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Effect of heat transfer and rotation on the peristaltic flow of a micropolar fluid in a vertical symmetric channel

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Abstract: In this paper, the peristaltic flow of a micropolar fluid in a vertical symmetric channel with rotation and heat transfer is investigated. The flow analysis has been developed for low Reynolds number and long wavelength approximation. The flow is investigated in a wave frame of reference moving with the velocity of the wave. The numerical solution for velocity, temperature and microrotation component have been obtained ,The system of differential equations is solved numerically using NDsolve Mathematica method. The numerical Solution computation is performed using the Mathematica inbuilt numerical Solver NDsolve method. The impact of various physical parameters on the velocity, the temperature and the microrotation component are discussed through graphs. Comparison was made with the results obtained in the presence and absence of rotation. The results indicate that the effect of the micropolar parameter k, rotation Ω, density ρ, the material constants γ Prandtl number $\Pr$ and heat source/sink β are very pronounced in the phenomena. Numerical results are graphically discussed for various values of physical parameters of interest. The present study has a wide range of applications in bio-medical engineering, i.e. peristaltic flow of a micropolar fluid.

Keywords: Biological index, Dam reservoirs, diatoms, Groundwater, streams.

1 Introduction

Today, interest in peristalsis issues has increased due to many applications in physics and medicine. The relaxation and contraction mechanism in the fluid movement along the wall is known as peristaltic motion. Peristalsis is important in many physiological processes, such as the urine transmission to the bladder through the ureter, the action of bile in the gallbladder, fluid movement through lymphatic vessels, spermatozoa movement in ducts, and movement of the oesophagus when swallowing food. Peristalsis is also important in many industrial applications as pumps to transport of many kinds of fluid, radar systems, micro-pumps in pharmacology and fuel control in the rocket chamber, and power generators. Khalid et al. [1] investigated the unsteady flow of a micropolar fluid with free convection caused due to temperature and concentration differences. Micropolar fluid is taken over a vertical plate oscillating in its own plane. Wall couple stress is engaged at the bounding plate together with isothermal temperature and constant mass diffusion. Abd-Alla and Abo-Dahab [2] studied Rotation effect on peristaltic transport of a Jeffrey fluid in an asymmetric channel with gravity field. Hayat et al. [3] introduced the peristaltic activity of Ree-Eyring fluid in a rotating frame. Heat transfer analysis with viscous dissipation and heat source/sink is taken into account. Con- vective conditions of heat transfer in the formulation are adopted. Mahmood et al. [4] discuss a new boundary condition for a slip in peristaltic transport for a micropolar fluid within an asymmetric medium. Power-law fluid with a thin film of coating will be used for lubrication purposes. Flow analysis is carried out for a two-dimensional asymmetric medium. Dar [5] examined Peristaltic Motion of Micropolar Fluid With Slip Velocity in A Tapered Asymmetric Channel in Presence of Inclined Magnetic Field and Thermal Radiation. Eldabe et al. [6] investigated The effect of heat generation and radiation on the peristaltic motion of micropolar fluid with heat and mass transfer through porous medium in a symmetric channel. Swarnalathamma et al. [7] discussed Hall effects on Unsteady MHD Rotating flow of Second grade fluid through Porous medium between two vertical plates. Ahmad et al [8] Micropolar fluids consist of microstructured polymeric additives, suspended in a non-symmetric way, and are exemplified as non-Newtonian fluids. The whirling microconstituents of micropolar fluids agitate the hydrodynamics of the fluid flow, and this mechanism provides a basis for successful implementation of micropolar fluids in modern engineering and biotechnology. Abd-Alla et al.[9] Investigations of the peristaltic flow of a fluid in a channel induced by a wave traveling on its wall have many applications in various branches of science. The physical mechanism of the flow induced by the traveling wave can be well understood and is known as the peristaltic transport mechanism. This mechanism is a natural cause of motion of fluids in the body

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of living creatures, and it frequently occurs in organs such as ureters, intestines, and arterioles. Tiwari et al. [10] studied Analytical study of micropolar fluid flow through porous layered microvessels with heat transfer approach. Dar and Elangovan [11] investigatived Influence of an Inclined Magnetic Field and Rotation on the Peristaltic Flow of a Micropolar Fluid in an Inclined Channel. S.Sridhar and V. Ramesh Babu [12] investigated the effects of heat generation and radiation on convective heat and mass transfer electrically conducting micropolar fluid through porous medium in a symmetric channel. Abd-Alla et al. [13]examined Effect of rotationon peristaltic flow of a micropolar fluid through a porous medium with an external magnetic field. Moayedi et al. [15] investigated the Electrohydrodynamic effect using

micropolar fluid model, The EHD flow for the forced convection heat transfer in a smooth channel is simulated. G.K. Ramesh et al. [16] examined Time-dependent squeezing flow of Casson-micropolar nanofluid with injection/suction and slip effects. Mahmood et al. [17] discussed a new boundary condition for a slip in peristaltic transport for a micropolar fluid within an asymmetric medium. Power-law fluid with a thin film of coating will be used for lubrication purposes. Abd-Alla et al. [18] studied Magnetic Field and Gravity Effects on Peristaltic Transport of a Jeffrey Fluid in an Asymmetric Channel. Eldabe and Ramadan [19] investigatived Impacts of peristaltic flow of micropolar fluid with nanoparticles through a porous medium under the effects of heat absorption and wall properties: Homotopy perturbation method.

In this paper, the effects of both rotation and heat transfer of the peristaltic transport of fluid through a medium in a symmetric channel are studied analytically and computed numerically. The material was represented by the constitutive equations for a fluid. Numerical solutions under the consideration of long wavelength and low-Reynolds number is presented. Effect of the rotation, micropolar parameters, density, and the heat source/sink in wave frame are computed numerically. Numerical results are given and illustrated graphically.

2 Formulation of the Problem

Let us consider the problem for three-dimensional peristaltic flow of unsteady incompressible micropolar fluid in asymmetric channel of width $2d'$. The channel walls are convectively heated. Thermal radiation and non-uniform heat source/sink effects are present. The whole system is in a rotating frame of reference in the presences rotation Ω. Flow configuration is presented in Fig. (1). Flow inside the channel is induced due to propagation of sinusoidal waves of wavelength λ along the flexible walls of the channel with constant speed c. The temperature of the lower and upper walls of the channel are T_0 and T_1 respectively. The geometry of the two wall surfaces is described by

The geometries of the wall surfaces are described by:

$$\bar{h}(\bar{X},\bar{t}) = a + b\cos\frac{2\pi}{\lambda}(\bar{X} - c\bar{t}) \qquad (1)$$

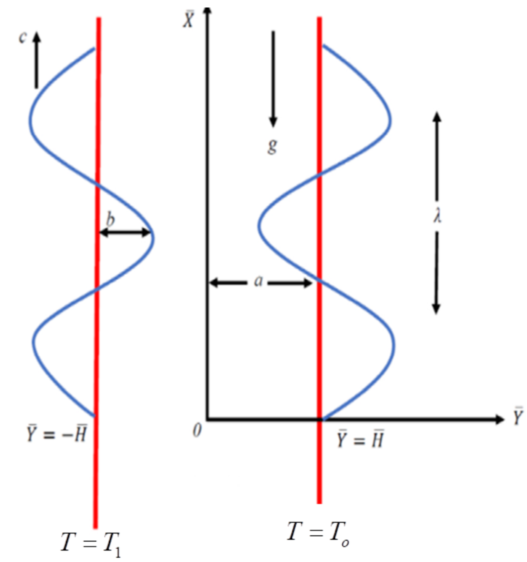

Fig. 1: Geomtery of the Problem

where a is the half-width at the inlet, b is the wave amplitude, λ is the wavelength, c is the propagation velocity, and $\grave{t}$ is the time. Neglecting the body couples, the equations of motion for unsteady flow of an incompressible micropolar fluid are

$$\frac{\partial\bar{U}}{\partial\bar{X}} + \frac{\partial\bar{V}}{\partial\bar{Y}} + \frac{\partial\bar{W}}{\partial\bar{Z}} = 0 \qquad (2)$$

$$\rho\left[\frac{\partial\bar{U}}{\partial\bar{t}} + \bar{U}\frac{\partial\bar{U}}{\partial\bar{X}} + \bar{V}\frac{\partial\bar{U}}{\partial\bar{Y}} + \bar{W}\frac{\partial\bar{U}}{\partial\bar{Z}}\right] + 2\rho\Omega\bar{W} = -\frac{\partial\bar{P}}{\partial\bar{X}} + K\frac{\partial\bar{\Phi}}{\partial\bar{Y}} + (K+\mu)\left[\frac{\partial^2\bar{U}}{\partial\bar{X}^2} + \frac{\partial^2\bar{U}}{\partial\bar{Y}^2} + \frac{\partial^2\bar{U}}{\partial\bar{Z}^2}\right] + \rho g\beta(T - T_0) \qquad (3)$$

$$\rho\left[\frac{\partial\bar{V}}{\partial\bar{t}} + \bar{U}\frac{\partial\bar{V}}{\partial\bar{X}} + \bar{V}\frac{\partial\bar{V}}{\partial\bar{Y}} + \bar{W}\frac{\partial\bar{V}}{\partial\bar{Z}}\right] = -\frac{\partial\bar{P}}{\partial\bar{Y}} - K\frac{\partial\bar{\Phi}}{\partial\bar{X}} + (K+\mu)\left[\frac{\partial^2\bar{V}}{\partial\bar{X}^2} + \frac{\partial^2\bar{V}}{\partial\bar{Y}^2} + \frac{\partial^2\bar{V}}{\partial\bar{Z}^2}\right] \qquad (4)$$

$$\rho\left[\frac{\partial\bar{W}}{\partial\bar{t}} + \bar{U}\frac{\partial\bar{W}}{\partial\bar{X}} + \bar{V}\frac{\partial\bar{W}}{\partial\bar{Y}} + \bar{W}\frac{\partial\bar{W}}{\partial\bar{Z}}\right] - 2\rho\Omega\bar{U} = -\frac{\partial\bar{P}}{\partial\bar{Z}} + (K+\mu)\left[\frac{\partial^2\bar{W}}{\partial\bar{X}^2} + \frac{\partial^2\bar{W}}{\partial\bar{Y}^2} + \frac{\partial^2\bar{W}}{\partial\bar{Z}^2}\right] \qquad (5)$$

$$\rho\acute{j}\left[\frac{\partial\bar{\Phi}}{\partial\bar{t}} + \bar{U}\frac{\partial\bar{\Phi}}{\partial\bar{X}} + \bar{V}\frac{\partial\bar{\Phi}}{\partial\bar{Y}} + \bar{W}\frac{\partial\bar{\Phi}}{\partial\bar{Z}}\right] = -2K\bar{\Phi} + k\left(\frac{\partial\bar{V}}{\partial\bar{X}} - \frac{\partial\bar{U}}{\partial\bar{Y}}\right) + \gamma\left[\frac{\partial^2\bar{\Phi}}{\partial\bar{X}^2} + \frac{\partial^2\bar{\Phi}}{\partial\bar{Y}^2}\right] + (\alpha+\beta+\gamma)\frac{\partial^2\bar{\Phi}}{\partial\bar{Z}^2} \qquad (6)$$

$$\rho c_p\left[\frac{\partial\bar{T}}{\partial\bar{t}} + \bar{U}\frac{\partial\bar{T}}{\partial\bar{X}} + \bar{V}\frac{\partial\bar{T}}{\partial\bar{Y}} + \bar{W}\frac{\partial\bar{T}}{\partial\bar{Z}}\right] = K\left[\frac{\partial^2\bar{T}}{\partial\bar{X}^2} + \frac{\partial^2\bar{T}}{\partial\bar{Y}^2} + \frac{\partial^2\bar{T}}{\partial\bar{Z}^2}\right] + Q_0 \qquad (7)$$

Where, $\bar{U}, \bar{V}, \bar{W}$ are velocity, $\bar{\Phi}$ is the microrotation, $\bar{P}$ is the fluid pressure, $\rho, \vec{J}$ are the fluid density, microgyration parameter and K is the thermal conductivity. The material constants μ, k, α, β and γ satisfy the following inequalities [14]:

$2\mu + k \geq 0, \quad k \geq 0, \quad 3\alpha + \beta + \gamma \geq 0, \quad \gamma \geq |\beta|.$ (7a)

We assume the pressure takes the form

$$\overline{P} = \overline{P} - \frac{1}{2}\rho\Omega^2\overline{R}. \tag{8}$$

Where, $\vec{\Omega} = \Omega\vec{J}$, $\vec{J}$ is the unit vector, $\vec{\Omega} = (0, \Omega, 0)$ is the rotation vector, $\vec{R}$ is given by $\vec{R}^2 = \overline{X}^2 + \overline{Y}^2 + \overline{Z}^2$, the equations of motion in the rotating frame have two additional terms, $\rho\left(\vec{\Omega} \wedge \left(\vec{\Omega} \wedge \vec{R}\right)\right)$, is the centrifugal force, $2\rho\left(\vec{\Omega} \wedge \vec{V}\right)$, is the Coriolis force, $\vec{R} = \left(\overline{X}, \overline{Y}, \overline{Z}\right)$, is the position vector, $\vec{V} = \left(\overline{U}, \overline{V}, \overline{W}\right)$ is the velocity vector, μ is the viscosity constant of the classical fluid dynamics, k, γ, areise viscosity constant for micropolar fluid, Φ is the microrotation vector, ρ and j are the fluid density and microgyration parameter.

For further analysis, we use the following non-dimensional variables and parameters:

$$x = \frac{\bar{x}}{\lambda\Gamma},\ y = \frac{\bar{y}}{a},\ z = \frac{\bar{z}}{\lambda},\ u = \frac{\bar{u}}{c},\ v = \frac{\lambda\bar{v}}{a\,c},\ w = \frac{\bar{w}}{c},\ \Phi = \frac{\bar{\Phi}}{c},\ h = \frac{\bar{h}}{a},\ p = \frac{a^2\bar{p}}{\lambda\mu c},\ t = \frac{c\,\bar{t}}{\lambda},\ j = \frac{\bar{J}}{a^2},\ \theta = \frac{\bar{T} - \bar{T}_0}{\bar{T}_1 - \bar{T}_0},$$
$$Re = \frac{\rho c a}{\mu},\ \beta = \frac{Q_0 a^2}{\mu\, c_p (T_1 - T_0)} \tag{9}$$

3 Solution of the Problem

After using dimensionless variables (9), after dropping bars, the Eqs.2-7 become:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{10}$$

$$Re\,\delta\left[u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial w}{\partial z}\right] + \frac{2\,\rho\,a^2\,\Omega}{\mu}w = -\frac{\partial p}{\partial x} + \frac{K\,a}{\mu}\frac{\partial \Phi}{\partial y} + \left[\frac{\mu + K}{\mu}\right]\left[\delta^2\,\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \delta^2\,\frac{\partial^2 u}{\partial z^2}\right] + m\theta \tag{11}$$

$$Re\,\delta^2\left[u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial w}{\partial z}\right] = -\frac{\partial p}{\partial y} - \frac{K\,a}{\mu}\delta^2\frac{\partial \Phi}{\partial y} + \left[\frac{\mu + K}{\mu}\right]\left[\delta^3\,\frac{\partial^2 v}{\partial x^2} + \delta\frac{\partial^2 v}{\partial y^2} + \delta^3\,\frac{\partial^2 v}{\partial z^2}\right] \tag{12}$$

$$Re\,\delta\left[u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial w}{\partial z}\right] - \frac{2\,\rho\,a^2\,\Omega}{\mu}u = -\frac{\partial p}{\partial z} + \left[\frac{\mu + K}{\mu}\right]\left[\delta^2\,\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \delta^2\,\frac{\partial^2 w}{\partial z^2}\right] \tag{13}$$

$$\rho acJ\delta\left[u\frac{\partial W}{\partial x} + v\frac{\partial W}{\partial y} + w\frac{\partial w}{\partial z}\right] = -2Kc\,a^2\Phi + \gamma\,c\left[\delta^2\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2}\right] + Kc\,a\left[\delta^2\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right] + c\,\delta^2\frac{\partial^2 \Phi}{\partial z^2} \tag{14}$$

$$Re\,\delta\left[u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial w}{\partial z}\right] = \frac{1}{Pr}\left[\delta^2\,\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \delta^2\,\frac{\partial^2 \theta}{\partial z^2}\right] + \beta \tag{15}$$

Under the assumption of long wavelength and low Reynolds number Eqs. (10)-(15) reduce to

$$\frac{2\,\rho\,a^2\,\Omega}{\mu}w = -\frac{\partial p}{\partial x} + \frac{K\,a}{\mu}\frac{\partial \Phi}{\partial y} + \left[\frac{\mu + K}{\mu}\right]\frac{\partial^2 u}{\partial y^2} + m\theta \tag{16}$$

$$\frac{\partial p}{\partial y} = 0 \tag{17}$$

$$-\frac{2\,\rho\,a^2\,\Omega}{\mu}u = -\frac{\partial p}{\partial z} + \left[\frac{\mu + K}{\mu}\right]\frac{\partial^2 w}{\partial y^2} \tag{18}$$

$$-2Kc\,a^2\Phi + \gamma\,c\frac{\partial^2 \Phi}{\partial y^2} + Kc\,a\frac{\partial u}{\partial y} = 0 \tag{19}$$

$$\frac{1}{Pr}\frac{\partial^2 \theta}{\partial y^2} + \beta = 0 \tag{20}$$

Where $m = \frac{\rho\,g\,\beta a^2\,(T_1 - T_0)}{\mu\,c}$

The corresponding boundary conditions in the wave frame are

$$u = -1\ ,\quad w = -1,\ \Phi = 0,\ \theta = 1,\ at\ y = 0 \tag{21}$$

$$u = -1,\ w = -1,\ \Phi = 0,\ \theta = 0 \quad at \quad y = h \tag{22}$$

4. Numerical Results and Discussion

The transformed dimensionless equations are treated numerically by NDsolve method -Solve in Mathematica. This methodology has advantages because it selects the appropriate algorithm and automatically track any possible error. Further, such procedure provides better computing outcomes with minimal CPU time (3–4 min) per evaluation. In fact, graphical descriptions are directly provided and avoided intricate solution expressions by such method. However, this method incorporates Shooting technique which provides graphical descriptions utilizing minimal to maximal range. The Eqs. (16), (18) and (19) subjected to boundary conditions (21) and (22) have been solved numerically by the NDsolve method. The obtained results are validated, a built-in function in the commercial software Mathematica. Getting the exact solution is impossible. Therefore, the numerical solution has been obtained.

5 Discussion

In the present work, our data available from our published papers are mostly new from this investigation. This section is dedicated to discussing the influence of pertinent parameters on common profiles (velocity, temperature, and microrotation component) with the assistance of graphical illustrations. Additionally, the numerical values of the reduced Predental number and heat source/sink are analyzed with the help of the tabular results. The effects of rotation Ω, Prandtl number $\Pr$ and heat source/sink β are discussed in detail. The numerical computation is performed using the Mathematica inbuilt numerical Solver NDsolve method.

Figure 2: shows the variations of the axial velocity u with respect to $y-axis$ for different values of micropolar parameter k, rotation Ω and density ρ. It is observed that the velocity decreases with increasing of micropolar parameter, while it increases with increasing of rotation and density, the axial velocity increases near the channel centre, but decreases near the wall due to the fixed value of the flux rate. It is evident from both the figures that the axial velocity profile is parabolic for fixed values of the parameters at the inlet $z=0$. It is noticed that the velocity satisfied the boundary conditions.

Figure 3: shows the variations of the axial velocity w with respect to $y-axis$ for different values of micropolar parameter k, rotation Ω and density ρ. It is observed that the velocity increases with increasing of micropolar parameter, while it decreases with increasing of rotation and density. It is evident from both the figures that the axial velocity profile is parabolic for fixed values of the parameters at the inlet $z=0$. It is noticed that the velocity satisfied the boundary conditions.

The effect of the micropolar parameters k and γ can be observed from Figure 4, in which the variations of the microrotation Φ with respect to $y-axis$ for different values of micropolar parameters k, and γ. It is observed that the microrotation decreases with increasing of micropolar parameter k in the interval $0 \le y \le 0.3$, while it increases with increasing of micropolar parameter k in the interval $0.3 \le y \le 0.6$, as well, it increases with increasing of micropolar parameter γ and it decreases with increasing of micropolar parameter γ in the interval $0.3 \le y \le 0.6$. It is noticed that the microrotation satisfied the boundary conditions.

The temperature θ versus $y-axis$ is given in Figure 5 to impact $\Pr$ and β, respectively. It is noted that the temperature θ increases with an increase in $\Pr$ and β, which results in a significant rise in the temperature distribution. Additionally, it is noticed that the temperature distribution satisfies the boundary conditions. It should be stated here that the present outcomes are acquired numerical technique not as in [14] by an exact solution. For the purpose of comparison, good agreement can be seen between our approximate results demonstrated in Figure 5.

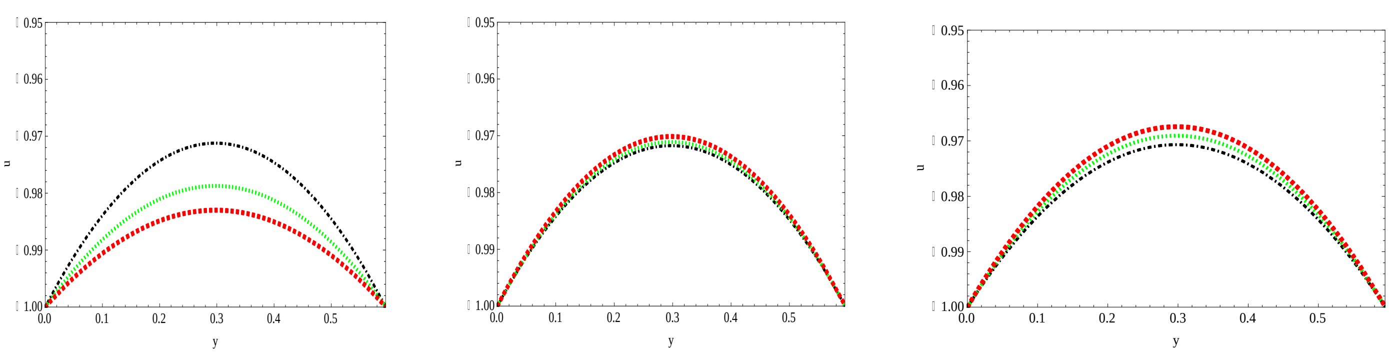

Fig. (2): Variation of the velocity u concerning the $y-$axis with different value of K, ρ, Ω

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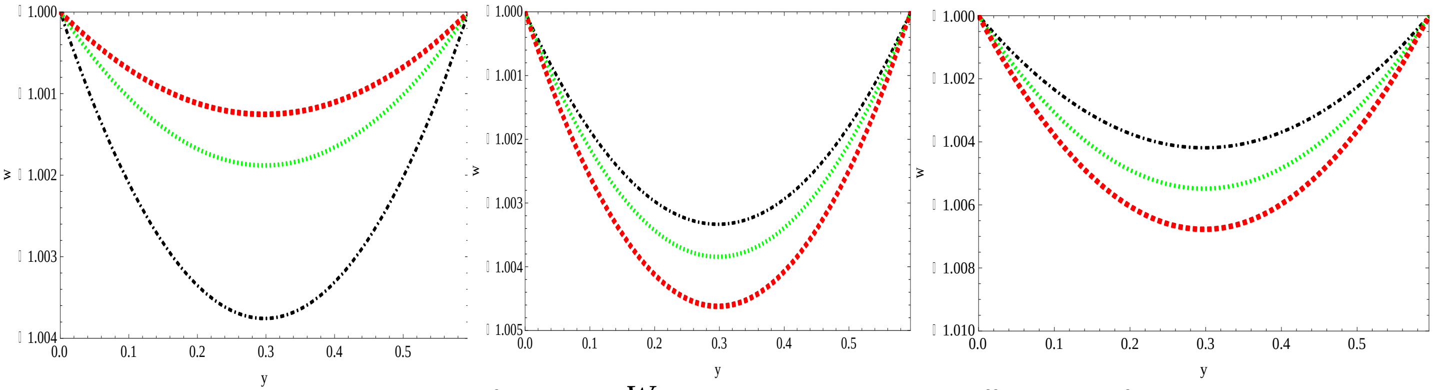

Fig. (3): Variation of the velocity W concerning the $y-$axis with different value of K, ρ, Ω

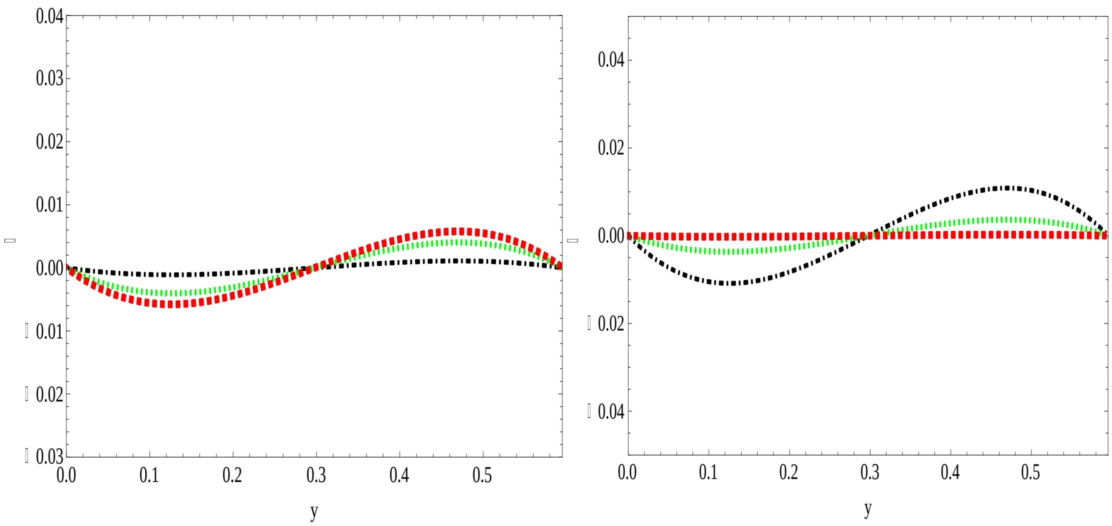

Fig. (4): Variation of the microrotation of velocity Φ concerning the axial –y with different values of K, γ

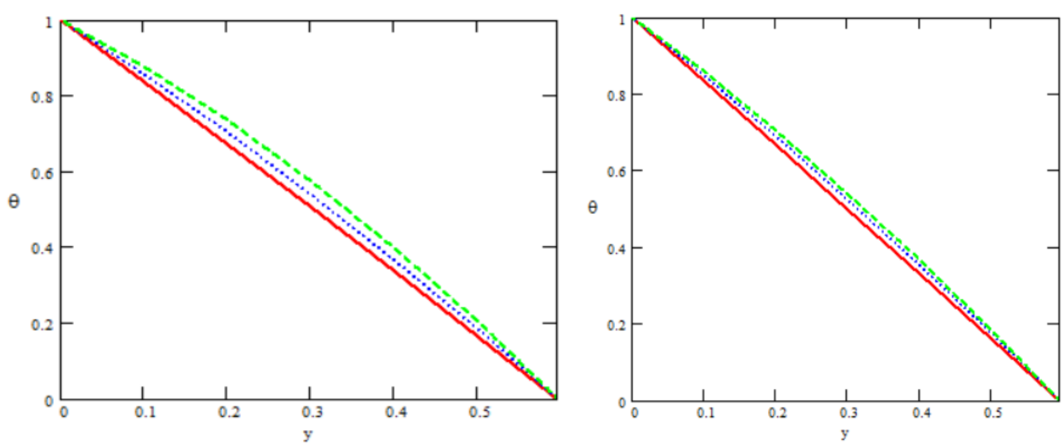

Fig. (5): Variation of the Temperature θ concerning the axial-y with different values of β, Pr

6 Conclusion

Due to vital applications in biomedical engineering, medicine, and chemistry, in this study, we investigated the peristaltic flow of a micropolar fluid symmetric channel. The exact solution is obtained for velocity, temperature, and microrotation component. Furthermore, the governing equations of the micropolar fluid model are derived. The highly nonlinear partial differential equations are simplified through assumptions of long wavelength and small Reynolds numbers. The nondimensional governing equations of the flow are solved numerically using the NDsolve method. The findings of this study are as follows:

I. Velocity diminishes in the middle of the channel, while the inverse behavior diminishes in the walls of the channel.

II. The fluid velocity profile is an increasing function near the upper channel for Gr and Ω.

III. The velocity distribution noticed a reverse trend on the walls of the channel to the micropolar fluid Prandtl number $\Pr$.

IV. The temperature profile increases with an increase in β and $\Pr$.

V. The overall conclusion is that the peristaltic flow of miropolar fluid under the influence of a rotation is less than that of a Newtonian fluid under the influence of the rotation (Fig. 2).

VI. It is clear that the behavior of the temperature and microrotation component are found and it has satisfied the boundary conditions.

VII. The results presented in this paper should prove useful for researchers in Science, Medicine and Engineering, as well as for those working on the development of fluid mechanics.

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