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Analysis of Combined Convective and Viscous Dissipation Effects for Peristaltic Flow of Rabinowitsch Fluid Model

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Abstract

In this article, mathematical modeling for peristaltic flow of Rabinowitsch fluid model is considered in a non-uniform tube with combined effects of viscous dissipation and convective boundary conditions. Wall properties analysis is also taken into account. Non-dimensional differential equations are simplified by using the well-known assumptions of low Reynolds number and long wavelength. The influence of various parameters connected with this flow problem such as rigidity parameter E_1, stiffness parameter E_2, viscous damping force parameter E_3, Brickman number and Biot number are plotted for velocity distribution, temperature profile and for stream function. Results are plotted and discussed in detail for shear thinning, shear thickening and for viscous fluid. It is found that velocity profile is an increasing function of rigidity parameter, stiffness parameter, and viscous damping force parameter for shear thinning and for viscous fluid, due to the less resistance offered by the walls but, quite opposite behavior is depicted for shear thickening fluids. It is seen that Brickman number relates to the viscous dissipation effects, so it contributes in enhancing fluid temperature for all cases.

Keywords: peristaltic flow, non-uniform tube, viscous dissipation, convective boundary condition, exact solution, non-newtonian fluid

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Nomenclatures

$\tilde{r}$, $\tilde{z}$	Radial and axial direction in wave frame
c	Wave speed
λ	Wave length
k_1	Thermal conductivity of the fluid
η_d	Heat transfer coefficient
C'	Coefficient of viscous damping force
$l(\tilde{z})$	Radius of non-uniform tube
B_r	Brickman number
κ	Biot number
ε	Amplitude ratio
$\tilde{p}$	Pressure
R_e	Reynold's number
ρ_f	Fluid particle density
δ	Elastic tension in the membrane
m	Mass per unit area
γ	Rabinowitsch fluid parameter
$\tau_{\tilde{r}\tilde{z}}, \tau_{\tilde{z}\tilde{z}}, \tau_{\tilde{r}\tilde{r}}$	Shear stresses
E_1	Rigidity parameter
E_2	Stiffness parameter
k	Non-uniform tube
E_3	Viscous damping force parameter

1 Introduction

Peristalsis is a notable spectacle to the physiologist due to the foremost mechanisms for fluid transport in many living organisms. For instance, peristaltic mechanism may be involved in swallowing of food through esophagus, urine transport from kidney to bladder through the ureter, transport of blood in heart, transport of lymph in the lymphatic vessels, in the vasomotion of small blood vessels, motion of spermatozoa in cervical canal, transport of bile in bile duct, also some worms practice peristalsis for locomotion. Many biological and industrial instruments such as finger pumps, roller pumps, blood pump machines, heart-lung machines and dialysis machines are engineered based on the peristaltic mechanism[1,2]. The peristaltic transport phenomenon of viscous fluid was first initiated by Latham[1]. After

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Latham, Shapiro *et al.*[2] explored the peristaltic flow problem of viscous fluid utilizing long wavelength and a low Reynolds number approximations. Later, some authors made useful analysis regarding the peristaltic transport phenomenon separately for viscous and non-Newtonian fluids in different flow geometries with different assumptions[3–11].

We deliberate here on the Rabinowitsch fluid model. Rabinowitsch fluid model is one of the fluid models where there exists a nonlinear relationship between the shear stress and strain rate. This fluid model has its significance as the three major categories for fluid are depicted for different values of nonlinear factor γ *i.e.* for $\gamma = 0$ this model represents Newtonian fluids, for $\gamma < 0$ it represents shear thickening fluids, and for $\gamma > 0$ it exhibits the behavior of shear thinning fluids. The experimental validation for this model was offered by Wada and Hayashi[12]. Singh *et al.*[13] adopted Rabinowitsch fluid model to discuss the performance of pivoted curved slider bearings. Akbar and Nadeem[14] discussed the applications of Rabinowitsch fluid model for peristalsis. Further investigations in the peristaltic motion of Rabinowitsch fluid model can be gathered in Refs. [15–17].

Recently, heat transfer in peristalsis has gained much importance due to its numerous applications in engineering and biomedical sciences. Heat transfer comprises many complicated processes such as assessing skin burns, destruction of undesirable cancer tissues, dilution technique in examining blood flow, paper making, vasodilation, food processing, metabolic heat generation and radiation between surface and its environment. It may be noticed that blood flow increases when a man does hard physical exercises also when the body is exposed to excessive heat environment. In order to take care of the increase in blood flow, the dimensions of the artery have to increase suitably. It is well known heat transfer takes place from the surface of the skin by the practice of evaporation through sweating when the temperature of the ambiances exceeds 20°C, and when the temperature is less 20°C, the heat in human body drops by both conduction and radiation. Sinha *et al.*[18] debated peristaltic flow of MHD and heat transfer in an asymmetric channel in the presence of variable viscosity, velocity-slip and temperature jump conditions. Eldabe *et al.*[19] analyzed the MHD peristaltic flow of a couple stress fluids with heat and mass transfer in a porous medium.

Wall properties such as wall stiffness, wall rigidity, wall tension, *etc*. have gained much importance in peristalsis due to the physical importance. In particular the increased intensity of such effects can significantly influence the blood pressure in human body. Dheia *et al.*[20] discussed the peristaltic flow of a Jaffery fluid in a porous medium channel with wall properties and heat transfer. Kumar *et al*. studied effects of wall properties and heat transfer on the peristaltic transport of a jeffrey fluid in a channe. For more aspects see Refs. [22, 23].

To the best of author's knowledge, no existing literature highlights the combined convective and viscous dissipation effects for peristaltic flow of Rabinowitsch fluid model with wall properties. Exact solutions are computed for velocity and temperature profile. The results are examined for temperature and velocity profile for different values of parameters, namely Biot number, Brickman number, rigidity, stiffness and viscous damping forces.

2 Mathematical model

We have considered the peristaltic motion phenomenon for the two dimensional flow of an incompressible fluid in a non-uniform annulus. The equations for conservation of mass, momentum and energy can be written as:

$$\frac{\partial \tilde{u}}{\partial \tilde{r}}+\frac{\tilde{u}}{\tilde{r}}+\frac{\partial \tilde{w}}{\partial \tilde{z}}=0, \tag{1}$$

$$\rho\left(\frac{\partial \tilde{u}}{\partial \tilde{t}}+\tilde{u}\frac{\partial \tilde{u}}{\partial \tilde{r}}+\tilde{w}\frac{\partial \tilde{u}}{\partial \tilde{z}}\right)=-\frac{\partial \tilde{p}}{\partial \tilde{r}}+\frac{1}{\tilde{r}}\frac{\partial(\tilde{r}\tau_{\tilde{r}\tilde{r}})}{\partial \tilde{r}}+\frac{\partial(\tau_{\tilde{r}\tilde{z}})}{\partial \tilde{z}}-\frac{\tau_{\tilde{\theta}\tilde{\theta}}}{\tilde{r}}, \tag{2}$$

$$\rho\left(\frac{\partial \tilde{w}}{\partial \tilde{t}}+\tilde{u}\frac{\partial \tilde{w}}{\partial \tilde{r}}+\tilde{w}\frac{\partial \tilde{w}}{\partial \tilde{z}}\right)=-\frac{\partial \tilde{p}}{\partial \tilde{z}}+\frac{1}{\tilde{r}}\frac{\partial(\tilde{r}\tau_{\tilde{r}\tilde{z}})}{\partial \tilde{r}}+\frac{\partial(\tau_{\tilde{z}\tilde{z}})}{\partial \tilde{z}}, \tag{3}$$

$$\begin{aligned}\rho c_p\left(\frac{\partial \tilde{T}}{\partial \tilde{t}}+\tilde{u}\frac{\partial \tilde{T}}{\partial \tilde{r}}+\tilde{w}\frac{\partial \tilde{T}}{\partial \tilde{z}}\right)=k_1\left(\frac{\partial^2 \tilde{T}}{\partial \tilde{r}^2}+\frac{1}{\tilde{r}}\frac{\partial \tilde{T}}{\partial \tilde{r}}+\frac{\partial^2 \tilde{T}}{\partial \tilde{z}^2}\right)+\\ \tau_{\tilde{r}\tilde{r}}\left(\frac{\partial \tilde{u}}{\partial \tilde{r}}\right)+\tau_{\tilde{z}\tilde{z}}\left(\frac{\partial \tilde{u}}{\partial \tilde{z}}\right)+\\ \tau_{\tilde{r}\tilde{z}}\left(\frac{\partial \tilde{w}}{\partial \tilde{r}}+\frac{\partial \tilde{u}}{\partial \tilde{z}}\right).\end{aligned} \tag{4}$$

In the above equations ρ is density, $\tilde{u}$ and $\tilde{w}$ are the respective velocity components in radial and axial directions respectively, c_p is specific heat.

Appropriate boundary conditions for the problem (shown in Fig. 1) are defined as:

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