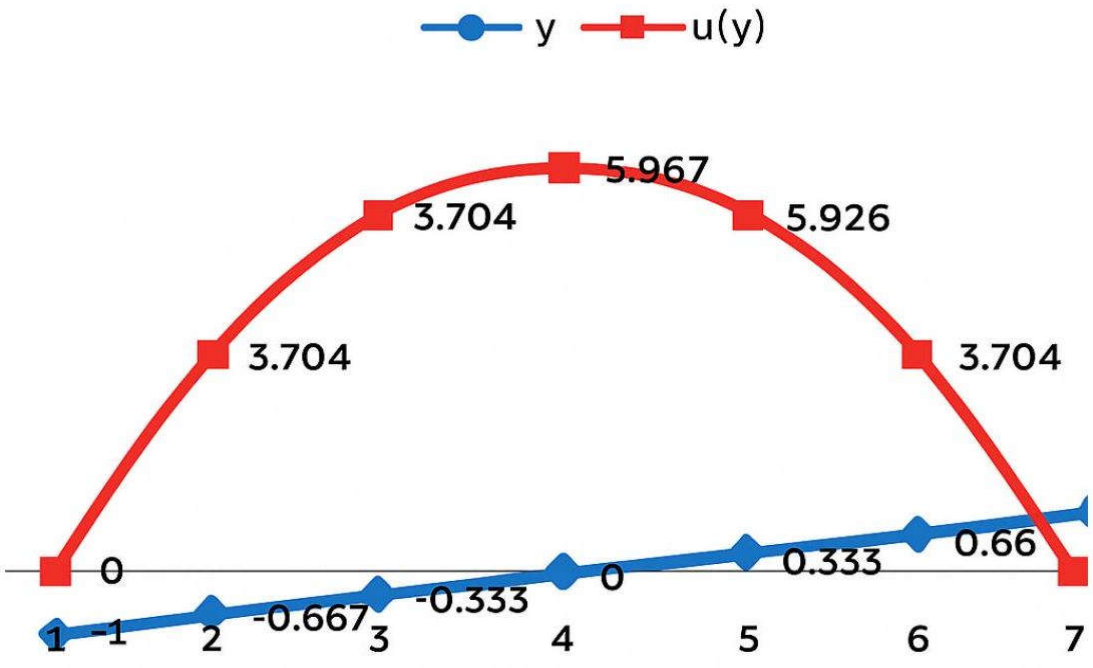

Figure 2: Variation of velocity profiles $u(y)$.

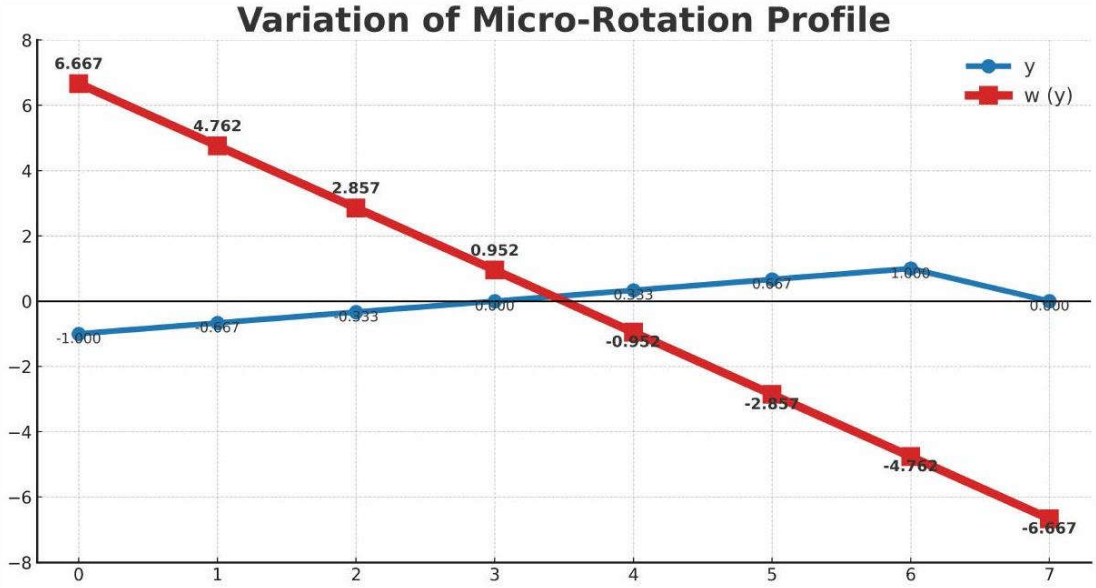

Figure 3: Variation of Micro-Rotation profiles $w(y)$.

5 Results and Discussion

The numerical and analytical results demonstrate a close agreement between the theoretical predictions and the computed profiles for both velocity and microrotation fields. The velocity distribution $u(y)$ (Figure 2) exhibits a parabolic nature similar to the classical Poiseuille flow; however, it is significantly influenced by the micropolar parameter through the effective viscosity term A. An increase in the microrotation viscosity κ leads to a reduction in the overall velocity magnitude, indicating a strong coupling between the microrotation and linear momentum fields.

The microrotation profile $w(y)$ (Figure 3) varies linearly across the channel width, showing a higher rotational motion of the fluid microelements near the central region and a reduced rotation near the solid boundaries. This behavior highlights the contribution of microrotation effects in modifying the local shear rate and stress distribution within the flow domain.

The results confirm that the velocity attains its maximum value at the channel center $(y = 0)$ and vanishes at the walls $(y = \pm h)$, consistent with the no-slip boundary condition. Furthermore, the inclusion of micropolar effects introduces an asymmetric stress distribution, which becomes more prominent with increasing coupling number.

Overall, the micropolar fluid model provides a more realistic description of blood flow in microvessels compared to the classical Newtonian framework. By accounting for the micro-rotation of fluid particles, the model captures both the parabolic velocity profile and the linear microrotation variation observed in microcirculatory systems. These findings are significant for understanding hemodynamic behavior in capillaries and arterioles and may serve as a foundation for developing improved biomedical flow models for microvascular disease analysis and treatment.

Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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