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Mathematical and Computational Analysis of Blood Flow Dynamics in a Tapered Stenosed Artery with Nanoparticle Suspension: Implications for Diagnostic and Therapeutic Applications

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Abstract: ***This study addresses the heat and mass transfer characteristics of blood flow through a tapered, stenosed artery, utilizing the Homotopy Perturbation Method. The blood's flow behavior is described using the Jeffrey fluid model, and the equations governing the flow are formulated in cylindrical coordinates. Analytical solutions for velocity, temperature, concentration, and flux are derived by solving the nonlinear coupled equations. The influence of varying thermophoresis and Brownian motion parameters on the velocity, temperature, concentration, and flux profiles is examined. MATLAB is employed to present the computational results graphically. The study highlights the advantages of this model over existing ones by comparing its results, both analytically and numerically, with other theoretical approaches.***

Keywords: Velocity Profile, Temperature Profile, Concentration Profile, Flux Profile, Thermophoresis, Brownian Motion, Rheology of Blood, Flow Dynamics, Stenosis Effects

1. Introduction

The Global Burden of Disease Study reported that cardiovascular diseases (CVDs) were responsible for 17.3 million deaths worldwide, representing a staggering 41% increase in CVD - related mortality since 1990. This rise underscores the urgent and growing challenge posed by cardiovascular conditions. Currently, CVDs stand as the leading cause of both morbidity and mortality, accounting for more than 30% of all deaths in individuals aged 35 and above. This statistic highlights the pervasive impact of these diseases on a significant portion of the global population, particularly in the prime years of life. Atherosclerosis, a major contributor to cardiovascular diseases, begins its insidious course early in life. It is characterized by the progressive deposition of plaques within the walls of major arteries. These plaques, primarily composed of lipids and inflammatory cells, accumulate silently over time. When such plaques enlarge within coronary arteries, they can obstruct blood flow, leading to conditions such as myocardial ischemia or infarction, commonly known as heart attacks. This blockage of blood flow deprives the heart muscle of oxygen and nutrients, resulting in significant tissue damage or even death if not promptly treated. The pathogenesis of atherosclerosis is a complex process that initiates at the cellular level. This means that effective prevention and treatment strategies must also begin at this foundational stage. The disease is recognized as a chronic inflammatory disorder of the arterial walls, driven by an imbalance in lipid metabolism and a maladaptive inflammatory response. This inflammation leads to the thickening and hardening of the arterial walls, reducing their elasticity and capacity to transport blood efficiently. Key to the development of atherosclerosis is the accumulation of low - density lipoprotein cholesterol in the arterial walls. This accumulation triggers an immune response, drawing white blood cells to the area. This research focuses on the application of nanotechnology in the treatment of CAD and highlights several opportunities where it could lead to innovative therapies or improve existing ones. We discuss the characteristics of current nanomedical formulations optimized for treating atherosclerosis and explain how these formulations can be engineered to target inflammatory processes within the arterial walls. Despite some limitations, nanomedical applications have the potential to pave the way for personalized medicine in treating atherosclerosis. Ongoing research is essential to enhance atherosclerosis - specific targeting and fully realize the benefits of nanotechnology in clinical settings.

2. Problem Statement and Mathematical Formulation

Consider a one - dimensional, pulsatile, axially symmetric, laminar, and incompressible flow of blood through an artery modeled as a tube. In this scenario, blood, treated as a Jeffrey fluid containing nanoparticles, flows with constant viscosity (μ) and density (ρ). The artery is assumed to have a radius R_0 and length L. The geometry of the arterial wall with overlapping stenosis is described by a function that depends on these parameters.

$$\frac{R(z)}{D(z)} = \left[1-\psi\left(L_0^{n-1}(z-d_0)-(z-d_0)^n\right]; \; d_0 < z \le d_0 + L_0$$

$$\frac{R(z)}{D(z)} = 1\text{, otherwise} \quad (1)$$

With

$$\psi = \frac{(\delta)\, n^{\frac{n}{n-1}}}{R_0 L_0^n (n-1)} \quad (2)$$

$$d(z) = R_0 + \xi z, \quad (3)$$

$$z = d_0 + \frac{L_0}{n^{\frac{n}{n-1}}} \quad (4)$$

The equations that describe the flow are:

$$\frac{v}{r} + \frac{\partial (v)}{\partial r} + \frac{\partial u}{\partial z} = 0 \quad (5)$$

$$\rho\left(v\frac{\partial v}{\partial r}+u\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial r}+\frac{1}{r}\frac{\partial}{\partial r}(rS_{rr})+\frac{\partial}{\partial z}(S_{rz})-\frac{1}{r}(S_{\theta\theta}),\quad(6)$$

$$\rho\left(v\frac{\partial u}{\partial r}+u\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial z}+\frac{1}{r}\frac{\partial}{\partial r}(rS_{rz})+\frac{\partial}{\partial z}(S_{zz})+\rho g\alpha_1(T-T_1)+\rho g\alpha_1(C-C_1)\quad(7)$$

$$\left(v\frac{\partial T}{\partial r}+u\frac{\partial T}{\partial z}\right)=\alpha_1\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right)+\tau\left[D_B\left(\frac{\partial C}{\partial r}\frac{\partial T}{\partial r}+\frac{\partial C}{\partial z}\frac{\partial T}{\partial z}\right)+\frac{D_T}{T_0}\left(\left(\frac{\partial T}{\partial r}\right)^2+\left(\frac{\partial T}{\partial z}\right)^2\right)\right]\quad(8)$$

$$\left(v\frac{\partial C}{\partial r}+u\frac{\partial C}{\partial z}\right)=D_B\left(\frac{\partial^2 C}{\partial r^2}+\frac{1}{r}\frac{\partial C}{\partial r}+\frac{\partial^2 C}{\partial z^2}\right)+\frac{D_T}{T_0}\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right)\quad(9)$$

where p is pressure, g − is the acceleration due to gravity, T - is temperature, C - is concentration, $\tau=\frac{(\rho c)_p}{(\rho c)_f}$ is the ratio between the effective heat capacity of the nanoparticle and heat capacity of the fluid. The ambient values of T and C as r tent to R are denoted by T_1 and C_1, D_B is the Browning diffusion coefficient and D_T is the thermospheric diffusion coefficient., $S_{rr}=\frac{2\mu}{1+\lambda_1}\left(1+\lambda_2\left(v\frac{\partial}{\partial r}+u\frac{\partial}{\partial z}\right)\right)\frac{\partial v}{\partial r}$, $S_{rr}=\frac{\mu}{1+\lambda_1}\left(1+\lambda_2\left(v\frac{\partial}{\partial r}+u\frac{\partial}{\partial z}\right)\right)\left(\frac{\partial v}{\partial z}+\frac{\partial u}{\partial r}\right)$, $S_{zz}=\frac{2\mu}{1+\lambda_1}\left(1+\lambda_2\left(v\frac{\partial}{\partial r}+u\frac{\partial}{\partial z}\right)\right)\frac{\partial u}{\partial z}$, $r'=\frac{r}{R_0}$; $z'=\frac{z}{L_0}$; $v'=\frac{L_0}{\delta U}$; $u'=\frac{u}{U}$; $R'=\frac{R}{R_0}$; $p'=\frac{R_0^2}{U\mu L_0}p$; $\varphi=\frac{T-T_1}{T_0-T_1}$; $\sigma=\frac{C-C_1}{C_0-C_1}$; $G_r=\frac{\rho g\alpha_1 R_0^2}{\mu}(T_0-T_1)$; $B_r=\frac{\rho g\alpha_1 R_0^3}{\mu}(C_0-C_1)$; $R_e=\frac{\rho U R_0}{\mu}$; $N_t=\frac{(\rho c)_p D_T T_0}{(\rho c)_f \alpha_1}$; $N_b=\frac{(\rho c)_p D_B C_0}{(\rho c)_f \alpha_1}$; (10)

$$\frac{R_e\delta n^{\frac{1}{n-1}}}{L_0}\ll 1,\ \delta^*=\frac{R_0 n^{\frac{1}{n-1}}}{L_0}\sim o(1),$$

$$\delta^*\left(\frac{\partial v}{\partial r}+\frac{v}{r}\right)+\frac{\partial u}{\partial z}=0,\quad(11)$$

$$\frac{\partial p}{\partial r}=0,\quad(12)$$

$$\frac{\partial p}{\partial z}=\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{r}{1+\lambda_1}\left(\frac{\partial u}{\partial r}\right)\right)+G_r\varphi+B_r\sigma,\quad(13)$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\varphi}{\partial r}\right)+N_b\frac{\partial\sigma}{\partial r}\frac{\partial\varphi}{\partial r}+N_t\left(\frac{\partial\varphi}{\partial r}\right)^2=0,\quad(14)$$

$$N_b\frac{\partial}{\partial r}\left(r\frac{\partial\sigma}{\partial r}\right)+N_t\frac{\partial}{\partial r}\left(r\frac{\partial\varphi}{\partial r}\right)=0\quad(15)$$

$$\sigma=-\varphi\frac{N_t}{N_b}\quad(16)$$

The boundary conditions are as follows:

$\frac{\partial u}{\partial r}=0,\frac{\partial\varphi}{\partial r}=0,\frac{\partial\sigma}{\partial r}=0$, at r=0, w=0, $\varphi=0,\sigma=0$ at r=R (z),

where, $\frac{R(z)}{1+\xi_1 z}=\left[1-\psi_1\left((z-d_0^*)-(z-d_0^*)^n\right)\right]$, $d_0^*<z\le d_0^*+1$,

$$\frac{R(z)}{1+\xi_1 z}=1,\ \text{otherwise},\quad(17)$$

where $d_0^*=\frac{d_0}{L_0},\xi_1=\frac{\xi L_0}{R_0},\psi_1=\delta^*\frac{n^{\frac{n}{n-1}}}{(n-1)}$.

Solution of the problem using numerical and analytical applied methods:

The solution of the equation (14) are calculated by homotopy perturbation method as

$$H(k,\varphi)=(1-k)[L(\varphi)-L(\varphi)_{10}]+k\left[L(\varphi)+N_b\frac{\partial\sigma}{\partial r}\frac{\partial\varphi}{\partial r}+N_t\left(\frac{\partial\varphi}{\partial r}\right)^2\right],\quad(18)$$

where k is the embedding parameter, which has the range $0\le k\le 1$, $L=\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right)$.

$$\varphi_{10}(r,z)=-\left(\frac{r^2-R^2}{4}\right)\quad(19)$$

$$\varphi=\varphi_0+k\varphi_1+k^2\varphi_2+o(k)^3\quad(20)$$

Putting equations (20) in equation (14), and taking $k\to 1$, the following expression for temperature profile is obtained as follows:

$$\varphi(r,z)=(2N_t+N_b)\left(\frac{r^4-R^4}{64}\right)-\left(\frac{r^6-R^6}{1152}\right)(2N_t+N_b)(N_t+N_b).\ (21)$$

$$\sigma(r,z)=\frac{N_t}{N_b}\left((2N_t+N_b)\left(\frac{r^4-R^4}{64}\right)-\left(\frac{r^6-R^6}{1152}\right)(2N_t+N_b)(N_t+N_b)\right).\ (22)$$

By putting equation (21) and (22) in equation (13) we get the result for velocity profile as

$$u(r,z)=\frac{r^2}{2}(1+\lambda_1)\frac{dp}{dz}-\left(G_r-B_r\frac{N_t}{N_b}\right)(2N_t+N_b)(1+\lambda_1)\left(\frac{r^7-21r^3R^4}{8064}-\frac{r^9-12r^3R^6}{82944}\right).\ (23)$$

3. Results and Discussions

In this study, the flow characteristics of blood in arteries, treated as a non - Newtonian fluid, are examined through analytical investigation. The Homotopy Perturbation Method is employed to solve the governing equation for the temperature profile. The results obtained for the temperature profile are then used to assess the profiles of concentration and velocity. To quantify the effects of various parameters involved in the analysis, computer codes were developed. These codes were utilized to evaluate the analytical results for temperature, concentration, and velocity profiles. The study emphasizes the significant impact of key flow parameters on blood flow with nanoparticles, as illustrated through graphs depicting the temperature profile (φ) concentration profile (σ) and velocity profile u (r, z). Specifically, the graphs present the variations in velocity profile u (r, z) concentration profile (σ), and temperature profile (φ) across different values of the Grashof number (G_r), local Grashof number (B_r), thermophoresis parameter (N_t) and Brownian motion parameter (N_b). These parameters collectively influence the flow dynamics and transport phenomena within the arterial system under consideration.

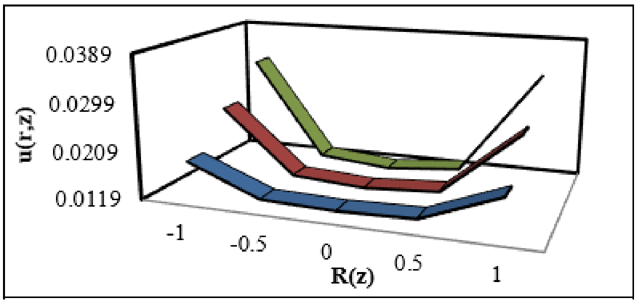

Figure 1: Variation of velocity profile for different values of Grashof number

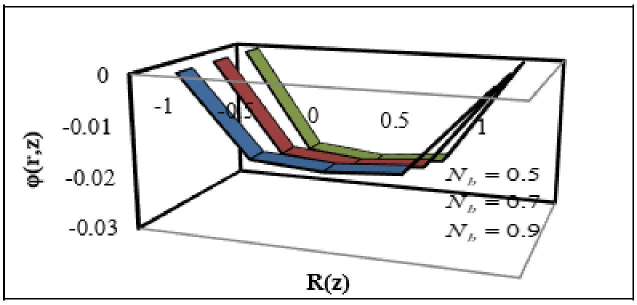

Figure 2: Variation of temperature profile for different values of Brownian motion parameter

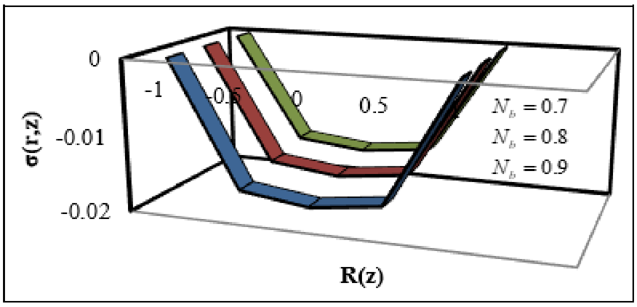

Figure 3: Variation of concentration profile for different values of Brownian motion parameter

Figure. (1) illustrates the variation of the velocity profile u (r, z) with the radius of the artery with stenosis, R (z), for different values of the Grashof number. As observed in the figure, an increase in the Grashof number leads to an increase in the velocity profile. Interestingly, it is noted that at R (z) =0 the velocity profiles vary differently; specifically, with an increase in the Grashof number the velocity profile decreases. Figure. (2) illustrates the variation of the temperature profile for different values of the Brownian motion parameter. It is evident from the figure that an increase in the Brownian motion parameter results in a decrease in the temperature profile. Figure. (3) shows the variation of the concentration profile σ (r, z) for different values of the Brownian motion parameter N_b. It is noted in the figure that an increase in the Brownian motion parameter N_b leads to an increase in the concentration profile.

4. Conclusion

In this study, focuses on metallic nanoparticles within an axisymmetric mild stenosis, where blood is modeled as a non - Newtonian fluid. The investigation includes considerations of heat and mass transfer facilitated by nanoparticles, which are crucial for understanding blood flow dynamics in arteries. The governing equations of flow are solved using the Homotopy Perturbation Method. The analysis includes the finding for velocity profile, temperature profile, concentration profile, Grashof number, Brownian motion parameter and thermophoresis parameter. It has shown the that the velocity profile decreases with increasing Grashof number and local Grashof number, the temperature profile decreases as the Brownian motion parameter and thermophoresis parameter increase. And the concentration profile decreases with increasing Brownian motion parameter and thermophoresis parameter. These observations highlight the significant influences of various parameters on flow characteristics and transport phenomena in the studied arterial model.

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