INTERACTION OF HEAT TRANSFER AND PERISTALTIC PUMPING OF FRACTIONAL SECOND GRADE FLUID THROUGH A VERTICAL CYLINDRICAL TUBE

by

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This paper deals with a theoretical investigation of the interaction of heat transfer with peristaltic pumping of a fractional second grade fluid through a tube, under the assumption of low Reynolds number and long wave length approximation. Analytical solution of problem is obtained by using Caputo's definition. Effect of different physical parameters material constant, amplitude ratio, friction force, temperature, and heat transfer on pumping action and frictional force are discussed with particular emphasis. The computational results are presented in graphical form.

Key words: *peristalsis, fractional second grade model, heat transfer, pressure, friction force, Caputo's fractional derivative*

Introduction

Peristalsis is an important well known mechanism for mixing and transporting fluid. Peristaltic flow can be generated by the propagation of waves along the flexible wall of channel or tube. This mechanism is used by a living body to propel or to mix the contents of the tube such as transport of urine through ureter, food mixing and chyme moment in the intestines, transport in bile duct, *etc*. Peristaltic flows have attracted a number of researchers because of wide applications in physiology and industry. The theoretical work on peristaltic transport primarily with inertia free Newtonian flow driven by sinusoidal transverse wave of small amplitude by Fung and Yih [1]. Burns and Parkes [2] studied the peristaltic motion of a viscous fluid through a pipe and a channel by considering sinusoidal variation at the walls. Abd El Naby and El-Misiery [3] picked up peristaltic pumping of a Carreau fluid in presence of an endoscope. Abd El Hakeem *et al.* [4] studied hydro magnetic flow of generalized Newtonian fluid through a uniform tube with peristalsis. Recently a study of ureteral peristalsis in cylindrical tube through porous medium has been discussed by Rathod *et al.* [5].

Existing literature indicates that little efforts are made to explain the heat transfer on peristaltic transport. Some authors [6-9] have analyzed the interaction of peristalsis with heat transfer. Peristaltic mechanism in an asymmetric channel with heat transfer has been presented

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by Hayat *et al*. [10]. Recently, Vasudeva *et al.* [11] have studied the peristaltic flow of a Newtonian fluid through a porous medium in vertical tube under the effect of magnetic field. The influence of heat transfer on peristaltic transport of Jeffrey fluid in vertical porous stratum has been studied by Vajarvelu *et al.* [12]. Vasudeva *et al.* [13] have investigated the effect of heat transfer on peristaltic flow of a Jeffrey fluid through a porous medium in a vertical annulus. Srinivas and Kothandapani [14] have presented the peristaltic transport in an asymmetric channel with heat transfer.

In the last few decades fractional calculus is increasingly using in the modeling of various physical and dynamical system. Fractional calculus has encountered much success in the description of viscoelastic characteristics. The starting point of the fractional derivative model of non-Newtonian model is usually a classical differential equation which is modified by replacing the time derivative of an integer order by the so-called Riemann-Liouville fractional calculus operators. This generalization allows one to define precisely non-integer order integrals or derivatives. Fractional second grade model is the model of viscoelastic fluid. In general, fractional second grade model is derived from well known second grade model by replacing the ordinary time derivatives to fractional order time derivatives and this plays an important role to study the valuable tool of viscoelastic properties.

In the past few decades, both mathematicians and physicists have made significant progress in this direction. Mention may be made to some recent investigations [15-20] that deals with fractional Oldroyed-B model, unsteady flows of viscoelastic fluid with fractional Maxwell model, fractional Burgers' model, and fractional generalized Burger's model through channel/tube/annulus. Very recent works on fractional second grade fluids have been made by Tripathi *et al*. [21] solutions for velocity field and pressure are obtained by homotopy perturbation method and Adomain decomposition methods. Further, Tripathi *et al.* [22] have studied the numerical study on peristaltic flow of generalized Burgers' fluids in uniform tubes in the presence of an endoscope. Peristaltic flow of a fractional second grade fluid through a cylindrical tube has been studied by Tripathi *et al.* [23]. Some important works [24-29] such as: Numerical and analytical simulation of peristaltic flow of generalized Oldroyd-B fluids, Mathematical model for the peristaltic flow of chyme movement in small intestine, Peristaltic transport of fractional Maxwell fluids in uniform tubes: applications in endoscopy, Peristaltic transport of a viscoelastic fluid in a channel, Numerical study on peristaltic transport of fractional biofluids model, A mathematical model for swallowing of food bolus through the oesophagus under the influence of heat transfer have been studied. Tripathi *et al.* [30] have studied the peristaltic transport of a generalized Burgers' fluid: application to the movement of chyme in small intestine. Heat and mass transfer effects on the peristaltic flows in annulus and endoscope [31, 32] are very important because of its practical engineering applications, such as food processing and blood pumps in heart lungs machines. Endoscopic and heat transfer effects on the peristaltic flow of a third-order fluid with chemical reactions have been studied by Nadeem and Akbar [33]. Peristaltic flow of a Williamson fluid in an inclined asymmetric channel with partial slip and heat transfer has been studied by Akbar *et al.* [34].

The present analysis is of viscoelastic fluid with fractional second grade model and heat transfer through a vertical cylindrical tube under the assumption of long wavelength and low Reynolds number. Caputo's definition is used to find fractional differentiation and numerical results of problem for different cases are discussed graphically. This model is applied to study of moment of chyme through small intestine and also applicable in mechanical point of view.

Caputo's definition

Caputo's definition [23] of the fractional order derivative is defined as:

$$D^{\alpha_1} f(t) = \frac{1}{\Gamma(n-\alpha)} \int_b^t \frac{f^n(\tau)}{(t-\tau)^{\alpha_1+1-n}} d\tau \quad (n-1, \mathrm{Re}(\alpha_1) \le n,\ n \in N)$$

where, α_1 is the order of the derivative and is allowed to be real or even complex and b – the initial value of function f. For the Caputo's derivatives we have:

$$D^{\alpha_1} t^{\beta_1} = \begin{cases} 0 & (\beta_1 \le \alpha_1 - 1) \\ \dfrac{\Gamma(\beta_1+1)}{\Gamma(\beta_1-\alpha_1+1)} t^{\beta-\alpha} & (\beta_1 > \alpha_1 - 1) \end{cases}$$

Mathematical formulation

Consider an incompressible fractional second grade fluid in vertical tube (fig. 1) induced by sinusoidal wave trains propagating with constant speed c. The walls of the tube are maintained at temperature T_0 and T_1, respectively.

The constitutive equation for viscoelastic fluid with fractional second grade model is given by:

$$\bar{S} = \mu\left(1 + \lambda_1^{\alpha_1} \frac{\partial^{\alpha_1}}{\partial \bar{t}^{\alpha_1}}\right)\dot{\gamma} \tag{1}$$

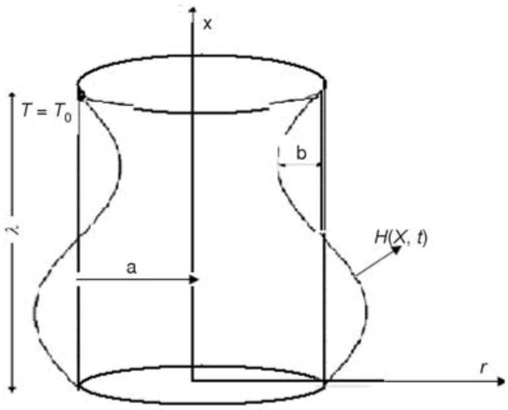

Figure 1. Flow geometry

where $\bar{S}, \bar{t}, \bar{\lambda}_1$ and $\dot{\gamma}$ are the, shear stress, time, material constants, and rate of shear strain, μ is the viscosity, and α_1 – the fractional time derivative parameters such that $0 < \alpha_1 \le 1$. This model reduces to second grade models with $\alpha_1 =$ 0 , and classical Navier-Stokes model is obtain by substituting $\bar{\lambda}_1 = 0$.

The governing equations of the motion of viscoelastic fluid with fractional second grade model for axi-symmetric flow are given by:

$$\frac{1}{\bar{r}} \frac{\partial}{\partial \bar{r}} (\bar{r}\bar{u}) + \frac{\partial \bar{u}}{\partial \bar{x}} = 0 \tag{2}$$

$$\rho\left(\frac{\partial \bar{u}}{\partial \bar{t}} + \bar{u}\frac{\partial \bar{u}}{\partial \bar{x}} + v\frac{\partial \bar{u}}{\partial \bar{r}}\right) = \frac{\partial \bar{p}}{\partial \bar{x}} + \mu\left(1 + \bar{\lambda}_1^{\alpha_1}\frac{\partial^{\alpha_1}}{\partial \bar{t}^{\alpha_1}}\right)\left[\frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left(\bar{r}\frac{\partial \bar{u}}{\partial \bar{r}}\right) + \frac{\partial^2 \bar{u}}{\partial \bar{x}^2}\right] + \rho g a(T - T_0) \tag{3}$$

$$\rho\left(\frac{\partial \bar{v}}{\partial \bar{t}} + \bar{u}\frac{\partial \bar{v}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{v}}{\partial \bar{r}}\right) = \frac{\partial \bar{p}}{\partial \bar{r}} + \mu\left(1 + \bar{\lambda}_1^{\alpha_1}\frac{\partial^{\alpha_1}}{\partial \bar{t}^{\alpha_1}}\right)\left[\frac{\partial}{\partial \bar{r}}\left(\frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}(\bar{r}\bar{v})\right) + \frac{\partial^2 \bar{v}}{\partial \bar{x}^2}\right] \tag{4}$$

$$\rho c_p\left(\frac{\partial \bar{T}}{\partial \bar{t}} + \bar{u}\frac{\partial \bar{T}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{T}}{\partial \bar{r}}\right) = k\left(\frac{\partial^2 \bar{T}}{\partial \bar{r}^2} + \frac{1}{r}\frac{\partial \bar{T}}{\partial \bar{r}} + \frac{\partial^2 \bar{T}}{\partial \bar{x}^2}\right) + Q_0 \tag{5}$$

In order to simplify the solution of this non-linear system, it is necessary to introduce non-dimensional parameters:

$$\left.\begin{aligned} x=\frac{\bar{x}}{\lambda},\quad r=\frac{\bar{r}}{a},\quad \lambda_1^{a_1}=\frac{c\bar{\lambda}_1^{a_1}}{\lambda},\quad u=\frac{\bar{u}}{c},\quad v=\frac{\bar{v}}{c\delta} \\ \delta=\frac{a}{\lambda},\quad \phi=\frac{\bar{\phi}}{a},\quad p=\frac{\bar{p}a^2}{\mu c\lambda},\quad \mathrm{Re}=\frac{\rho c a\delta}{\mu} \\ \theta=\frac{\bar{T}-T_0}{T_0},\quad \mathrm{Gr}=\frac{\rho g\alpha a^3 T_0}{\mu},\quad \mathrm{Pr}=\frac{\mu c_p}{k},\quad \beta=\frac{a^2 Q_0}{kT_0} \end{aligned}\right\} \tag{6}$$

where ρ is the fluid density, δ – is defined as wave number, p, c, v, u, t, r, ϕ, λ, and Q stand for pressure, wave velocity, axial velocities, radial velocities, time, radial co-ordinate, amplitude, wavelength, and volume flow rate, T is the temperature, g – the acceleration due to gravity, c_p – the specific heat, Q_0 – the constant heat addition/absorption, β – the dimensionless heat source/sink parameter, Gr – the Grashof number, and Pr – the Prandtl number, respectively. Using the non-dimensional parameters of eq. (6) and taking long wavelength approximation and low Reynolds number, eqs. (2-5) reduces to:

$$\frac{\partial p}{\partial x}=\left(1+\lambda_1^{\alpha_1}\frac{\partial^{\alpha_1}}{\partial \bar{t}^{\alpha_1}}\right)\left\{\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}\right\}+\mathrm{Gr}\,\theta \tag{7}$$

$$\frac{\partial p}{\partial r}=0 \tag{8}$$

$$\frac{\partial^2 \theta}{\partial r^2}+\frac{1}{r}\frac{\partial \theta}{\partial r}+\beta=0 \tag{9}$$

Boundary conditions are given by:

$$\frac{\partial u}{\partial r}=0 \quad \text{at} \quad r=0, \quad u=0 \quad \text{at} \quad r=h \tag{10}$$

$$\frac{\partial \theta}{\partial r}=0 \quad \text{at} \quad r=0, \quad \theta=0 \quad \text{at} \quad r=h \tag{11}$$

Solving eq. (9) using the boundary conditions (11), we get:

$$\theta=\frac{\beta}{4}(h^2-r^2) \tag{12}$$

Substituting eq. (12) into eq. (7) and solving with boundary condition (10) we obtain:

$$\left(1+\lambda_1^{\alpha_1}\frac{\partial^{\alpha_1}}{\partial t^{\alpha_1}}\right)u=\frac{1}{4}\frac{\partial p}{\partial x}(r^2-h^2)+\frac{\mathrm{Gr}\beta}{64}(r^4+3h^4-4h^2r^2) \tag{13}$$

The volume flow rate is defined as:

$Q=\int_0^h 2ru\,\mathrm{d}r$, which by virtue of eq. (13), reduces to:

$$\left(1+\lambda_1^{\alpha_1}\frac{\partial^{\alpha_1}}{\partial t^{\alpha_1}}\right)Q=-\frac{h^4}{8}\left[\left(\frac{\partial p}{\partial x}\right)-\mathrm{Gr}\beta\left(\frac{h^2}{8}-\frac{h}{20}\right)\right] \tag{14}$$

The transformation between the wave and laboratory frames, in the dimensionless form is given by:

$$X=x-1,\quad R=r,\quad U=u-1,\quad V=v,\quad q=Q-h^2 \tag{15}$$

Further the wall undergoes contraction and relaxation is mathematically formulated as:

$$h=1-\phi\cos^2(\pi X) \tag{16}$$

The existing relations between the averaged flow rate, the flow rate in the wave frame and that in the laboratory frame are:

$$Q=q+1-\phi+\frac{3\phi^2}{8}=Q-h^2+1-\phi+\frac{3\phi^2}{8} \tag{17}$$

In view of eq. (17), eq. (14), has the form:

$$\frac{\partial p}{\partial x}=\frac{\mathrm{Gr}\beta}{8}\left(1+\frac{8h}{20}\right)-\frac{8\left(\overline{Q}+h^2-1-\phi+\dfrac{3\phi^2}{8}\right)}{h^4}\left[1+\lambda_1^{\alpha_1}\frac{t^{a_1}}{\Gamma(1-\alpha_1)}\right] \tag{18}$$

It is observed that as $\beta\to 0$, eqs. (13), (14), and (18) are reduces to the corresponding results of Tripathi [23].

The dimensionless pressure rise Δp and friction force F_λ per one wave length are defined by:

$$\Delta p=\int_0^1\frac{\partial p}{\partial x}\mathrm{d}x \tag{19}$$

$$F_\lambda=\int_0^1\left(-h^2\frac{\partial p}{\partial x}\right)\mathrm{d}x \tag{20}$$

The heat transfer coefficient at the outer wall is given by:

$$Z=\left(\frac{\partial\theta}{\partial r}\frac{\partial r}{\partial x}\right)_{r=h}=-\frac{\phi\beta h\pi}{2}[\sin(2\pi x)] \tag{21}$$

Results and discussion

In order to see the quantitative effects of the various emerging parameters involved in the results on the pumping characteristics and the heat transfer coefficient we have used the MATHEMATICA package. The salient features of temperature θ, heat transfer coefficient Z, and pressure rise and friction forces are analyzed through the figs. 2-15 carefully. Figures 2-5 demonstrate that there is a linear relation between pressure and the time-averaged flow rate. It is worth mentioning that an increase in the averaged flow rate makes the pressure fall and thus the maximum flow rate is achieved at zero pressure and the maximum pressure occurs at zero time-averaged flow rate. The variation of pressure rise Δp against flow rate $\overline{Q}$ for various values of a_1 at $\phi=0.4$, $t=0.5$, $\lambda_1=1$, $\mathrm{Gr}=3$, and $\beta=5$ is depicted in fig. 2. It is observed that the pumping rate decreases with increase of a_1 for pumping ($\Delta p>0$) and as well as for free pumping ($\Delta p=0$). Also it can be noted that the fractional behavior of second grade fluids increases, the pressure

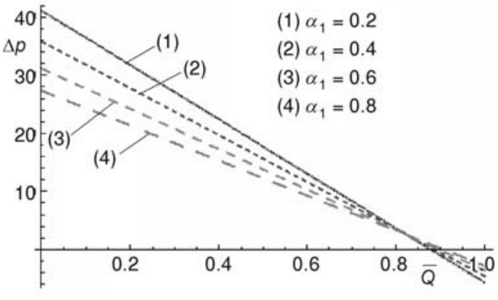

Figure 2. Pressure *vs.* averaged flow rate for various values of α_1 at ϕ = 0.4, *t* = 0.5, λ = 1, Gr = 3, and β = 5

for flow diminishes. Figure 3 shows the variation of pressure rise Δp against flow rate $\overline{Q}$ for various values of ϕ at $\alpha = 0.2, \lambda_1 = 1, \mathrm{Gr} = 3, \beta = 5$. It is observed that the pressure increases with increasing amplitude ratio ϕ. Figure 4 shows that the graph between Δp and $\overline{Q}$ for various values of t at $a_1 = 0.2, \phi = 0.4, \lambda_1 = 1, \beta = 5$. It is found that pressure increases with an increase in the magnitude of the parameter *t*. Figure 5 depicts the variation of pressure rise Δp with time averaged flow rate $\overline{Q}$ for different values of λ_1 at α = 0.2, ϕ = = 0.4, t = 0.5, Gr = 3, β = 5.It is revealed

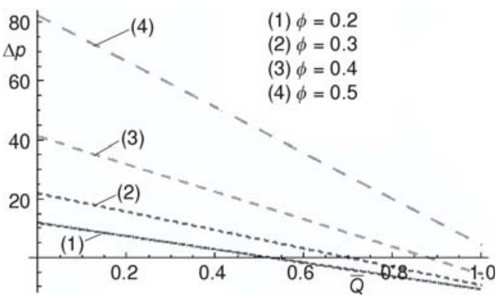

Figure 3. Pressure *vs.* averaged flow rate for various values of ϕ at α_1 = 0.2, *t* = 0.5, λ = 1, Gr = 3, and β = 5

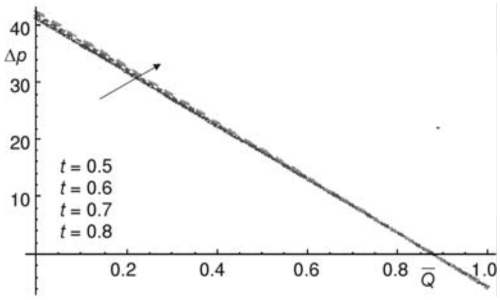

Figure 4. Pressure *vs.* averaged flow rate for various values of *t* atα_1 = 0.2, ϕ = 0.4, λ = 1, Gr = 3, and β = 5

that the pressure increase with increasing λ_1.This means that the viscoelastic behavior of fluids increases, the pressure for flow of fluids decreases, *i. e.*, the flow for second grade fluid requires more pressure than that of Newtonian fluids ($\lambda_1 \to 0$). The variation of pressure rise Δp against flow rate $\overline{Q}$ for various values of Grashof number Gr at $a_1 = 0.2, \phi = 0.4, t = 0.5, \lambda_1 = 1, \beta = 5$ is presented in fig. 6. It is evident that an increase in the flow rate $\overline{Q}$ reduces the pressure. Volume flow rate increases with increasing magnitude of Grashof number.

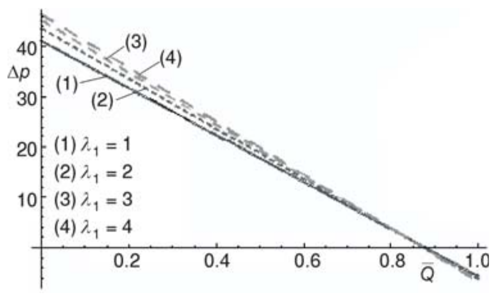

Figure 5. Pressure *vs.* averaged flow rate for various values of λ_1 at α_1 = 0.2, ϕ = 0.4, *t* = 0.5, λ = 1, Gr = 3, and β = 5

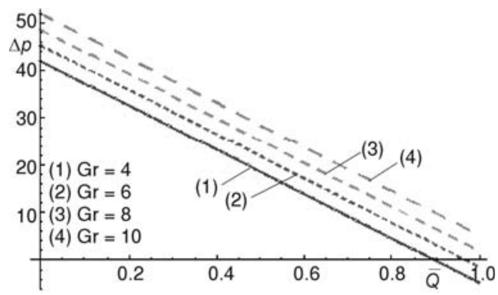

Figure 6. Pressure *vs.* averaged flow rate for various values of Gr at α_1 = 0.2, ϕ = 0.4, *t* = 0.5, λ = 1, and β = 5

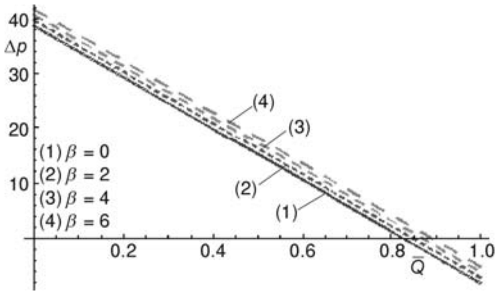

Figure 7. Pressure *vs.* averaged flow rate for various values of β at α_1 = 0.2, ϕ = 0.4, *t* = 0.5, λ_1 = 1, and Gr = 3

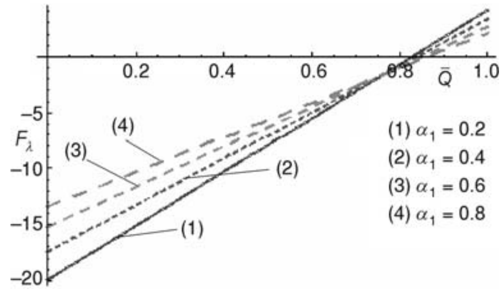

Figure 8. Friction force *vs.* averaged flow rate for various values of α_1 at ϕ = 0.4, *t* = 0.5, λ_1 = 1, Gr = 3, and β = 5

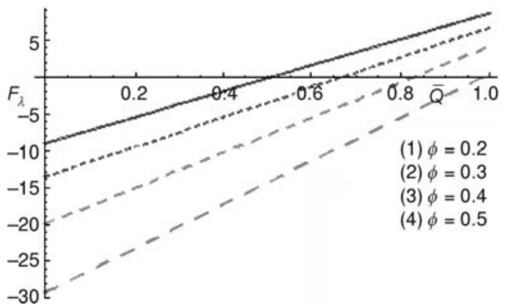

Figure 9. Friction force *vs.* averaged flow rate for various values of ϕ at α_1 = 0.2, *t* = 0.5, λ_1 = 1, Gr = 3, and β = 5

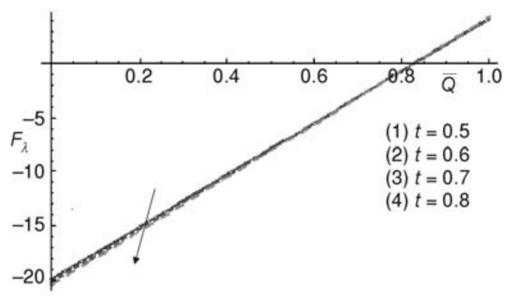

Figure 10. Friction force *vs.* averaged flow rate for various values of *t* at ϕ = 0.4, α_1 = 0.2, λ_1 = 1, Gr = 3, and β = 5

The variation of pressure rise Δp against flow rate $\overline{Q}$ for various values of heat source/sink parameter β at $a_1 = 0.2$, $\phi = 0.4$, $t = 0.5$, $\lambda_1 = 1$, Gr = 4 is presented in fig. 7. It is observed that an increase in β increases the time averaged flow rate $\overline{Q}$ in all the three (pumping, free-pumping and co-pumping) regions.

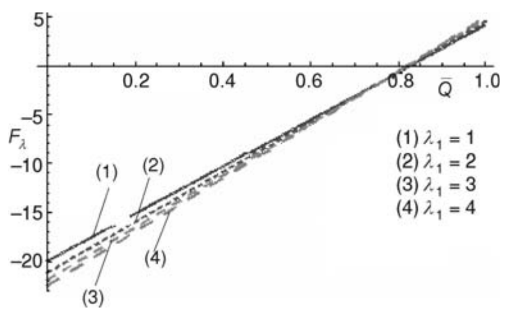

Figure 11. Friction force *vs.* averaged flow rate for various values of λ_1 at α_1 = 0.2, ϕ = 0.4, *t* = 0.5, Gr = 3, and β = 5

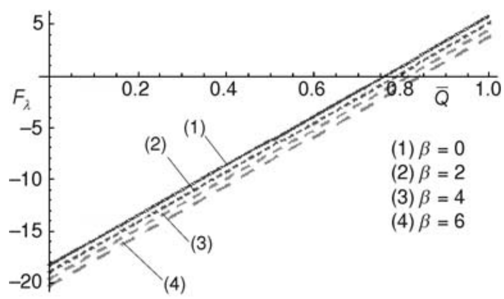

Figure 12. Friction force *vs.* averaged flow rate for various values of β at α_1 = 0.2, ϕ = 0.4, *t* = 0.5, λ_1 = 1, and Gr = 3

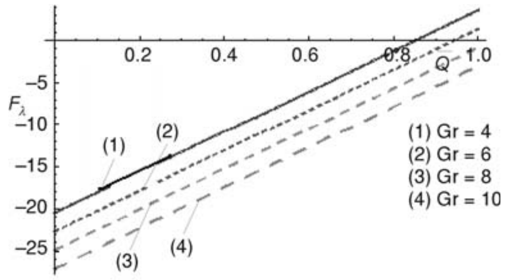

Figure 13. Friction force *vs*. averaged flow rate for various values of Gr at $\alpha_1 = 0.2$, $\phi = 0.4$, $t = 0.5$, $\lambda_1 = 1$, and $\beta = 5$

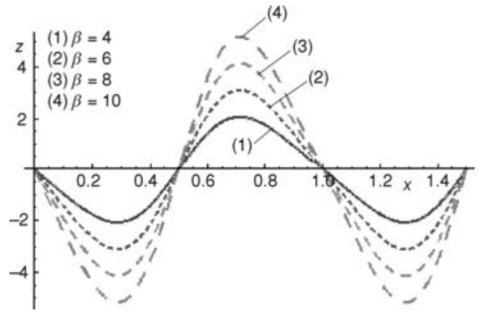

Figure 14. Coefficient of heat transfer for various values of Gr at $\phi = 0.4$

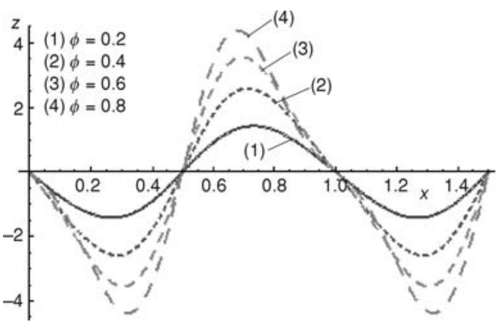

Figure 15. Coefficient of heat transfer for various values of ϕ at $\beta = 5$

The variation of fractional force against flow rate is shown in figs. 8-13. It can be seen that the effect of all parameters on friction force have opposite behavior as compared to the pressure rise.

Figures 14 and 15 depict the behavior of heat transfer coefficient at the wall. Heat transfer coefficient has an oscillatory behavior due to peristalsis. Figure 14 shows the variation of heat transfer coefficient z with β. Absolute value of heat transfer coefficient increases with an increase in β. Figure 15 illustrates that with increasing ϕ the magnitude of the heat transfer coefficient increases.

Conclusions

The study examines the interaction of heat transfer and peristaltic pumping of a fractional second grade fluid through cylindrical tube under low Reynolds number and long wavelength approximation. The Caputo's definition is used for differentiating the fractional derivatives. Closed form solutions are derived for velocity and temperature. The main points of the performed analysis are as follows.

- Pressure rise decrease with an increase in fractional parameter α.
- The qualitative behaviors of ϕ, t, λ_1, Gr and β on the pressure are similar.
- It is observed that frictional forces have an opposite behavior to that of pressure rise.
- The absolute value of heat coefficient increases with increase of β and ϕ.

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