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# PERISTALTIC PUMPING OF A MICROPOLAR FLUID IN A TUBE WITH PERMEABLE WALL

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***ABSTRACT***

*In the present study, the peristaltic transport of an incompressible micropolar fluid in a tube with permeable wall is investigated. The flow is investigated in a wave frame of reference moving with the velocity of the wave. The expressions for velocity, pressure gradient, pressure rise and friction force are obtained. The features of the flow characteristics are analyzed through graphs and the obtained results are discussed in detail. Further, the friction force is studied for various micropolar parameters in all pumping ranges.*

***Keywords**: Peristaltic pumping, Micropolar Fluid, tube, Permeable wall,*

## 1. INTRODUCTION

Peristaltic transport is a form of fluid transport generated by a progressive wave of area contraction or expansion along the length of a distensible tube containing fluid. Peristalsis is an inherent property of many biological systems having smooth muscle tubes which transports bio-fluids by its propulsive movements and is found in the transport of urine from kidney to the bladder, the movement of chyme in the gastro-intestinal tract, intra-uterine fluid motion, vasomotion of the small blood vessels and in many other glandular ducts. The mechanism of peristaltic transport has been exploited for industrial applications like sanitary fluid transport, blood pumps in heart lung machine and transport of corrosive fluids where the contact of the fluid with the machinery parts is prohibited.

In recent years a number of investigations of peristaltic flow of Newtonian/non-Newtonian fluids have been reported under different conditions. Vajravelu *et al.* [13, 14, 15, 16] studied the peristaltic transport of non-Newtonian fluids in channels and tubes.

Radhakrishnamacharya and Srinivasulu [21] investigated the influence of wall property on peristaltic transport with heat transfer. Peristaltic transport of a Jeffery fluid under the effect of magnetic field in an asymmetric channel is discussed by Kothandapani and Srinivas [23]. The influence of heat transfer on the peristaltic transport of a Jeffrey fluid in a vertical porous stratum is investigated by Vajravelu *et al.* [7]. Noreen Sher Akbar and Nadeem [22] describes the peristaltic flow of a Phan-Thien-Tanner nanofluid in a diverging tube. Tripathi [20] Studied the transient peristaltic heat flow through a finite porous channel.

Among several non-Newtonian models proposed for physiological fluids, there is an important model known as micropolar fluid which closely describes the blood flow in an artery. The model of micropolar fluid introduced by Eringen [1,2,3] represents fluids consisting of rigid, randomly oriented (or spherical) particles suspended in a viscous medium where the deformation of the particles is ignored. Micropolar fluids exhibit some microscopic effects arising from the local structure and micromotion of the fluid elements. A detailed survey of microcontinum fluid mechanics with several applications in physiological fluid flows has been presented by Ariman *et al.* [4, 5] Some interesting aspects of theory and applications of micropolar fluids are dealt in a recent book by Lukasazewicz [6]. Girija Devi and Devanathan [8] have considered the peristaltic transport of micropolar fluid in a laboratory frame of reference. Philip and Chandra [9] have investigated the peristaltic transport of a simple microfluid which accounts for microrotation and microstretching of the particles contained in a small volume element, using long wavelength approximation.

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Muthu *et al.* [10] have studied the influence of wall properties on the peristaltic transport of a micropolar fluid. Srinivasacharya *et al.* [17] investigated the peristaltic transport of a micropolar fluid in a tube. Ali and Hayat [18] analyzed the peristaltic flow of a micropolar fluid in an asymmetric channel. Sreenadh *et al.* [19] discussed the peristaltic flow of micropolar fluid in an asymmetric channel with permeable walls. It is speculated that blood flow in arteries exhibit peristalsis, (Fung and yin [11], Antanovskii and Ramkissoon [12]) and it is well-known that blood behaves like a non-Newtonian fluid in microcirculation. Therefore, modeling blood by a micropolar fluid may be more appropriate.

In view of the above observations it is interesting to study the peristaltic transport of an incompressible micropolar fluid in a tube with permeable wall. The expressions for the velocity field, pressure gradient and the pressure rise (per wavelength) are obtained. The interesting and important features of the peristaltic pumping are discussed in detail.

## 2. MATHEMATICAL FORMULATION AND SOLUTION

Let $(r', \theta, z')$ be the cylindrical polar coordinates system with $r' = 0$ as the axis of symmetry of the tube. Consider the flow of an incompressible micropolar fluid in an axisymmetric tube of radius a, with permeable wall with a periodic peristaltic wave traveling along the wall with velocity c, wavelength $\lambda$, amplitude b is given by

$$z' = H\left(\frac{r' - ct}{\lambda}\right) \tag{1}$$

The flow is unsteady in the fixed frame (laboratory frame) of reference $(r', \theta, z')$. However, in a coordinate system moving with the wave speed c (wave frame) $(r, \theta, z)$ the boundary shape is stationary. The transformation from fixed frame to wave frame is given by

$$r = r', z = z' - ct, V_z = V_z' - c \text{ and } V_r = V_r' \tag{2}$$

where $(V_r', V_z')$ and $(V_r, V_z)$ are radial and axial velocity component in the lab and wave moving frames respectively.

The equations governing the steady flow of an incompressible fluid in the absence of body force and body couple are

$$\nabla.\vec{V} = 0 \tag{3}$$

$$\rho(\vec{V}.\nabla.\vec{V}) = -\nabla P + k\nabla \times \vec{\omega} + (\mu + k)\nabla^2 \vec{V} \tag{4}$$

$$\rho_j(\vec{V}.\nabla\vec{\omega}) = 2k\vec{\omega} = K\nabla \times \vec{V} - \gamma(\nabla \times \nabla \times \vec{\omega}) + (\alpha + \beta + \gamma)\nabla(\nabla.\vec{\omega}) \tag{5}$$

where $\vec{V}$ is the velocity vector, $\vec{\omega}$ is the microrotation vector, p is the fluid pressure, $\rho$ and $j$ are the fluid density and microgyration parameters. Further, the material constants $\mu, k, \alpha, \beta and \gamma$ satisfy the following inequalities,

$$2\mu + k \geq 0,\ k \geq 0,\ 3\alpha + \beta + \gamma \geq 0,\ \gamma \geq |\beta| \tag{6}$$

Since the flow is axisymmetric, all the variables are independent of $\theta$. Hence for this flow the velocity vector is given by $\vec{V} = (V_r, 0, V_z)$ and microrotation vector is $\vec{\omega} = (0, \Omega, 0)$. It is well known that for ordinary fluids the law of conservation gives the symmetry of the stress tensor.

Introducing the following non-dimensional variables

$$r = a\bar{r},\ z = \lambda\bar{z},\ V_z = c\bar{V_z},\ V_r = \frac{ac}{\lambda}\bar{V_r},\ \Omega = \frac{c}{a}\bar{\Omega},\ P = \frac{\lambda\mu c}{a^2}\bar{P},\ t = \frac{\lambda}{c}\bar{t},$$

$$h = \frac{H}{a}, \quad j = \bar{j}a^2 \tag{7}$$

Using the above non-dimensional quantities in the equations (3-5) and dropping tildes, we obtained the following equations.

$$\frac{\partial V_r}{\partial r} + \frac{V_r}{r} + \frac{\partial V_r}{\partial z} = 0 \tag{8}$$

$$R_e\delta^3\left(V_r\frac{\partial V_r}{\partial r} + V_z\frac{\partial V_r}{\partial z}\right) = -\frac{\partial P}{\partial r} + \frac{\delta^2}{1-N}\left(-N\frac{\partial v_\theta}{\partial z} + \frac{\partial^2 V_r}{\partial r^2} + \frac{1}{r}\frac{\partial V_r}{\partial r} - \frac{V_r}{r^2} + \delta^2\frac{\partial^2 V_r}{\partial z^2}\right) \tag{9}$$

$$R_e\delta\left(V_r\frac{\partial V_z}{\partial r}+V_z\frac{\partial V_z}{\partial z}\right)=-\frac{\partial P}{\partial z}+\frac{1}{1-N}\left(\frac{N}{r}\frac{\partial(r\Omega)}{\partial r}+\frac{\partial^2 V_z}{\partial r^2}+\frac{1}{r}\frac{\partial V_z}{\partial r}+\delta^2\frac{\partial^2 V_z}{\partial z^2}\right) \tag{10}$$

$$\frac{jR_e\delta(1-N)}{N}\left(V_r\frac{\partial\Omega}{\partial r}+V_x\frac{\partial\Omega}{\partial z}\right)=-2\Omega+\left(\delta^2\frac{\partial V_r}{\partial z}-\frac{\partial V_z}{\partial r}\right)+\frac{2-N}{m^2}\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(r\Omega)}{\partial r}\right)+\delta^2\frac{\partial^2\Omega}{\partial z^2} \tag{11}$$

where $\delta=\frac{a}{\lambda}$, is the Reynolds number, $N=\frac{k}{\mu+k}$ is the coupling number $(0\le N<1)$ and $m^2=\frac{k(2\mu+k)}{\gamma(\mu+k)}a^2$ is the micropolar parameter.

Under the assumptions of long wavelength $\delta<<1$ and negligible inertia $(R_e=0)$, equations (9-11) reduce to

$$\frac{\partial V_r}{\partial r}+\frac{V_r}{r}+\frac{\partial V_z}{\partial z}=0 \tag{12}$$

$$\frac{\partial P}{\partial r}=0 \tag{13}$$

$$\frac{N}{r}\frac{\partial(r\Omega)}{\partial r}+\left(\frac{\partial^2 V_z}{\partial r^2}+\frac{1}{r}\frac{\partial V_z}{\partial r}\right)=(1-N)\frac{\partial P}{\partial z} \tag{14}$$

$$2\Omega+\left(\frac{\partial V_z}{\partial r}\right)-\frac{2-N}{m^2}\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(r\Omega)}{\partial r}\right)=0 \tag{15}$$

The boundary conditions in the wave frame are

$$\frac{\partial V_z}{\partial r}=0 \quad \text{at} \quad r=0 \tag{16}$$

$$V_z=-1-\frac{\sqrt{Da}}{\alpha}\frac{\partial V_z}{\partial r} \quad \text{at} \quad r=h \tag{17}$$

$$\Omega=\frac{-\sqrt{Da}}{\alpha_0}\frac{\partial\Omega}{\partial r} \quad \text{at} \quad r=h \tag{18}$$

And $V_z$ and $\Omega$ are finite at $r=0$ (19)

**Solution of the problem:**

From (13), we observed that P is function of z and r then equation (14) reduces to

$$\frac{\partial}{\partial r}\left[r\frac{\partial V_z}{\partial r}+Nr\Omega-(1-N)\frac{r^2}{2}\frac{dP}{dz}\right]=0 \tag{20}$$

Integrating (20) and dividing by r, we get

$$\frac{\partial V_z}{\partial r}=(1-N)\left[\frac{r}{2}\frac{dP}{dz}+\frac{C_1(z)}{r}\right]-N\Omega \tag{21}$$

Using (21) in (15) we get

$$\frac{\partial^2\Omega}{\partial r^2}+\frac{1}{r}\frac{\partial\Omega}{\partial r}-\left(m^2+\frac{1}{r^2}\right)\Omega=\frac{m^2(1-N)}{(2-N)}\left[\frac{r}{2}\frac{dP}{dz}+\frac{C_1(z)}{r}\right] \tag{22}$$

The general solution of (22) is

$$\Omega=C_2(z)I_1(mr)+C_3(z)K_1(mr)-\frac{1-N}{(2-N)}\left[\frac{r}{2}\frac{dP}{dz}+\frac{C_1(z)}{r}\right] \tag{23}$$

where $I_1(mr)$ and $K_1(mr)$ are modified Bessel functions of first order, first and second kind respectively.

Substituting (23) into (21) and integrating we get

$$V_z = \frac{-N}{m}[C_2(z)I_0(mr) + C_3(z)K_0(mr)] + \frac{1-N}{(2-N)}\left(\frac{r^2}{2}\frac{dP}{dz} + 2C_1(z)\log(r) + C_4(z)\right) \tag{24}$$

where $I_0$ and $K_0$ are modified Bessel function of zeroth order. The arbitrary functions $C_1(z) = C_3(z) = 0$ in (23) as we require $\Omega$ to be finite on $r = 0$. The other constants $C_2(z)$ and $C_4(z)$ are determined using equations (17) and (18) and the solutions are given by

$$V_z = -1 + \frac{(1-N)}{2(2-N)}\frac{dP}{dz}\left[r^2 - h^2 - 2h\frac{\sqrt{Da}}{\alpha} + \frac{N}{m}\left(h + \frac{\sqrt{Da}}{\alpha_0}\right)G\right] \tag{25}$$

where $$G = \frac{I_0(mh) - I_0(mr) - m\frac{\sqrt{Da}}{\alpha_0}I_1(mh)}{\left(1 - m\frac{\sqrt{Da}}{\alpha_0}\right)I_1(mh)}$$

$$\Omega = \frac{1-N}{2(2-N)}\frac{dP}{dz}\left[\frac{\left(h + \frac{\sqrt{Da}}{\alpha_0}\right)I_0(mr)}{\left(1 - m\frac{\sqrt{Da}}{\alpha_0}\right)I_1(mh)} - r\right] \tag{26}$$

We observed that $\Omega = 0$ on $r = 0$ as we expect microrotation to become zero on the axis

The dimensionless flux is given by

$$q = \int_0^h 2rV_z dr = -h^2 - \frac{(1-N)}{4(2-N)}\frac{dP}{dz}\left[h^4 + 4h^3\frac{\sqrt{Da}}{\alpha} + f(h)\right] \tag{27}$$

where

$$f(h) = \frac{4Nh}{m}\left[\frac{\left(\frac{h}{m}\right)I_1(mh) - \frac{h^2}{2}I_0(mh) - m\frac{\sqrt{Da}}{\alpha}h^2 I_1(mh)}{I_1(mh)}\right] \tag{28}$$

The pressure gradient is obtained from equation (27) as

$$\frac{dP}{dz} = -\frac{4(2-N)}{(1-N)}\left[\frac{q + h^2}{h^4 + 4h^3\frac{\sqrt{Da}}{\alpha} + f(h)}\right] \tag{29}$$

Integrating (29) over one wave length, we get

$$\Delta P = P_1 - P_0 = -\frac{4(2-N)}{(1-N)}(qL_1 + L_2) \tag{30}$$

where $L_1 = \int_0^1 \frac{dz}{h^4 + f(h)}$ and $L_2 = \int_0^1 \frac{h^2 dz}{h^4 + f(h)}$

The physical quantity of interest, the non-dimensional time averaged flux over one period in the fixed frame of reference, Shapiro e al, is

$$\overline{Q} = \frac{1}{T}\int_0^T (q + h^2)d\tau = q + q_1 \tag{31}$$

where $q_1 = \int_0^1 h^2 dz$.

From (30) and (31) the relation between $\Delta P$ and $\overline{Q}$ is obtained

$$\Delta P = -\frac{4(2-N)}{(1-N)}[(\overline{Q} - q_1)L_1 + L_2] \tag{32}$$

Equation (32) is written in the form

$$\overline{Q} = q_1 - \frac{L_2}{L_1} - \left[\frac{1-N}{4(2-N)}\right]\frac{\Delta P}{L_1} \tag{33}$$

In the limit of micropolar parameter (32) and (33) reduce to the corresponding relations for a viscous fluid given by Shapiro *et al.*

**Friction force:**

The stress tensor is not symmetric. The non-zero dimensionless shear stresses in our problem are given by

$$\tau_{xr} = \frac{\delta Vz}{\delta r} - \frac{N}{1-N}\Omega \tag{34}$$

$$\tau_{yx} = \frac{1}{1-N}\frac{\delta Vz}{\delta r} + \frac{N}{1-N}\Omega \tag{35}$$

The dimensionless friction force $F_1$ on the inner wall of the tube using (34) over one wavelength is

$$F_1 = -2\int_0^1 h(z)(\tau_{xr})_{r=h(z)} dz = -2\int_0^1 h(z)\left(\frac{\delta V_z}{\delta r}\right)_{r=h(z)} dz \tag{36}$$

as $\Omega = 0$ at $r = h(z)$. Substituting for $V_z$ from (25) in (36) and using (29), (33) after some simplification, we get

$$F_1 = -(1-N)\int_0^1 h^2 \frac{dP}{dz} dz = 4(2-N)\left(L_3 - \frac{L_2^{\,2}}{L_1}\right) - (1-N)\Delta P \frac{L_2}{L_1} \tag{37}$$

where $L_3 = \int_0^1 \frac{h^4 dz}{h^4 + f(h)}$

Similarly, using the other expression $\tau_{rz}$ we get the frictional force as

$$F_2 = -\int_0^1 h^2 \frac{dP}{dz} dz \tag{38}$$

## 3. DISCUSSION OF RESULTS

From equation (33), we have calculated the pressure difference as a function of $\overline{Q}$ for different values of amplitude ratios $\phi$ and is shown in figure (1) for a fixed values of Da=0.0001, N=0.4, $\alpha$ =0.75 and m=2. We observe that the larger the amplitude ratio, the pressure rise against which the pump works. For a given $\Delta$P, the flux $\overline{Q}$ for a micropolar fluid depends on $\phi$ and it increases with increasing $\phi$.

From equation (33), we have calculated the pressure difference as a function of $\overline{Q}$ for different values of coupling number N for fixed Da=0.0001, m=2, $\phi$=0.4 and $\alpha$ =0.75 and is shown in figure (2). We observe that the larger the coupling number N, the greater the pressure rise against which the pump works. For a given $\overline{Q}$, the pressure difference increases with increasing N. For free pumping the flux $\overline{Q}$ increases with increasing coupling parameter N.

The variation of pressure rise with time averaged flow rate is calculated from equation (33) for different values of micropolar parameter m and is shown in figure (3), for fixed Da=0.0001, N=0.2, $\phi$=0.4 and $\alpha$ =0.75. We observe that for a given flux $\overline{Q}$, the pressure difference $\Delta P$ increases with increasing m. For a given $\Delta P$, the flux $\overline{Q}$ depends on m and it increases with decreasing m. For free pumping the flux $\overline{Q}$ increases with increasing micropolar parameter m.

From equation (33), we have calculated the pressure difference as a function of $\overline{Q}$ for different values of Darcy number Da, for fixed $\phi$=0.4, m=2, $\alpha$ =0.75, and N=0.4 and is shown in figure (4). We observe that for a given $\Delta P$, the flux $\overline{Q}$ depends on Darcy number and it decreases with increasing Darcy number Da. For free pumping the flux $\overline{Q}$ is constant and it is independent of Da. The variation of pressure rise with time averaged flow rate is calculated from (33) for different values of $\alpha$ and is shown in figure (5) for fixed Da=0.001, m=2, N=0.4 and $\phi$=0.4. We observe that the longer the slip parameter, the greater the pressure rise against which the pump works. For a given $\Delta P$, the flux $\overline{Q}$ increases with increasing '$\alpha$'. For a given flux $\overline{Q}$, the pressure difference $\Delta P$ increases with increasing $\alpha$.

The variation of frictional force $F_1$ for different values of Da, $\alpha$, N, m and $\phi$ are presented in shown in figures (6) to (9). It is observed that the frictional force $F_1$ has the opposite behavior compared to the pressure rise ($\Delta P$). It is observed that the friction force reduces with increasing N but it increases with increasing $\phi$. Further, we observe that the friction force for a Newtonian fluid is always greater than that for a micropolar fluid. We calculate $F_2$ from (38) for different values of Da, $\alpha$, N, m and $\phi$ and is shown in figures (10) to (13). It is observed that the frictional force $F_2$ has the opposite behavior compared to the pressure rise ($\Delta P$).

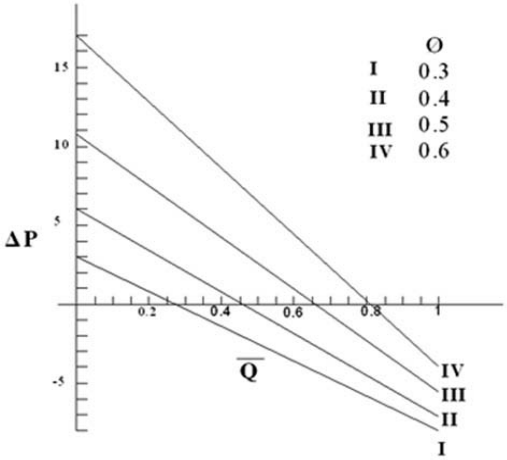


**Fig**.1: The variation of $\Delta P$ with $\overline{Q}$ for different $\phi$ with N=0.4, m=2, Da=0.0001, $\alpha$=0.75

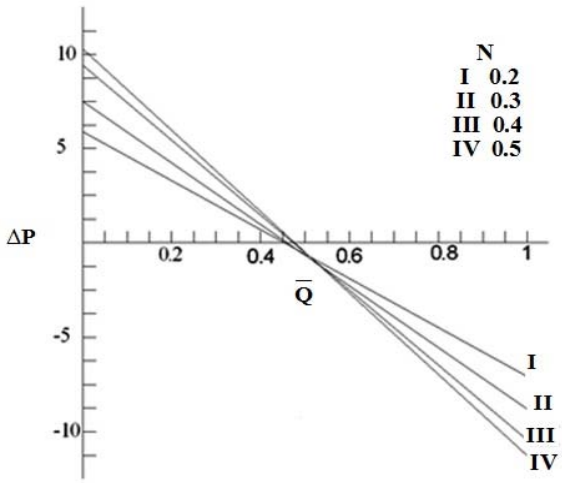


**Fig**.2: The variation of $\Delta P$ with $\overline{Q}$ for different $N$ with $\phi$=0.4, m=2, Da=0.0001, $\alpha$=0.75

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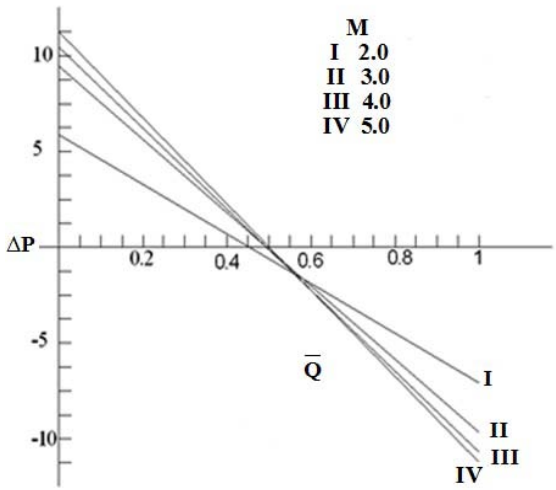


**Fig**.3 : The variation of $\Delta P$ with $\overline{Q}$ for different $m$ with $\phi$=0.4,Da=0.0001,N=0.4,$\alpha$=0.75

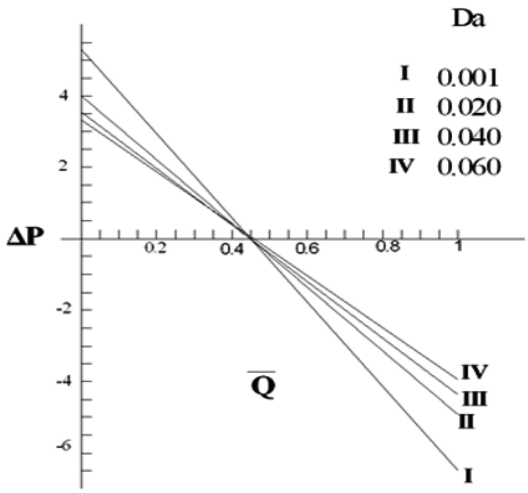


**Fig**.4 : The variation of $\Delta P$ with $\overline{Q}$ for different $Da$ with $\phi$=0.4, m=2,N=0.4,$\alpha$=0.75

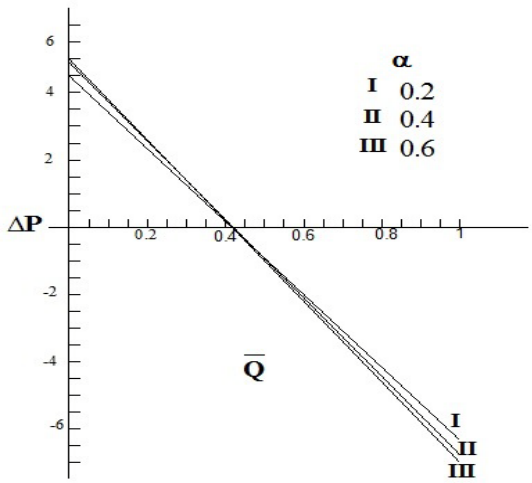


Fig.5 : The variation of $\Delta P$ with $\overline{Q}$ for different $\alpha$ with $\phi$=0.4, Da=0.0001,N=0.4,m=2

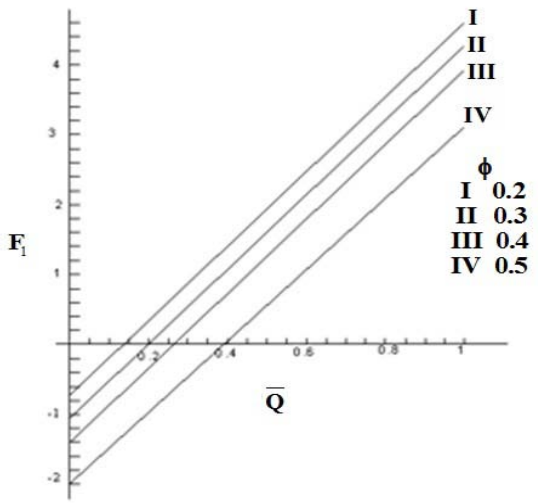


**Fig**.6 : The variation of $F_1$ with $\overline{Q}$ for different $\phi$ with N=0.4, Da=0.0001,m=2,$\alpha$=0.75

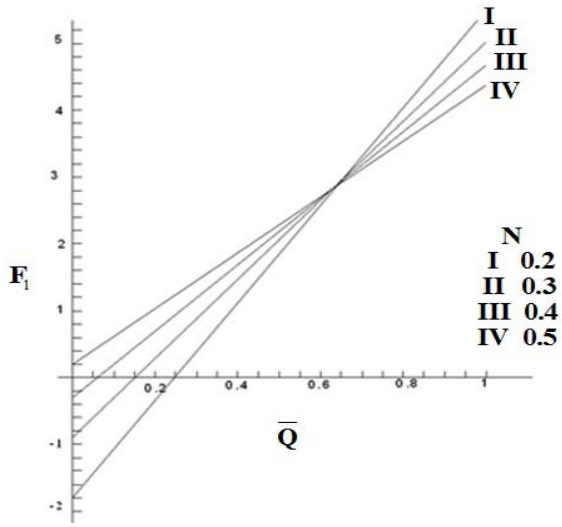


**Fig**.7 : The variation of $F_1$ with $\overline{Q}$ for different N with $\phi$=0.4,$Da$=0.0001,m=2,$\alpha$=0.75

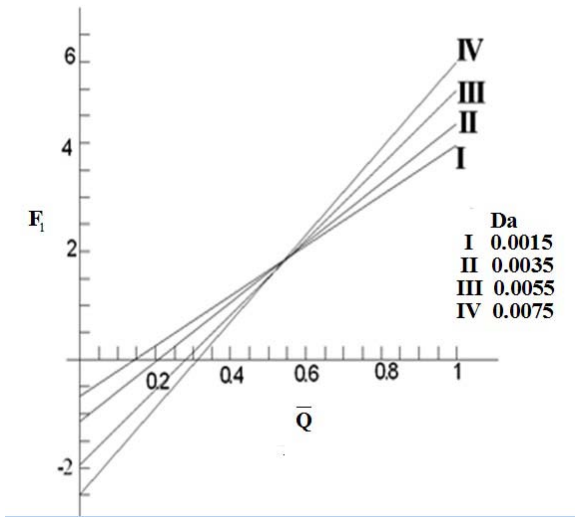


**Fig**.8 : The variation of $F_1$ with $\overline{Q}$ for different Da with $\phi$=0.4, $N$=0.4,m=2,$\alpha$=0.75

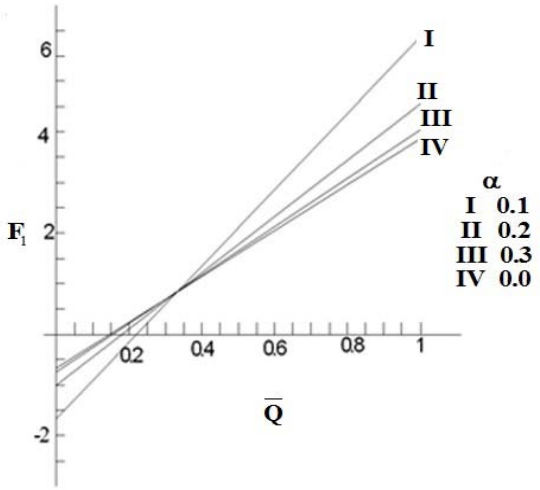


**Fig**.9 : The variation of $F_1$ with $\overline{Q}$ for different $\alpha$ with $\phi$=0.4, $N$=0.4, m=2, $Da$=0.0001

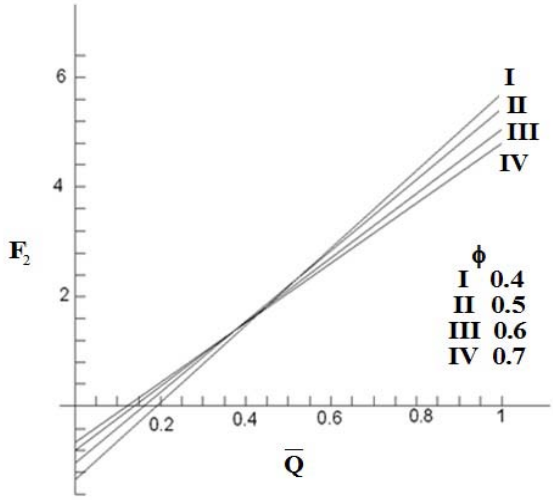


**Fig**.10 : The variation of $F_2$ with $\overline{Q}$ for different $\phi$ with $N$=0.4, $Da$=0.0001, m=2, $\alpha$=0.75

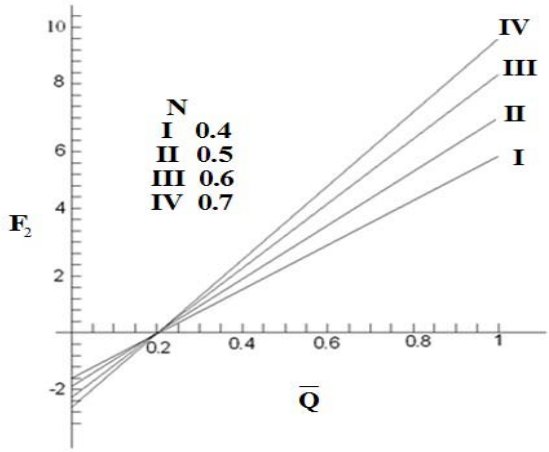


**Fig**.11: The variation of $F_2$ with $\overline{Q}$ for different N with $\phi$=0.4, $Da$=0.0001,m=2,$\alpha$=0.75

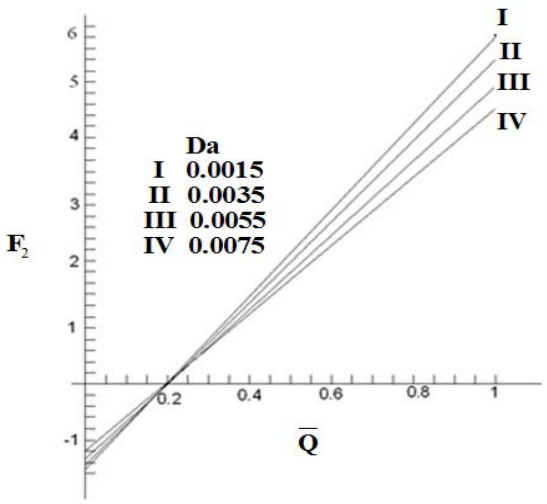


**Fig.**12 : The variation of $F_2$ with $\overline{Q}$ for different Da with $\phi$=0.4, $N$=0.4,m=2,$\alpha$=0.75

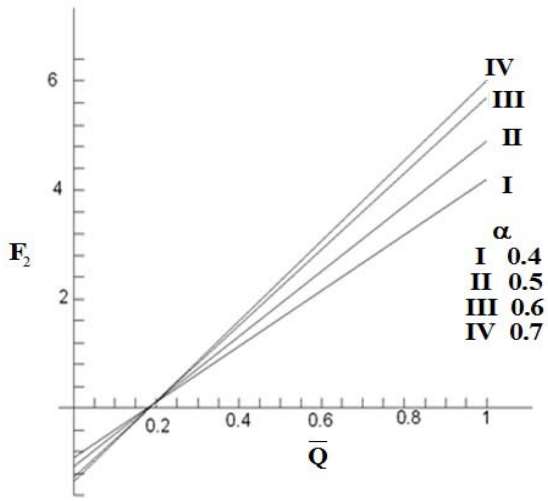


**Fig.**13 : The variation of $F_2$ with $\overline{Q}$ for different $\alpha$ with $\phi$=0.4,$N$=0.4,m=2,$Da$=0.0001

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