Peristaltic flow of a Hyperbolic tangent fluid through a porous medium in a vertical channel

Dr. B. Jayarami Reddy, Dr. M. V. Subba Reddy

***Abstract*— In this paper, we investigated the peristaltic transport of a hyperbolic tangent fluid through a porous medium in a vertical channel under the assumption of long wavelength. The expression for the velocity and axial pressure gradient are obtained by employing perturbation technique. The effects of various pertinent parameters on the time-averaged flow rate are discussed with the help of graphs.**

***Index Terms*— Darcy number, Hyperbolic tangent fluid, peristalsis. Vertical Channel.**

I. INTRODUCTION

A Peristaltic pump is a device for pumping fluids, generally from a region of lower to higher pressure, by means of a contraction wave traveling along a tube–like structure. This traveling wave phenomenon is referred to as 'Peristalsis'. Peristalsis originated naturally as a means of pumping physiological fluids from one place in the body to another, and is the primary pumping physiological fluids from one place in the body to another, and is the primary pumping mechanism in swallowing (and indeed all the way through the alimentary canal) in the ureter, the bile duets, the ductus efferentes of the male reproductive tract, and even in some small blood vessels. Humankind has borrowed the idea and used it in applications where the material being pumped must not be contaminated (eg blood) or is corrosive and should not be in contact with the moving parts of ordinary pumping machinery. Analytical solutions were obtained for peristaltic flows by assuming either small amplitude but arbitrary Reynolds number [1] –[2] or arbitrary amplitude with small curvature and negligible inertia [3].

It is well known that some fluids which are encountered in chemical applications do not adhere to the classical Newtonian viscosity prescription and are accordingly known as non-Newtonian fluids. One especial class of fluids which are of considerable practical importance is that in which the viscosity depends on the shear stress or on the flow rate. The viscosity of most non-Newtonian fluids, such as polymers, is usually a nonlinear decreasing function of the generalized shear rate. This is known as shear-thinning behavior. Such fluid is a hyperbolic tangent fluid [4]. Reference [5] have first investigated the peristaltic flow of a hyperbolic tangent fluid in an asymmetric channel. Reference [6] have analyzed the peristaltic transport of a Tangent hyperbolic fluid in an endoscope numerically. Reference [7] have discussed the peristaltic flow of a hyperbolic tangent fluid in an inclined asymmetric channel with slip and heat transfer.

Flows through a porous medium occur in filtration of fluids. Hall effects on peristaltic flow of a Maxwell fluid in a porous medium were investigated by [8]. Reference [9] have discussed the effect of magnetic field on the peristaltic motion of a Carreau fluid through a porous medium with heat transfer. Peristaltic motion of a couple stress fluid through a porous medium in a channel with slip condition was studied by [10]. Reference [11] have studied the peristaltic MHD flow of a Bingham fluid through a porous medium in a channel. Peristaltic flow of a non-Newtonian fluid through a porous medium in a tube with variable viscosity using Adomian decomposition method was investigated by [12].

In view of these, we studied the peristaltic flow of a hyperbolic tangent fluid through a porous medium in an inclined channel under the assumption of long wavelength. The expression for the velocity and axial pressure gradient are obtained by employing perturbation technique. The effects of various pertinent parameters on the time-averaged flow rate are discussed with the help of graphs.

II. FORMULATION OF THE PROBLEM

We consider the peristaltic motion of a hyperbolic tangent fluid through a porous medium in a two-dimensional symmetric vertical channel of width $2a$. The flow is generated by sinusoidal wave trains propagating with constant speed c along the channel walls. Fig. 1 illustrates the schematic diagram of the channel.

The wall deformation is given by

$$Y = \pm H(X,t) = \pm a \pm b\cos\frac{2\pi}{\lambda}(X - ct), \qquad (2.1)$$

where b is the amplitude of the wave, λ - the wave length and X and Y - the rectangular co-ordinates with X measured along the axis of the channel and Y perpendicular to X. Let (U,V) be the velocity components in fixed frame of reference (X,Y).

The flow is unsteady in the laboratory frame (X,Y). However, in a co-ordinate system moving with the propagation velocity c (wave frame (x, y)), the boundary shape is stationary. The transformation from fixed frame to wave frame is given by

$$x = X - ct, y = Y, u = U - c, v = V \qquad (2.2)$$

where (u,v) and (U,V) are velocity components in the wave and laboratory frames respectively.

Dr. B. Jayarami Reddy, Principal and Professor of Civil Engineering, YSR Engineering College of Yogi Vemana University, Proddatur-516360, A.P., India. +91-9703216827.

Dr. M. V. Subba Reddy, Professor and Dean Academics, Department of CSE, Sri Venkatesa Perumal college of Engineering & Technology, Puttur-517583, A.P., India. +91-9000923005

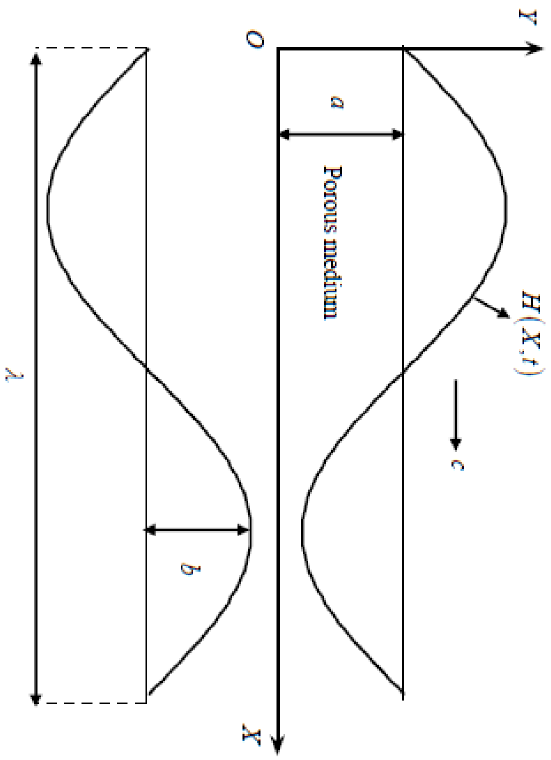

Fig. 1 The physical model

The constitutive equation for a Hyperbolic Tangent fluid is

$$\tau = -\left[\eta_\infty + (\eta_0 + \eta_\infty)\tanh(\Gamma\dot{\gamma})^n\right]\dot{\gamma} \qquad (2.3)$$

where τ is the extra stress tensor, η_∞ is the infinite shear rate viscosity, η_o is the zero shear rate viscosity, Γ is the time constant, n is the power-law index and $\dot{\gamma}$ is defined as

$$\dot{\gamma} = \sqrt{\frac{1}{2}\sum_i\sum_j \dot{\gamma}_{ij}\dot{\gamma}_{ji}} = \sqrt{\frac{1}{2}\pi} \qquad (2.4)$$

where π is the second invariant stress tensor. We consider in the constitutive equation (2.3) the case for which $\eta_\infty = 0$ and $\Gamma\dot{\gamma} < 1$, so the Eq. (2.3) can be written as

$$\tau = -\eta_0(\Gamma\dot{\gamma})^n\dot{\gamma} = -\eta_0(1+\Gamma\dot{\gamma}-1)^n\dot{\gamma} = -\eta_0(1+n[\Gamma\dot{\gamma}-1])\dot{\gamma} \qquad (2.5)$$

The above model reduces to Newtonian for $\Gamma = 0$ and $n = 0$.

The equations governing the flow in the wave frame of reference are

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (2.6)$$

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} - \frac{\partial \tau_{xx}}{\partial x} - \frac{\partial \tau_{yx}}{\partial y} - \frac{\eta_0}{k}(u+c) + \rho g \qquad (2.7)$$

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial y} - \frac{\partial \tau_{xy}}{\partial x} - \frac{\partial \tau_{yy}}{\partial y} - \frac{\eta_0}{k}v \qquad (2.8)$$

where ρ is the density and k is the permeability of the porous medium.

The corresponding dimensional boundary conditions are

$$u = -c \quad \text{at} \quad y = H \qquad (2.9)$$

$$\frac{\partial u}{\partial y} = 0 \quad \text{at} \quad y = 0 \qquad (2.10)$$

Introducing the non-dimensional variables defined by

$$\bar{x} = \frac{x}{\lambda}, \bar{y} = \frac{y}{a}, \bar{u} = \frac{u}{c}, \bar{v} = \frac{v}{c\delta}, \delta = \frac{a}{\lambda},$$
$$\bar{p} = \frac{pa^2}{\eta_0 c\lambda}, \phi = \frac{b}{a}, h = \frac{H}{a}, \bar{t} = \frac{ct}{\lambda},$$
$$\bar{\tau}_{xx} = \frac{\lambda}{\eta_0 c}\tau_{xx}, \bar{\tau}_{xy} = \frac{a}{\eta_0 c}\tau_{xy}, \bar{\tau}_{yy} = \frac{\lambda}{\eta_0 c}\tau_{yy},$$
$$\mathrm{Re} = \frac{\rho a c}{\eta_0}, \; We = \frac{\Gamma c}{a}, \bar{\dot{\gamma}} = \frac{\dot{\gamma} a}{c}, \bar{q} = \frac{q}{ac}, Fr = \frac{c^2}{ag} \qquad (2.11)$$

into the Equations (2.6) - (2.8), reduce to (after dropping the bars)

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (2.12)$$

$$\mathrm{Re}\,\delta\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} - \delta^2\frac{\partial \tau_{xx}}{\partial x} - \frac{\partial \tau_{xy}}{\partial y} - \frac{1}{Da}(u+1) + \frac{\mathrm{Re}}{Fr} \qquad (2.13)$$

$$\mathrm{Re}\,\delta^3\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} - \delta^2\frac{\partial \tau_{xy}}{\partial y} - \delta\frac{\partial \tau_{yy}}{\partial y} - \frac{\delta^2}{Da}v \qquad (2.14)$$

here

$$\tau_{xx} = -2\left[1+n(We\dot{\gamma}-1)\right]\frac{\partial u}{\partial x},$$

$$\tau_{xy} = -\left[1+n(We\dot{\gamma}-1)\right]\left(\frac{\partial u}{\partial y} + \delta^2\frac{\partial v}{\partial x}\right),$$

$$\tau_{yy} = -2\delta\left[1+n(We\dot{\gamma}-1)\right]\frac{\partial v}{\partial y},$$

$$\dot{\gamma} = \left[2\delta^2\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y} + \delta^2\frac{\partial v}{\partial x}\right)^2 + 2\delta^2\left(\frac{\partial v}{\partial y}\right)^2\right]^{\frac{1}{2}},$$

Re is the Reynolds number, Fr is the Froude number and $Da = \frac{k}{a^2}$ is the Darcy number.

Under long wavelength approximation $(\delta \to 0)$, the Eqs. (2.13) and (2.14) become

$$\frac{\partial p}{\partial x} = \frac{\partial}{\partial y}\left\{\left[1+n\left(We\frac{\partial u}{\partial y}-1\right)\right]\frac{\partial u}{\partial y}\right\} - \frac{1}{Da}(u+1) + \frac{Re}{Fr} \qquad (2.15)$$

$$\frac{\partial p}{\partial y} = 0 \qquad (2.16)$$

From Eq. (2.15) and (2.16), we get

$$\frac{dp}{dx} = (1-n)\frac{\partial^2 u}{\partial y^2} + nWe\frac{\partial}{\partial y}\left[\left(\frac{\partial u}{\partial y}\right)^2\right] - \frac{1}{Da}(u+1) + \frac{Re}{Fr} \qquad (2.17)$$

The corresponding non-dimensional slip boundary conditions in the wave frame are given by

$$u = -1 \quad \text{at} \quad y = h = 1 + \phi\cos 2\pi x \qquad (2.18)$$

$$\frac{\partial u}{\partial y} = 0 \quad \text{at} \quad y = 0 \qquad (2.19)$$

The volume flow rate q in a wave frame of reference is given by

$$q=\int_0^h u\,dy\,. \tag{2.20}$$

The instantaneous flow $Q(X,t)$ in the laboratory frame is

$$Q(X,t)=\int_0^h U\,dY=\int_0^h (u+1)\,dy=q+h \tag{2.21}$$

The time averaged volume flow rate $\bar{Q}$ over one period $T\left(=\frac{\lambda}{c}\right)$ of the peristaltic wave is given by

$$\bar{Q}=\frac{1}{T}\int_0^T Q\,dt=q+1 \tag{2.22}$$

III. Solution

Since Eq. (2.17) is a non-linear differential equation, so it is not possible to obtain closed form solution. Therefore we employ regular perturbation to find the solution.

For perturbation solution, we expand $u,\frac{dp}{dx}$ and q as follows

$$u=u_0+We\,u_1+O\left(We^2\right) \tag{3.1}$$

$$\frac{dp}{dx}=\frac{dp_0}{dx}+We\frac{dp_1}{dx}+O\left(We^2\right) \tag{3.2}$$

$$q=q_0+We\,q_1+O\left(We^2\right) \tag{3.3}$$

Substituting these equations into the Eqs. (2.17) - (2.19), we obtain

3.1. System of order We^0

$$\frac{dp_0}{dx}=(1-n)\frac{\partial^2 u_0}{\partial y^2}-\frac{1}{Da}(u_0+1)+\frac{Re}{Fr} \tag{3.4}$$

and the respective boundary conditions are

$$u_0=-1 \quad \text{at} \quad y=h \tag{3.5}$$

$$\frac{\partial u_0}{\partial y}=0 \quad \text{at} \quad y=0 \tag{3.6}$$

3.2. System of order We^1

$$\frac{dp_1}{dx}=(1-n)\frac{\partial^2 u_1}{\partial y^2}+\frac{\partial}{\partial y}\left[\left(\frac{\partial u_o}{\partial y}\right)^2\right]-\frac{1}{Da}u_1 \tag{3.7}$$

and the respective boundary conditions are

$$u_1=0 \quad \text{at} \quad y=h \tag{3.8}$$

$$\frac{\partial u_1}{\partial y}=0 \quad \text{at} \quad y=0 \tag{3.9}$$

3.3 Solution for system of order We^0

Solving Eq. (3.4) using the boundary conditions (3.5) and (3.6), we obtain

$$u_0=\frac{1}{\sigma^2(1-n)}\left(\frac{dp_0}{dx}-\frac{Re}{Fr}\right)\left[\frac{\cosh\sigma y}{\cosh\sigma h}-1\right]-1 \tag{3.10}$$

where $\sigma=1/\sqrt{Da(1-n)}$.

The volume flow rate q_0 is given by

$$q_0=\frac{1}{\sigma^3(1-n)}\left(\frac{dp_0}{dx}-\frac{Re}{Fr}\right)\left[\frac{\sinh\sigma h-\sigma h\cosh\sigma h}{\cosh\sigma h}\right]-h \tag{3.11}$$

From Eq. (3.11), we have

$$\frac{dp_0}{dx}=\frac{(q_0+h)\sigma^3(1-n)\cosh\sigma h}{\left[\sinh\sigma h-\sigma h\cosh\sigma h\right]}+\frac{Re}{Fr} \tag{3.12}$$

3.4 Solution for system of order We^1

Substituting Eq. (3.10) in the Eq. (3.7) and solving the Eq. (3.7), using the boundary conditions (3.8) and (3.9), we obtain

$$u_1=\left(\begin{array}{l}\frac{1}{\sigma^2(1-n)}\frac{dp_1}{dx}\left[\frac{\cosh\sigma y}{\cosh\sigma h}-1\right]\\ +\frac{n}{3}\frac{\left(\frac{dp_0}{dx}-\frac{Re}{Fr}\right)^2}{\left[\sigma(1-n)\cosh\sigma h\right]^3}\left[\begin{array}{l}(\sinh 2\sigma h-2\sinh\sigma h)\cosh\sigma y\\ +(2\sinh\sigma y-\sinh 2\sigma y)\cosh\sigma h\end{array}\right]\end{array}\right) \tag{3.13}$$

The volume flow rate q_1 is given by

$$q_1=\left(\begin{array}{l}\frac{1}{\sigma^3(1-n)}\frac{dp_1}{dx}\left[\frac{\sinh\sigma h-\sigma h\cosh\sigma h}{\cosh\sigma h}\right]\\ +\frac{An}{6\sigma^4(1-n)^3}\left(\frac{dp_0}{dx}-\frac{\mathrm{Re}}{Fr}\right)^2\frac{1}{\cosh^3\sigma h}\end{array}\right) \tag{3.14}$$

where

$A=4-\cosh\sigma h+2\sinh 2\sigma h\sinh\sigma h-\cosh\sigma h\cosh 2\sigma h$.

From Eq. (3.14) and (3.12), we have

$$\frac{dp_1}{dx}=\left(\begin{array}{l}\frac{q_1\sigma^3(1-n)\cosh\sigma h}{\left[\sinh\sigma h-\sigma h\cosh\sigma h\right]}\\ -\frac{An}{6\sigma(1-n)^2}\frac{\left(\frac{dp_0}{dx}-\frac{Re}{Fr}\right)^2}{\cosh^2\sigma h(\sinh\sigma h-\sigma h\cosh\sigma h)}\end{array}\right) \tag{3.15}$$

Substituting Equations (3.12) and (3.15) into the Eq. (3.2) and using the relation $\frac{dp_0}{dx}=\frac{dp}{dx}-We\frac{dp_1}{dx}$ and neglecting terms greater than $O(We)$, we get

$$\frac{dp}{dx}=\left(\begin{array}{l}\frac{(q+h)\sigma^3(1-n)\cosh\sigma h}{\left[\sinh\sigma h-\sigma h\cosh\sigma h\right]}\\ -\frac{WeAn\sigma^5}{6}\frac{(q+h)^2}{(\sinh\sigma h-\sigma h\cosh\sigma h)^3}+\frac{\mathrm{Re}}{Fr}\end{array}\right) \tag{3.16}$$

The dimensionless pressure rise per one wavelength in the wave frame is defined as

$$\Delta p=\int_0^1\frac{dp}{dx}dx \tag{3.17}$$

Note that, as $Da\to\infty$, $We\to 0, \mathrm{Re}\to 0$ and $n\to 0$ our results coincide with the results of Shapiro et al. (1969).

IV. Discussion of the Results

Fig. 2 illustrates the variation of pressure rise Δp with time-averaged volume flow rate $\bar{Q}$ for different values of We with $\phi=0.5$, $n=0.5$, $\mathrm{Re}=1$, $Fr=0.2$ and $Da=0.01$. It is found that, the time- averaged volume flow rate $\overline{Q}$ increases with increasing We in all the three regions (namely, pumping $(\Delta p > 0)$, free-pumping $(\Delta p = 0)$ and co-pumping $(\Delta p < 0)$ regions).

The variation of pressure rise Δp with time-averaged volume flow rate $\overline{Q}$ for different values of n with $\phi = 0.5$, $We = 0.05$, $\mathrm{Re} = 1$, $Fr = 0.2$ and $Da = 0.01$ is shown in Fig. 3. It is observed that, the time-averaged volume flow rate $\overline{Q}$ decreases with an increase in n in both the pumping and free pumping regions, while it increases with increasing n in co-pumping region for chosen $\Delta p(<0)$.

Fig. 4 depicts the variation of pressure rise Δp with time-averaged volume flow rate $\overline{Q}$ for different values of Da with $\phi = 0.5$, $n = 0.5$, $\mathrm{Re} = 1$, $Fr = 0.2$ and $We = 0.05$. It is noted that, the time-averaged volume flow rate $\overline{Q}$ decreases with increasing Da in the pumping region, while it increases with increasing Da in both the free-pumping and co-pumping regions.

The variation of pressure rise Δp with time-averaged volume flow rate $\overline{Q}$ for different values of ϕ with $We = 0.05$, $n = 0.5$, $\mathrm{Re} = 1$, $Fr = 0.2$ and $Da = 0.01$ is depicted in Fig. 5. It is found that, the time-averaged volume flow rate $\overline{Q}$ increases with an increase in ϕ in both the pumping and free-pumping regions, while it decreases with increasing ϕ in the co-pumping region for chosen $\Delta p(<0)$.

Fig. 6 illustrates the variation of pressure rise Δp with time-averaged volume flow rate $\overline{Q}$ for different values of Re with $\phi = 0.5$, $n = 0.5$, $We = 0.05$, $Fr = 0.2$ and $Da = 0.01$. It is observed that, the time-averaged volume flow rate $\overline{Q}$ increases with increasing Reynolds number Re in all the three regions.

The variation of pressure rise Δp with time-averaged volume flow rate $\overline{Q}$ for different values of Fr with $\phi = 0.5$, $n = 0.5$, $\mathrm{Re} = 1$, $We = 0.05$ and $Da = 0.01$ is shown in Fig. 7. It is found that, the time-averaged volume flow rate $\overline{Q}$ decreases with increasing Froud number Fr in all the three regions.

V. Conclusions

In this paper, we studied the peristaltic flow of a hyperbolic tangent fluid through a porous medium in a vertical channel under the assumption of long wavelength. The expression for the velocity and axial pressure gradient are obtained by using perturbation technique. It is found that in the pumping region the time-averaged flow rate $\overline{Q}$ increases with increasing We, ϕ and Re, while it decreases with increasing n, Da and Fr. Further, it is observed that the pumping is more for hyperbolic tangent fluid than that of Newtonian fluid.

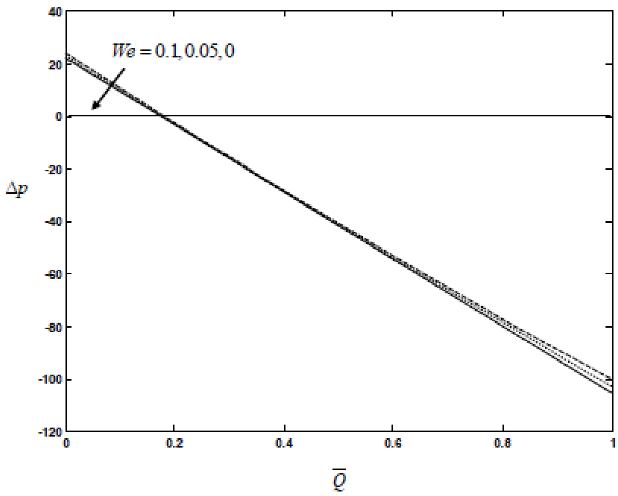

Fig. 2 The variation of pressure rise Δp with time-averaged volume flow rate $\overline{Q}$ for different values of We with $\phi = 0.5$, $n = 0.5$, $\mathrm{Re} = 1$, $Fr = 0.2$ and $Da = 0.01$.

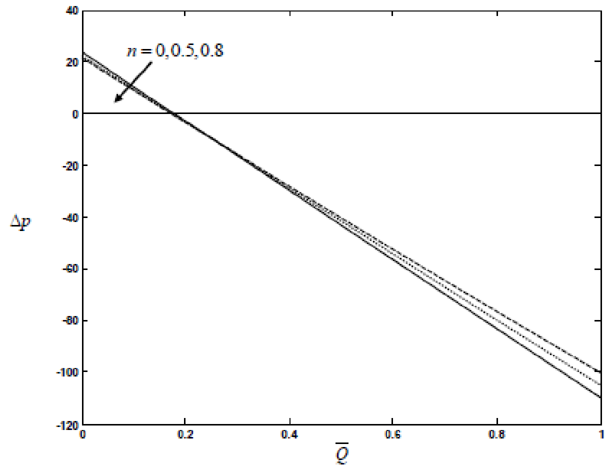

Fig. 3 The variation of pressure rise Δp with time-averaged volume flow rate $\overline{Q}$ for different values of n with $\phi = 0.5$, $We = 0.05$, $\mathrm{Re} = 1$, $Fr = 0.2$ and $Da = 0.01$.

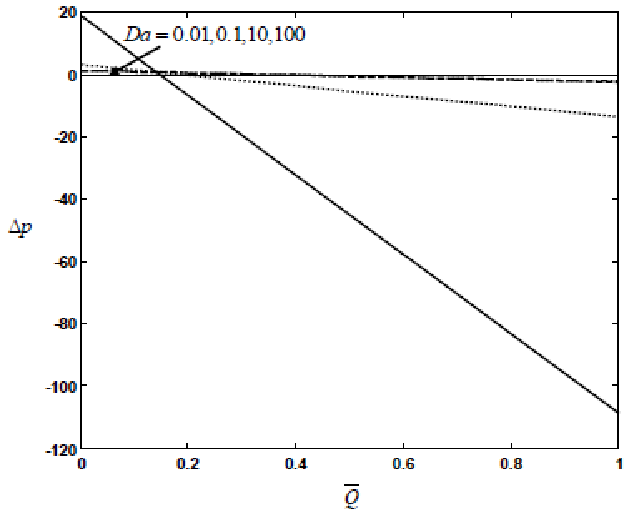

Fig. 4 The variation of pressure rise Δp with time-averaged volume flow rate $\overline{Q}$ for different values of Da with $\phi = 0.5$, $n = 0.5$, $\mathrm{Re} = 1$, $Fr = 0.2$ and $We = 0.05$.

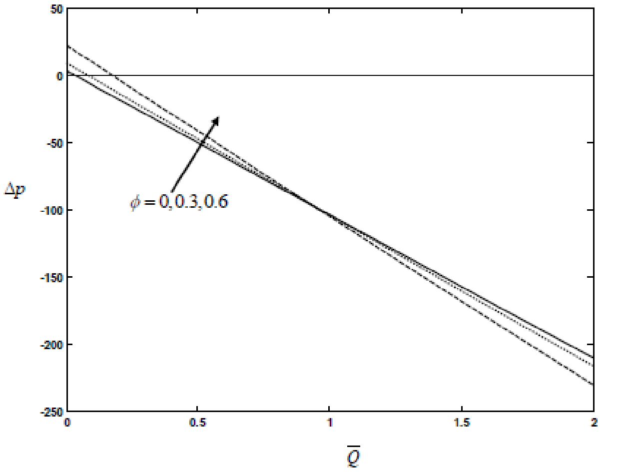

Fig. 5 The variation of pressure rise Δp with time-averaged volume flow rate $\overline{Q}$ for different values of ϕ with $We = 0.05$, $n = 0.5$, $\mathrm{Re} = 1$, $Fr = 0.2$ and $Da = 0.01$.

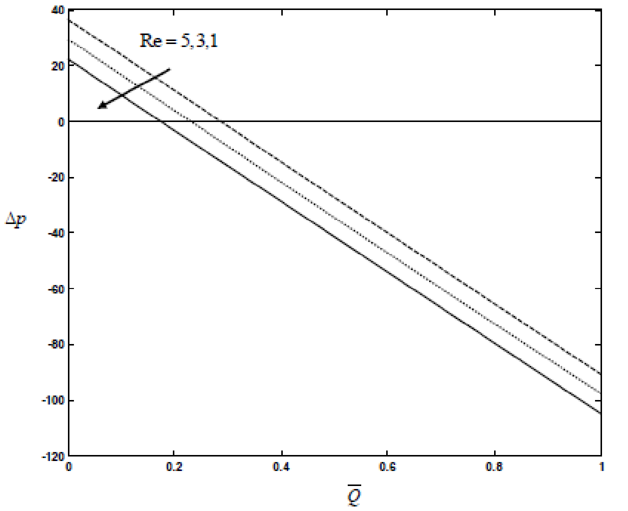

Fig. 6 The variation of pressure rise Δp with time-averaged volume flow rate $\overline{Q}$ for different values of Re with $\phi = 0.5$, $n = 0.5$, $We = 0.05$, $Fr = 0.2$ and $Da = 0.01$.

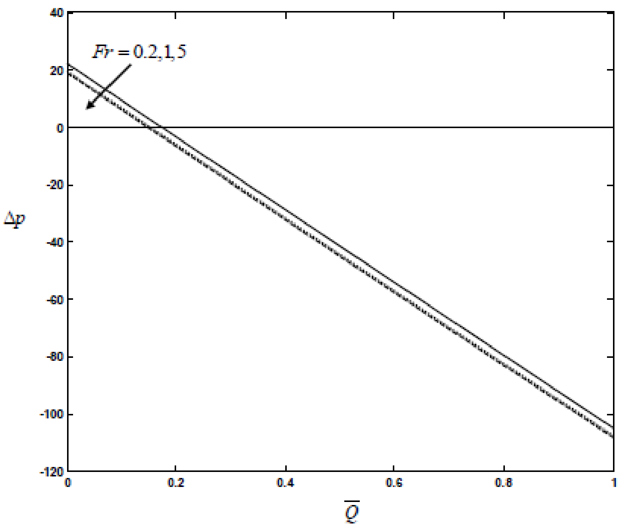

Fig. 7 The variation of pressure rise Δp with time-averaged volume flow rate $\overline{Q}$ for different values of Fr with $\phi = 0.5$, $n = 0.5$, $\mathrm{Re} = 1$, $We = 0.05$ and $Da = 0.01$.

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Dr. B. Jayarami Reddy is working as Principal at YSR Engineering College of Yogi Vemana University Proddatur. He received his M.Tech (CSE) degree and Ph. D (Civil Engineering) degree from JNTU Hyderabad. He published several research papers in International and National Journals/Conferences.

Dr. M. V. Subba Reddy is working as Professor & Dean of Computer Science and Engineering at Sri Venkatesa Peruimal College of Engineering & Technology, Puttur,India. He received his M. Tech (CSE) from JNTUA, Anantapur and Ph. D degree from Sri Venkateswara University, India in 2005. He is awardee of CSIR – RA Fellow Ship. He is member of FMFP, India. He published more than 57 research articles in International and National Journals. He is also guided Two Ph. D's , Five M. Phil's. & Five M. Tech's. He completed One UGC Minor research project.