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Peristaltic Couple Stress Flow of Blood through Coaxial Channel with Effect of Porous Medium: Blood Flow Study

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Abstract

Peristaltic couple stress flow of blood through coaxial channel with effect of porous medium: blood flow study. The velocity, pressure gradient, flow rate and pressure rises of blood are investigated by using appropriate analytical and numerical methods. Numerical computations were carried out to investigate the effect of couple stress parameter S and Porous parameter D on axial velocity, axial pressure gradient and pressure rise. The computational results are presented in graphical form.

Keywords: Peristaltic fluid flow, Couple stress fluid flow, porous medium and coaxial channel

Introduction

Peristalsis is an important mechanism for mixing and transporting fluids, which is generated by a progressive wave of contraction or expansion moving on the wall of the tube. Deep research on peristalsis has been attempted and is still demanded due to its practical applications especially in physiology. Examples include urine transport from kidney to bladder through the ureter, chyme movement inside the gastro-intestinal tract, transport of spermatozoa in the ductus efferentes of the male reproductive tracts, in the cervical canal, movement of ovum in the female fallopian tube, transport of lymph in the lymphatic vessels, vasomotion of small blood vessels such as arterioles, venules and capillaries and so on. Even though it is observed in living systems for many centuries; the mathematical modeling of peristaltic transport began with trend setting works by Shapiro et al. [1] using wave frame of reference and Fung and Yih [2] using laboratory frame of reference. Many of the contributors to the area of peristaltic transport have either followed Shapiro or Fung. Peristaltic pumping of a particle-fluid mixture has been investigated by Hung and Brown [3], Srivastava and coworker [4-10], Mekheimer et al. [11], Medhavi and Singh [12-14] and B Gupta and Seshadri [15], most of the studies in the literature have been conducted in uniform geometry only whereas it is well known that in most of the practical applications, the flow geometry is found to be non-uniform. With increasing interest in particulate suspension flow due to its applications to diverse physical problems, the present study is therefore devoted to study the flow of a particulate suspension in a non-uniform tube induced by sinusoidal peristaltic waves. The peristaltic fluid flow through channels with flexible walls has been studied by Ravi Kumar et al [16-23]. In view of the theoretical model for blood flow applied in Srivastava and Srivastava [24] to discuss the effect of hematocrit on flow characteristics in a catheterized artery, it is strongly believed that the study conducted here may be applied to discuss the peristaltic induced flow of blood in small vessels of varying diameter.

The study of couple stress fluid is very useful in understanding various physical problems because it possesses the mechanism to describe rheological complex fluids such as liquid crystals and human blood. By couple stress fluid, we mean a fluid whose particles sizes are taken into account, a special case of non-Newtonian fluids. In further investigation many authors have used one of the simplification is that they have assumed blood to be a suspension of spherical rigid particles (red cells), this suspension of spherical rigid particles will give rise to couple stresses in a fluid. The theory of couple stress was first developed by Stokes [25] and represents the simplest generalization of classical theory which allows for polar effects such as presence of couple stress and body couples. For couple stress fluids,

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there have been a number of studies carried out due to its widespread industrial and scientific applications, such as the works of Srivastava [26], Mekheimer and Abd elmaboud [27] and Sobh [28]. A number of studies containing couple stress have been investigated by Valanis and Sun [29], Chaturani [30], Srivastava [31], Elshehawey and Mekheimer [32], Mekheimer [33]. Recently, Sohail Nadeem and Safia Akram [34], Alemayehu and Radhakrishnamacharya [35], Sreedah et al.[36], Raghunatha Rao and Prasada Rao [37] have studied peristaltic transport of a couple stress fluid under different conditions.The MHD fluid flow in a parallel plate channel is an interesting area in the study of fluid mechanics because of its relevance to various engineering applications. The MHD flow in the planar channels leads to a startup process implying thereby a viscous layer at the boundary is suddenly set into motion and becomes important in the application of various branches of geophysics, astrophysics and fluid engineering. Currently, MHD effects are widely exploited in different industrial processes ranging from metallurgy to the production pure crystals. A field in which MHD will play an essential role is nuclear fusion, where it is involved in at least two different problems: the confinement and dynamics of plasma, and the behaviour of the liquid metal alloys employed in some of the currently considered designs of tritium breeding blankets. In recently years the hydro magnetic flow in a rotating channel in the presence of an applied uniform magnetic field as well as constant pressure gradient has been considered by a number of research workers, taking into account the various aspects of the problem. Rathod and Shrikanth [38] have studied the MHD flow of Rivlin-Ericksen fluid between two infinite parallel inclined plates.

Mathematical modelling and analysis

Consider the unsteady hydromagnetic flow of a viscous, incompressible and electrically conducting couple-stress fluid through a two-dimensional channel of non- uniform thickness with a sinusoidal wave travelling down its wall. The plates of the channel are assumed to be electrically insulated. We choose a rectangular coordinate system for the channel with x along centerline in the direction of wave propagation and y transverse to it.

The geometry of the wall surface is defined as

$$h(x, t) = a_0 + kx + b \,\mathrm{Sin}\, \frac{2\pi}{\lambda}(x-ct) \qquad (1)$$

where a(x) is the half-width of the channel at any axial distance x from inlet, a_0 is the half-width at inlet, k(<<1) is a constant whose magnitude depends on the length of the channel and exit and inlet dimensions, b is the wave amplitude, λ is the wave length, c is the propagation velocity and t is the time.

The constitutive equations and equations of motion for a couple stress fluid are

$$T_{ji,j} + \rho f_i = \rho \frac{\partial v_i}{\partial t} \qquad (2)$$

$$e_{ijk} + T^A_{jk} + M_{ji,j} + \rho C_i = 0 \qquad (3)$$

$$\tau_{ij} = -p' + 2\mu\, d_{ij} \qquad (4)$$

$$\mu_{ij} = 4\eta\omega_{j,i} + \eta'\omega_{j,i} \qquad (5)$$

Where f_i is the body force vector per unit mass, C_i is the body moment per unit mass, v_i is the velocity vector, τ_{ij} and T^A_{jk} are the symmetric and antisymmetric parts of the stress tensor T_{jk} respectively, M_{ij} is the couple stress tensor, μ_{ij} is the deviatoric part of M_{ij}, ω_i is the vorticity vector, d_{ij} is the symmetric part of the velocity gradient, η and η' are constants associated with the couple stress, p' is the pressure, and the other terms have their usual meaning from tensor analysis

We introduce a wave frame of reference (*x*, *y*) moving with velocity *c* in which the motion becomes independent of time when the channel length is an integral multiple of the wavelength and the pressure difference at the ends of the channel is a constant (Shapiro et al., (1969)). The transformation from the fixed frame of reference (*X*, *Y*) to the wave frame of reference (*x*, *y*) is given by

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

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (6)$$

$$\rho\left[\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right] = -\frac{\partial p}{\partial x} + \mu\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right] - \eta\left[\frac{\partial^4 u}{\partial x^4} + \frac{\partial^4 u}{\partial y^4} + 2\frac{\partial^4 u}{\partial x^2\,\partial y^2}\right] - \left[\frac{\mu}{k_1}\right](u + c) \qquad (7)$$

$$\rho\left[\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right] = -\frac{\partial p}{\partial y} + \mu\left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right] - \eta\left[\frac{\partial^4 v}{\partial x^4} + \frac{\partial^4 v}{\partial y^4} + 2\frac{\partial^4 v}{\partial x^2\,\partial y^2}\right] - \left[\frac{\mu}{k_1}\right] \qquad (8)$$

u and v are the velocity components in the corresponding coordinates p is the fluid pressure, ρ is the density of the fluid, μ is the coefficient of the viscosity, η is the coefficient of couple stress, k_1 is the permeability of the porous medium and *k* is the thermal conductivity.

Since it is presumed that the couple stress is caused by the presence of the suspending particles, obviously the clear fluid cannot support couple stress at the boundary, hence we have tactically assumed

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that, the components of the couple stress tensor at the wall vanish, the boundary conditions are

Using the following the non-dimensional variables

$x^* = \frac{x}{\lambda}$ $y^* = \frac{y}{a_0}$ $u^* = \frac{u}{c}$ $v^* = \frac{\lambda v}{a_0 c}$

$p^* = \frac{a_0{}^2 p}{\lambda \mu c}$ $t^* = \frac{ct}{\lambda}$

$Re = \frac{\rho c\, a_0}{\mu}$ $M = \sqrt{\frac{\sigma}{\mu}} B_0 a_0$ $\delta = \frac{a_0}{\lambda}$ $h = 1 + \frac{\lambda kx}{a_0} + \phi\, sin\{2\pi(x-t)\}$

Where ϕ (amplitude ratio) = b/a_0 < 1

Equations of motion and boundary conditions in the dimensionless form become

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (9)$$

$$Re\delta[u_t + u\, u_x + v u_y] = \left[-\frac{\partial p}{\partial x} + \delta^2 u_{xx} + u_{yy} - S\delta^4 u_{xxxx} - S\, u_{yyyy} - 2S\delta^2 u_{xxyy} - \frac{1}{D}u - \frac{1}{D}\right] \qquad (10)$$

$$Re\delta^3[v_t + u\, v_x + v v_y] = \left[-\frac{\partial p}{\partial y} + \delta^4 v_{xx} + \delta^2 v_{yy} - S\delta^2 v_{xxxx} - S\delta^2\, v_{yyyy} - 2S\delta^4 v_{xxyy} - \delta^2 \frac{1}{D}\right] \qquad (11)$$

Using long wavelength (i.e., □□□□□1) and negligible inertia (i.e., Re□□0) approximations, we have

$$S\frac{\partial^4 u}{\partial y^4} - \frac{\partial^2 u}{\partial y^2} + \left(\frac{1}{D}\right)u = -\left(\frac{\partial p}{\partial x} + \frac{1}{D}\right) \qquad (12)$$

$$\frac{\partial p}{\partial y} = 0 \qquad (13)$$

With dimensionless boundary conditions

$$\frac{\partial u}{\partial y} = 0 \quad \frac{\partial^3 u}{\partial y^3} = 0 \text{ at } y = 0 \qquad (14)$$

$$u = 0 \quad \frac{\partial^2 u}{\partial y^2} = 0 \quad \text{at } y = h(x,t) = 1 + \frac{\lambda kx}{a_0} + \phi\sin\{2\pi(x-t)\} \qquad (15)$$

Solving equation (12) using the boundary conditions (14 and 15), we get

$$u = -\frac{A}{\left(\frac{1}{D}\right)(\alpha_1{}^2-\alpha_2{}^2)}\left[\alpha_2{}^2\frac{Cosh[\alpha_1 y]}{Cosh[\alpha_1 h]} - \alpha_1{}^2\frac{Cosh[\alpha_2 y]}{Cosh[\alpha_2 h]} + (\alpha_1{}^2-\alpha_2{}^2)\right] \qquad (16)$$

Where $\alpha_1 = \sqrt{\frac{1+\sqrt{1-\frac{4S}{D}}}{2S}}$ $\alpha_2 = \sqrt{\frac{1-\sqrt{1-\frac{4S}{D}}}{2S}}$, $A = \left[\frac{dp}{dx} + \frac{1}{D}\right]$

The rate of volume flow 'q' through each section is a constant (independent of both x and t).It is given by

q = $\int_0^h u dy$

$$= -\frac{A}{\left(\frac{1}{D}\right)(\alpha_1{}^2-\alpha_2{}^2)}\left[\frac{\alpha_2{}^2}{\alpha_1}\mathrm{Tan}[\alpha_1 h] - \frac{\alpha_1{}^2}{\alpha_2}\mathrm{Tan}[\alpha_2 h] + (\alpha_1{}^2-\alpha_2{}^2)h\right] \qquad (17)$$

Hence the flux at any axial station in the fixed frame is found to be given by

$$Q(x,t) = \int_0^h (u+1)dy = q + h \qquad (18)$$

while the expression for the time-averaged volumetric flow rate over one period $T\left(=\frac{\lambda}{c}\right)$ of the peristaltic wave is obtained as

$$\bar{Q} = \frac{1}{T}\int_0^T Q dt = \frac{1}{T}\int_0^T (Q+h)dt = q + 1 \qquad (19)$$

The pressure gradient obtained from equation (18) can be expressed as

$$\frac{dp}{dx} = -\left[\frac{\left(\frac{1}{D}\right)(\alpha_1\alpha_2)(\alpha_1{}^2-\alpha_2{}^2)(\bar{Q}-1)}{\alpha_2{}^3\mathrm{Tan}[\alpha_1 h] - \alpha_1{}^3\mathrm{Tan}[\alpha_2 h] + \alpha_1\alpha_2(\alpha_1{}^2-\alpha_2{}^2)h}\right] - \frac{1}{D} \qquad (20)$$

The pressure rise Δ_{P_L} (at the wall) in the channel of length L, non-dimensional form is given by $\Delta_P = \int_0^1 \left(\frac{dp}{dx}\right) dx$

Numerical results and discussion

In this paper, we investigate the Peristaltic couple stress flow of blood through coaxial channel with effect of porous medium: blood flow study, we have presented the graphical results of the solutions axial velocity u and pressure gradient dp/dx. We now discuss the behavior of axial velocity for various in the governing parameters Couple stress parameter (S) and Porous parameter (D) (See figures 1-6). Figures 1to 3 reveal the axial velocity distribution (u) increases by increasing the Couple stress parameter (S) with D ≥ 10, $\frac{dp}{dx}$ = 0.5.Thus the phenomenon of axial velocity increases by increasing the Couple stress parameter (S) and also the axial velocity distribution gradually increases by increasing the porous parameter (D) with S ≥ 0.1, $\frac{dp}{dx}$ = 0.5 (See figures 4 to 6). It is interesting to note that, there is no appreciable effect of Porous medium on the axial velocity u at D ≥ 100. (See figures 4 to 6).

Figs.7-17 shows the pressure gradient for different value of S and $\bar{Q}$. Figures 7- 9 reveals that the pressure gradient is maximum at x = 0.7 for ϕ = 0.7, t =0, λ = 10, k = 0.0005, a_0= 0.01, $\bar{Q}$ = 0.5 with D ≥10. We observed that through the region $x \in (0.5, 0.9)$, i.e. narrowing part of the channel, the flow cannot pass easily. Therefore, it required large pressure gradient to maintain the same flux to pass it in the narrow part of the channel. In the wider part of

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the channel $x\epsilon\ (0\ ,0.4\ ) \cup x\epsilon\ (0.9, 1)$, where the flow can easily pass without giving any large pressure gradient. We observed that as the values the of the couple stress parameter (S) increases the magnitude of the axial pressure gradient also increases. Figures 10- 12 depicts variation of pressure gradient for variation of couple stress parameter when t = 0.5 and being fixed other parameters x = 0.7 for ϕ = 0.7, λ = 10, k = 0.0005, a_0= 0.01, $\bar{Q} = 0.5$ with D ≥10. The axial pressure gradient is maximum is maximum at x = 0.2. We notice that through the region$x\ \epsilon\ (0.1, 0.4)$, i.e. narrow part of the channel, we apply large pressure gradient to make it as normal fluid flow. In the wider part of the channel$x\epsilon\ (0\ , 0.1) \cup x\epsilon\ (0.4, 1)$, the fluid flow can easily pass because of low pressure gradient. Figures 13-14 reveals the variation axial pressure gradient for variation of couple stress parameter (S) with t =0.75 and being fixed other parameters x = 0.7 for ϕ = 0.7, λ = 10, k = 0.0005, a_0= 0.01, $\bar{Q} = 0.5$ with D ≥10. We notice that the pressure gradient is increases with increase in couple stress parameter. We notice that the flow cannot pass easily in the narrowing part of the channel, i.e. $\epsilon(0.3, 0.7)$ because of large pressure gradient. We notice that the magnitude of the pressure gradient increases within couple stress parameter (S). Figures 15-17 depicts the variation of axial pressure gradient for variation of averaged flow rate$\bar{Q}$. It is interesting to note that the axial pressure gradient decreases with increase in averaged flow rate $\bar{Q}$. We notice that the magnitude of pressure gradient decreases with increase in averaged flow rate $\bar{Q}$.

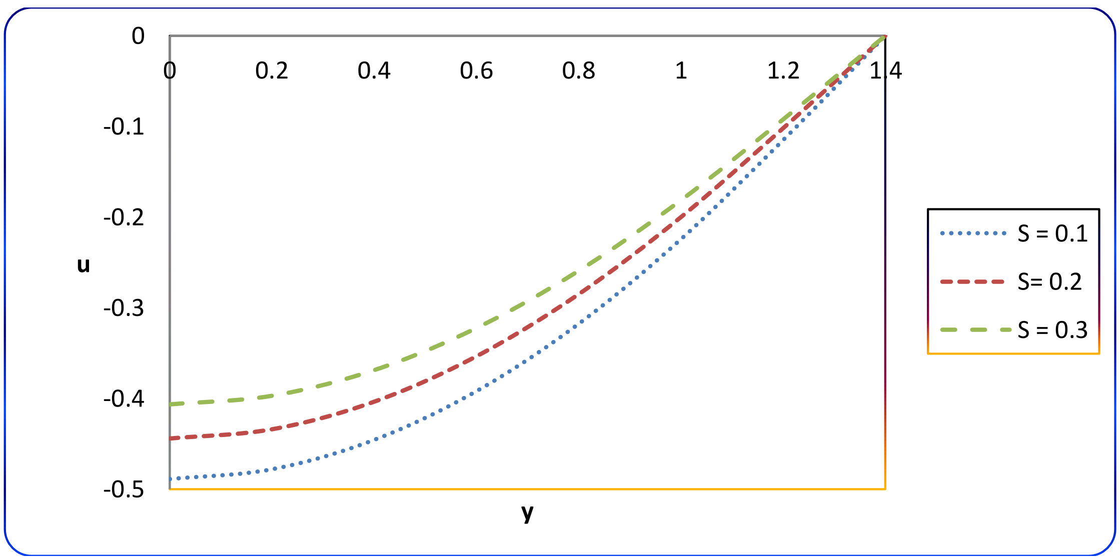

Figure (1): Distribution of axial velocity for different values of S with fixed D = 10, $\frac{dp}{dx}$ = 0.5, ϕ = 0.7, x = t = $\frac{\pi}{4}$, λ = 10, k = 0.0005, a_0= 0.01

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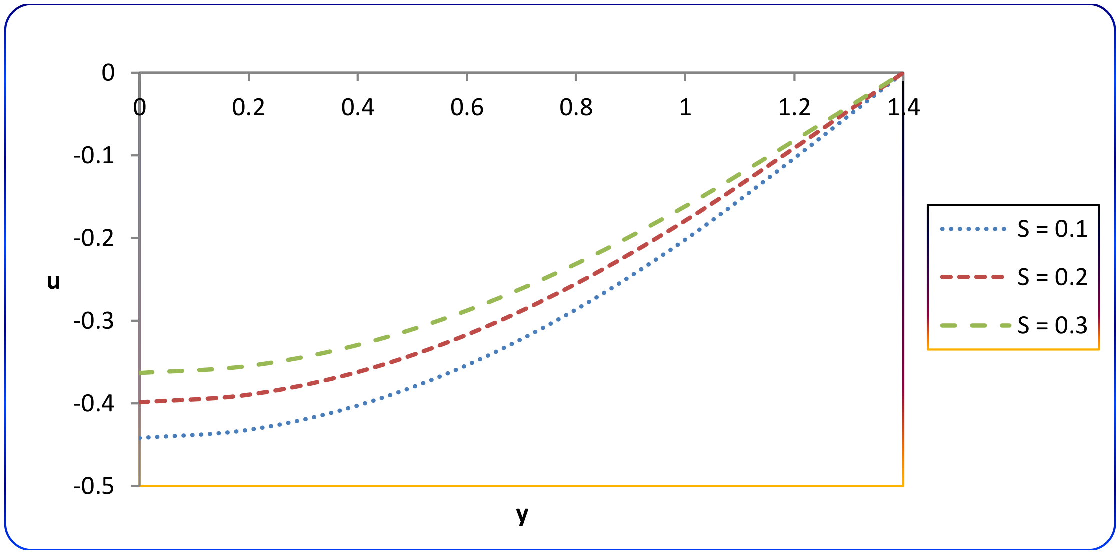

Figure (2): Distribution of axial velocity for different values of S with fixed D = 100, $\frac{dp}{dx}$ = 0.5, ϕ = 0.7, x = t = $\frac{\pi}{4}$, λ = 10, k = 0.0005, a_0= 0.01

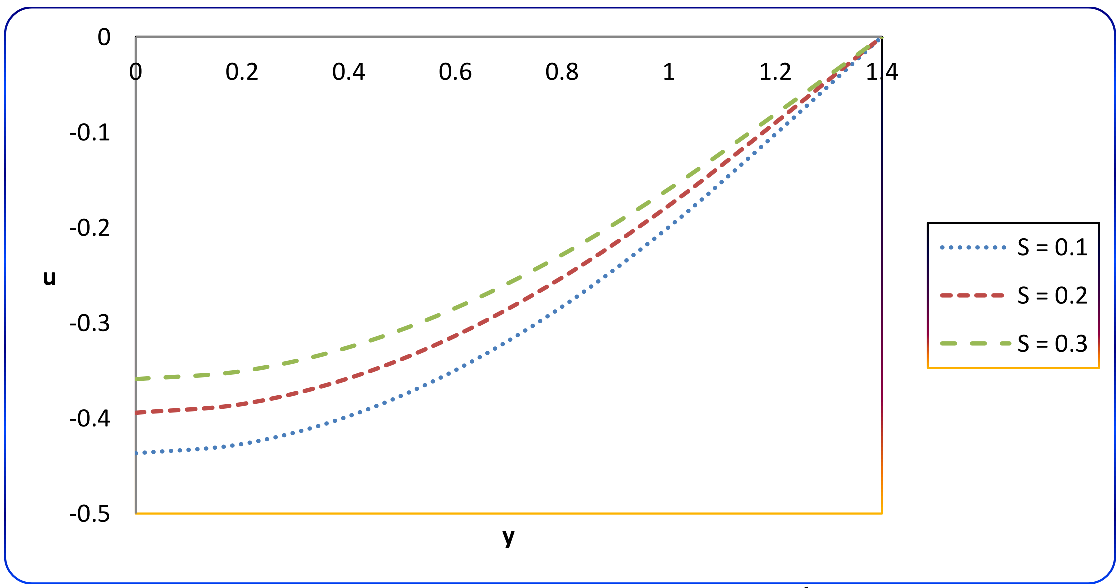

Figure (3): Distribution of axial velocity for different values of S with fixed D = 1000, $\frac{dp}{dx}$ = 0.5, ϕ = 0.7, x = t = $\frac{\pi}{4}$, λ = 10, k = 0.0005, a_0= 0.01

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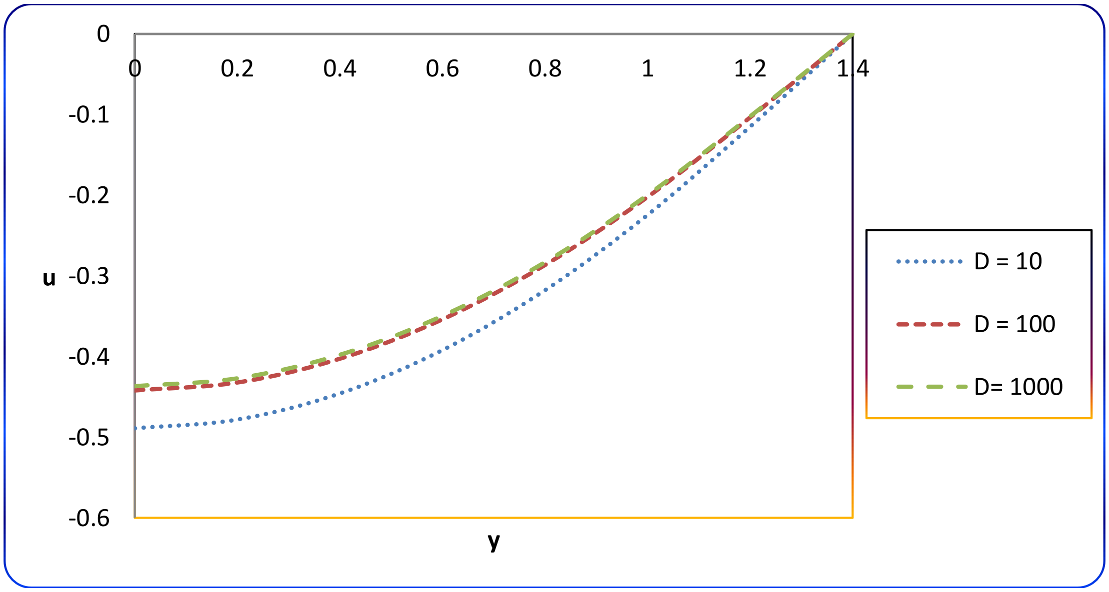

Figure (4): Distribution of axial velocity for different values of D with fixed S = 0.1, $\frac{dp}{dx}$ = 0.5, ϕ = 0.7, x = t = $\frac{\pi}{4}$, λ = 10, k = 0.0005, a_0= 0.01

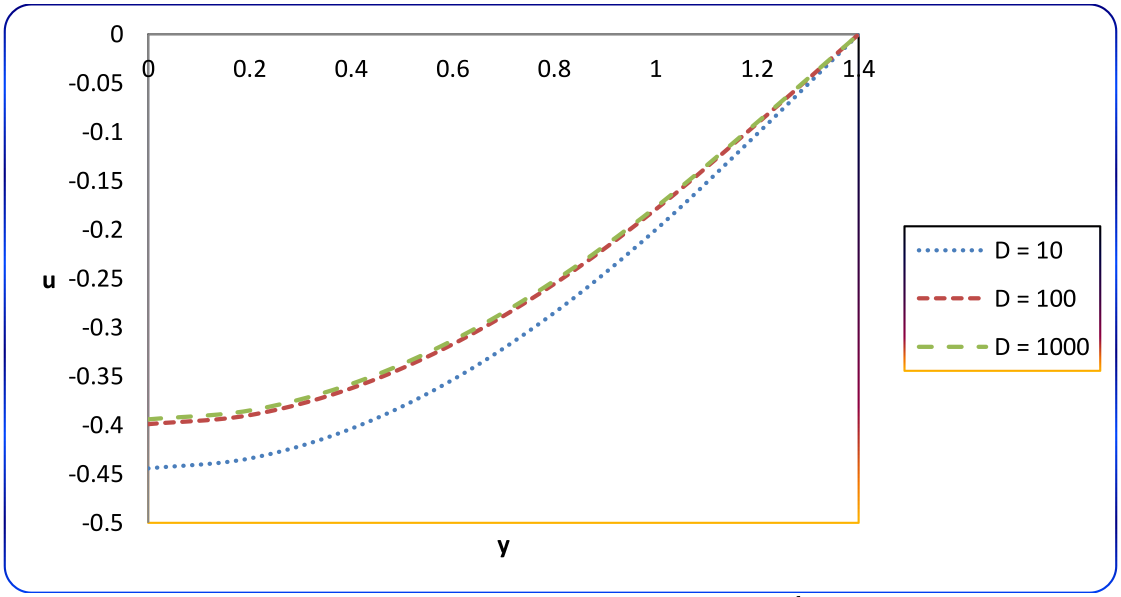

Figure (5): Distribution of axial velocity for different values of D with fixed S = 0.2, $\frac{dp}{dx}$ = 0.5, ϕ = 0.7, x = t = $\frac{\pi}{4}$, λ = 10, k = 0.0005, a_0= 0.01

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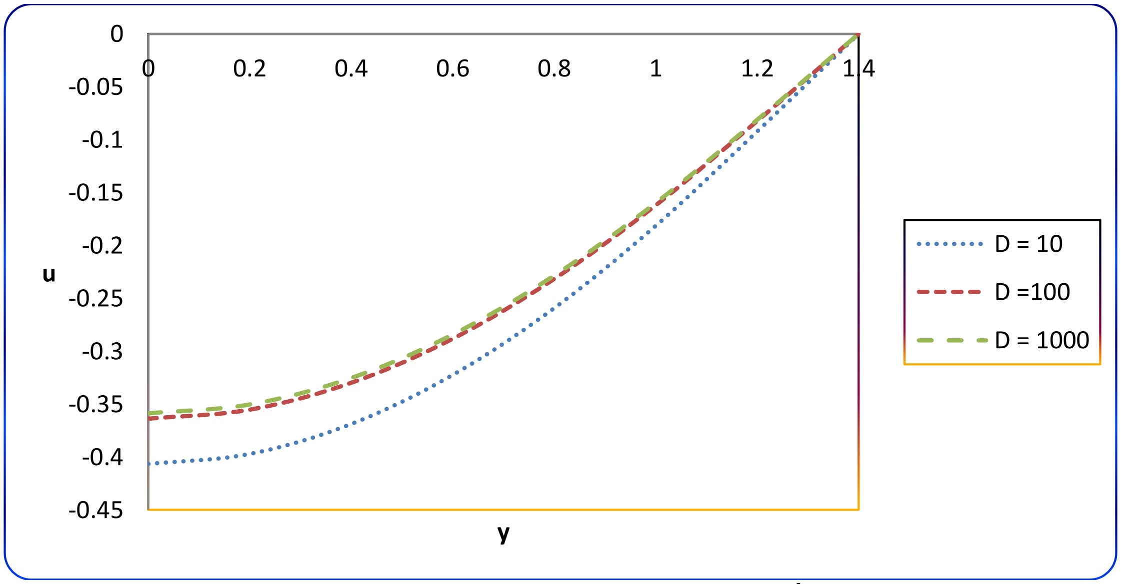

Figure (6): Distribution of axial velocity for different values of D with fixed S = 0.3, $\frac{dp}{dx}$ = 0.5, ϕ = 0.7, x = t = $\frac{\pi}{4}$, λ = 10, k = 0.0005, a_0= 0.01

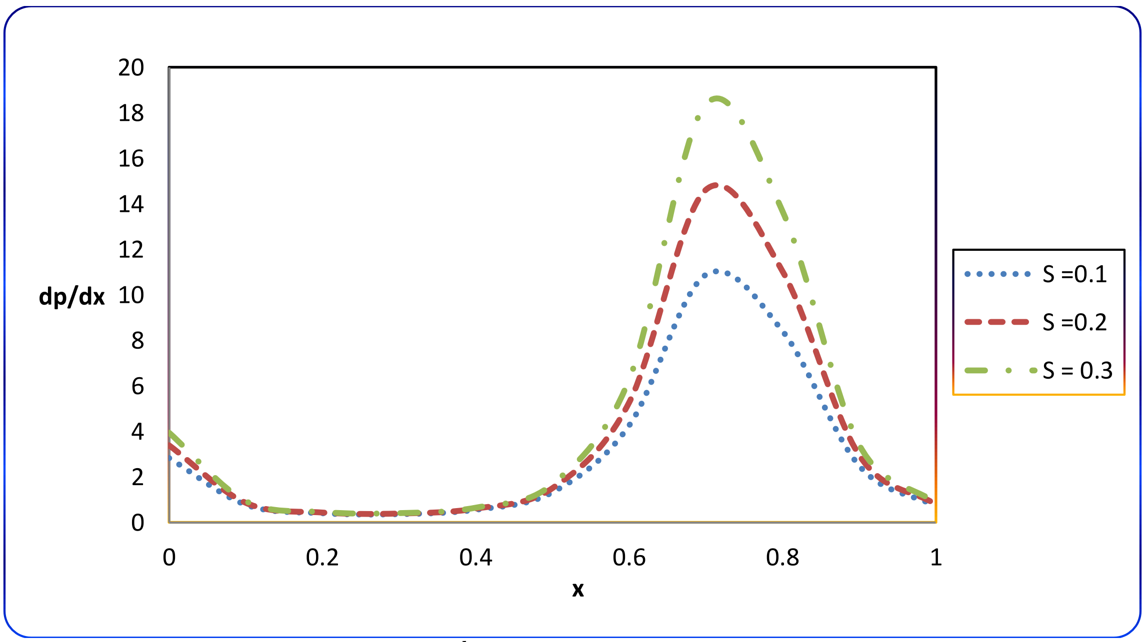

Figure (7): Distribution of axial pressure gradient $\frac{dp}{dx}$ versus x for ϕ = 0.7, t =0, λ = 10, k = 0.0005, a_0= 0.01, $\bar{Q} = 0.5$, D = 10.

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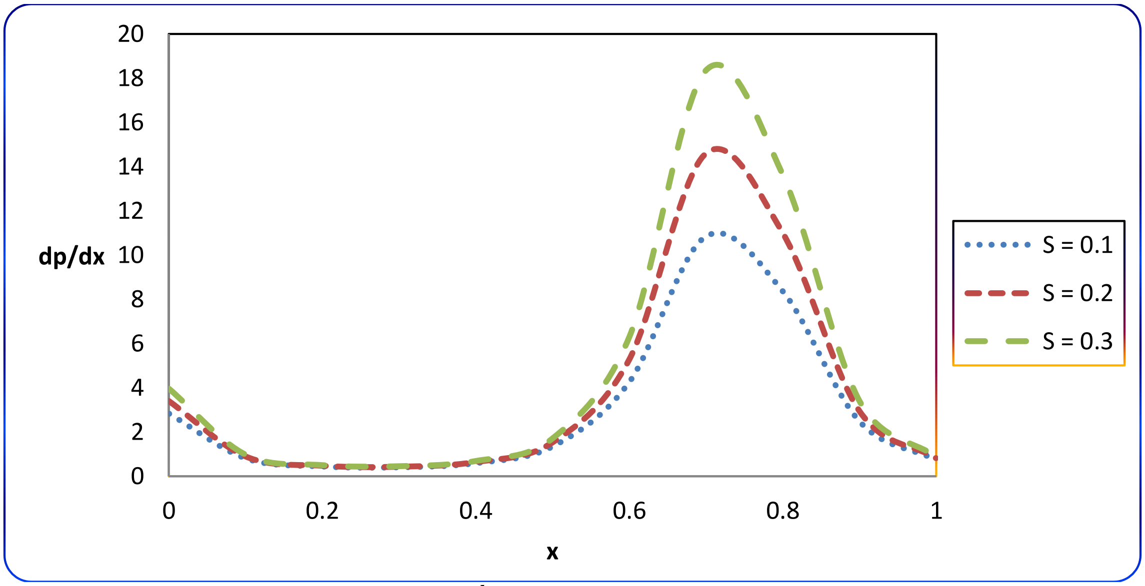

Figure (8): Distribution of axial pressure gradient $\frac{dp}{dx}$ versus x for ϕ = 0.7, t =0, λ = 10, k = 0.0005, a_0= 0.01,$\bar{Q}$ = 0.5, D = 100.

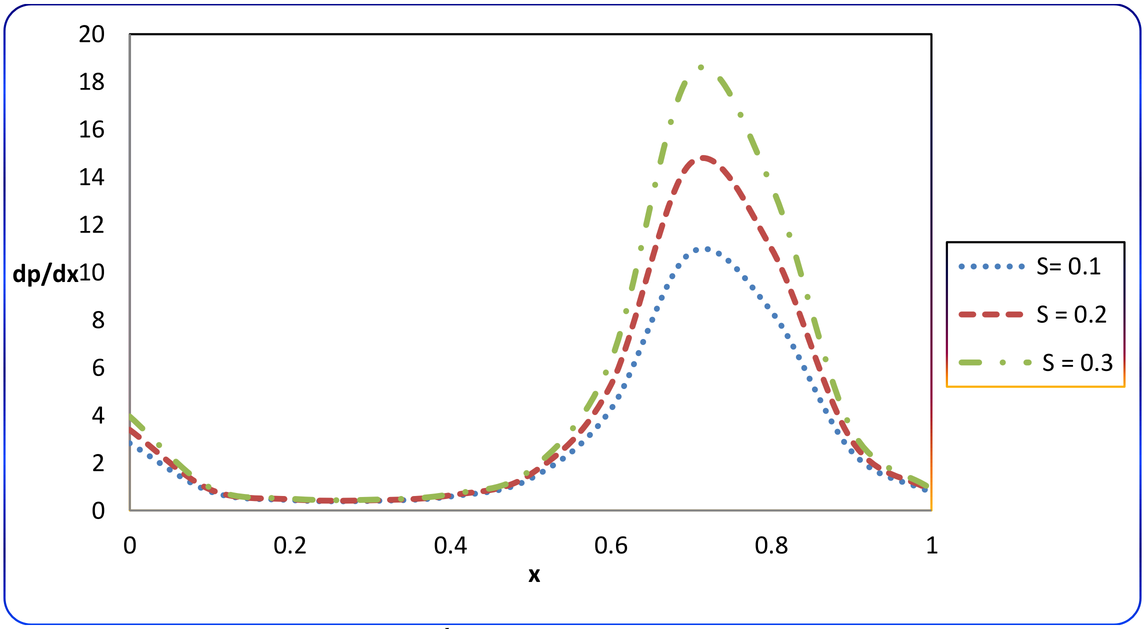

Figure (9 Distribution of axial pressure gradient $\frac{dp}{dx}$versus x for ϕ = 0.7, t =0, λ = 10, k = 0.0005, a_0= 0.01,$\bar{Q}$ = 0.5, D = 1000.

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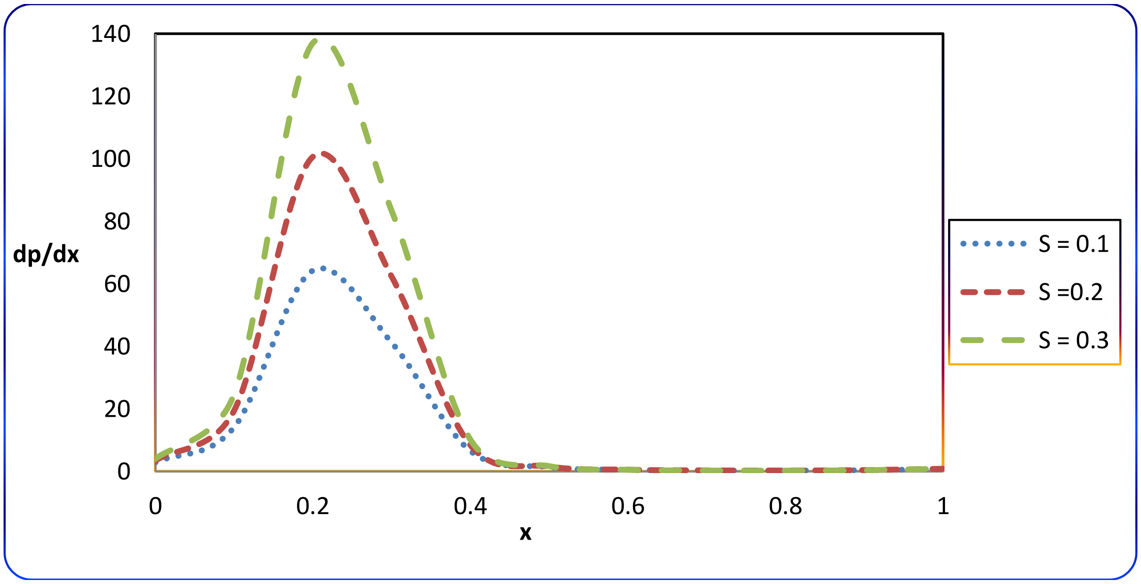

Figure (10): Distribution of axial pressure gradient $\frac{dp}{dx}$ *versus x for* ϕ *= 0.7, t = 0.5,* λ *= 10, k = 0.0005,* a_0*= 0.01,*$\bar{Q} = 0.5$*, D = 10.*

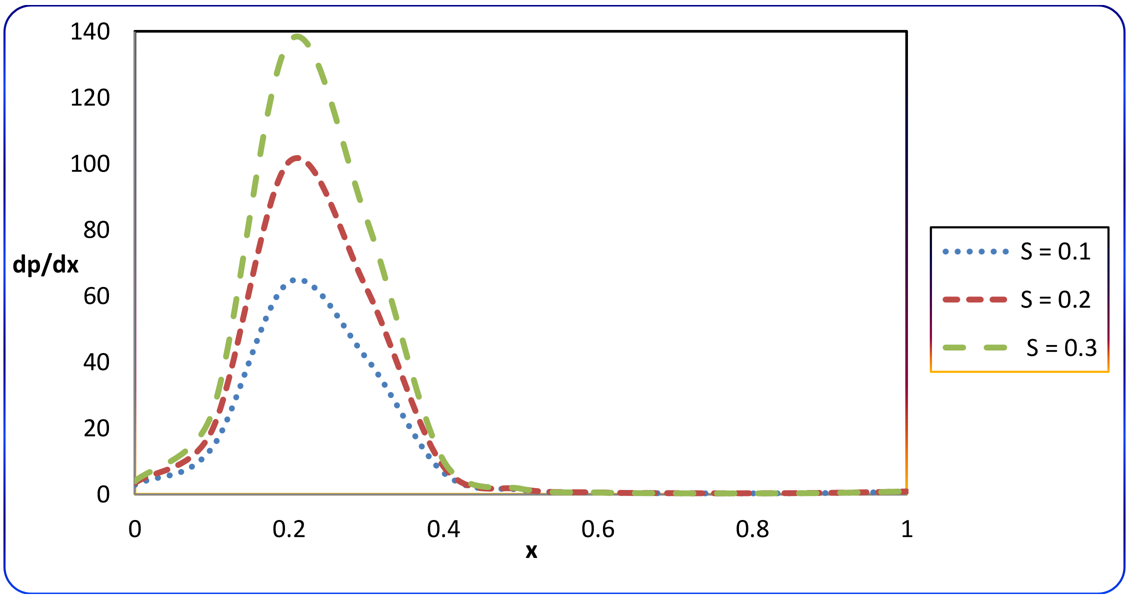

Figure (11): Distribution of axial pressure gradient $\frac{dp}{dx}$ *versus x for* ϕ *= 0.7, t = 0.5,* λ *= 10, k = 0.0005,* a_0*= 0.01,*$\bar{Q} = 0.5$*, D = 100.*

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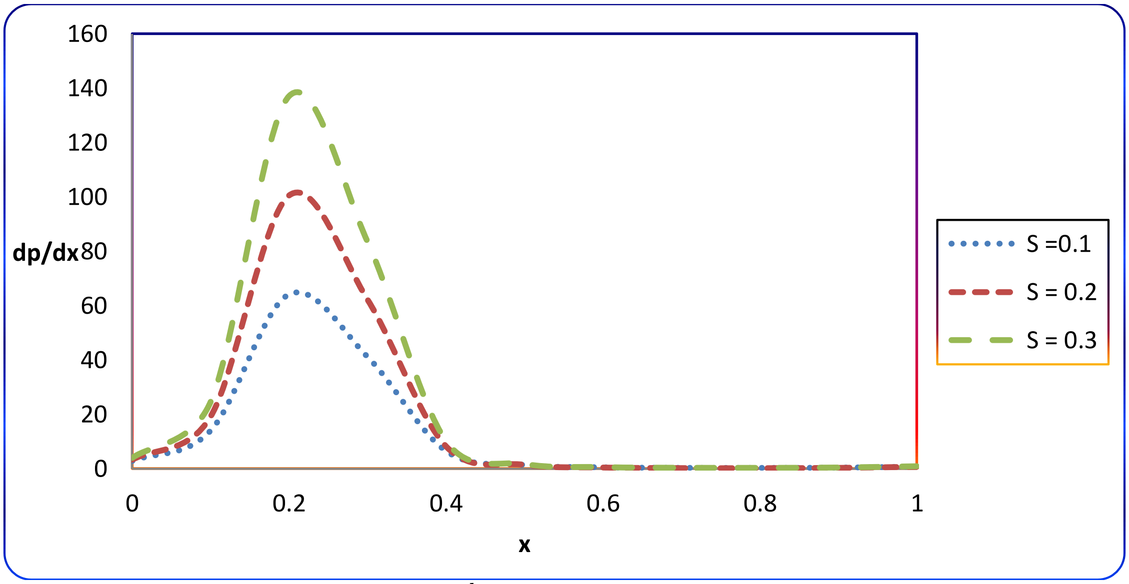

Figure (12): Distribution of axial pressure gradient $\frac{dp}{dx}$versus x for ϕ = 0.7, t = 0.5, λ = 10, k = 0.0005, a_0= 0.01,$\bar{Q}$ = 0.5, D = 1000.

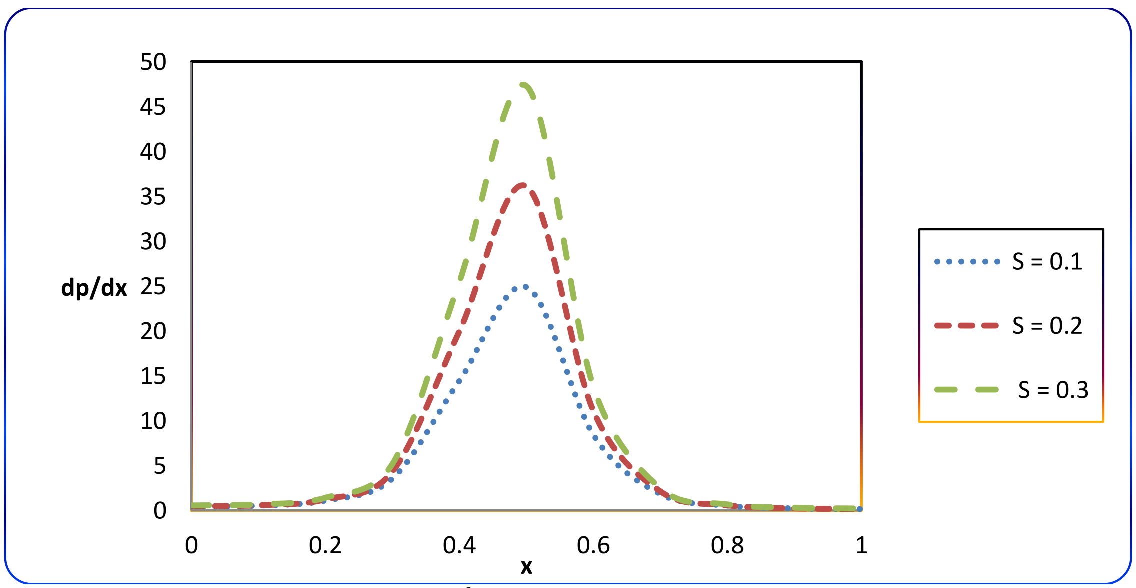

Figure (13): Distribution of axial pressure gradient $\frac{dp}{dx}$versus x for ϕ = 0.7, t = 0.75, λ = 10, k = 0.0005, a_0= 0.01,$\bar{Q}$ = 0.5, D = 10.

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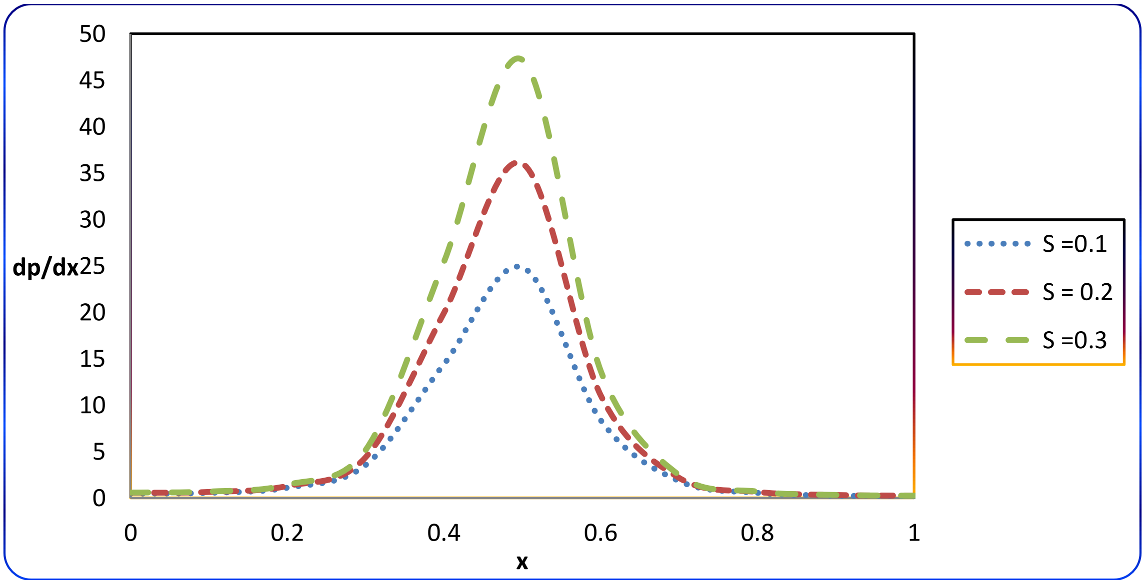

Figure (14): Distribution of axial pressure gradient $\frac{dp}{dx}$*versus x for* ϕ *= 0.7, t = 0.75,* λ *= 10, k = 0.0005,* a_0*= 0.01,*$\bar{Q} = 0.5$*, D = 100.*

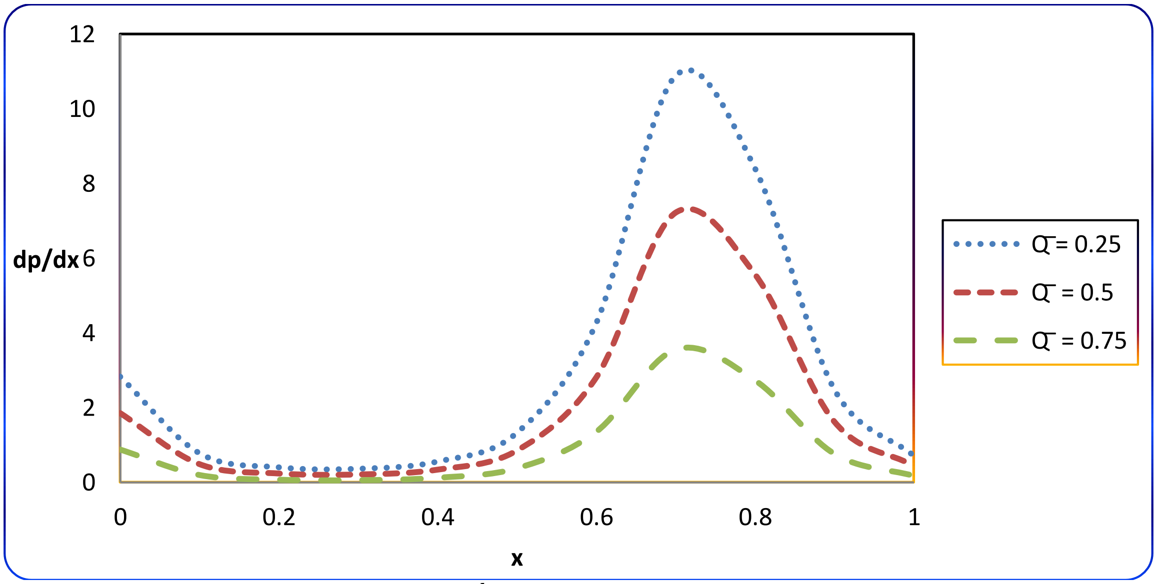

Figure (15): Distribution of axial pressure gradient $\frac{dp}{dx}$*versus x for* ϕ *= 0.7, t = 0,* λ *= 10, k = 0.0005,* a_0*= 0.01, S = 0.1, D = 10.*

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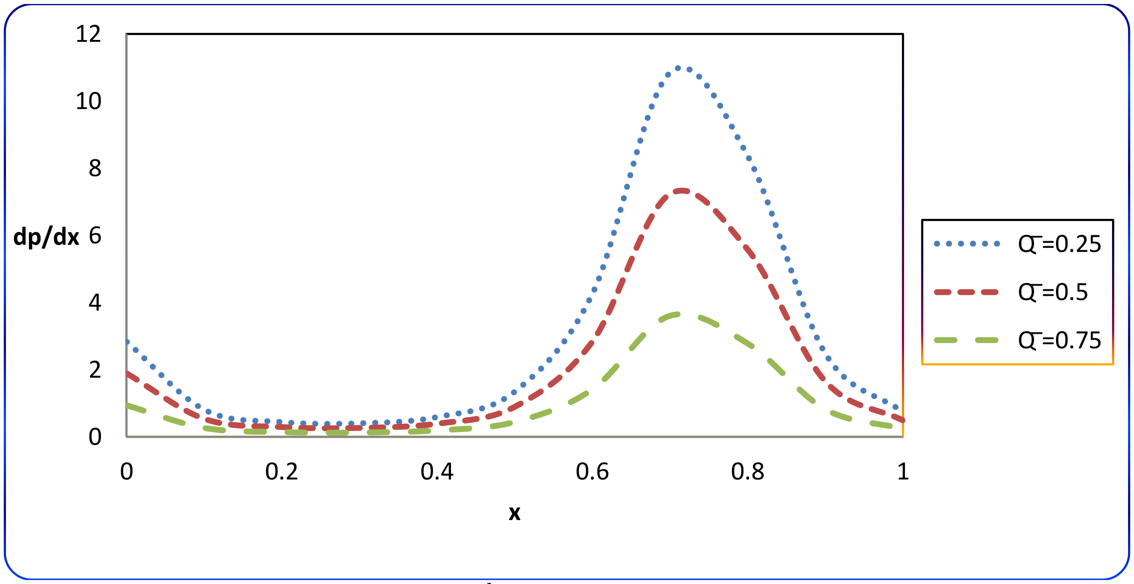

Figure (16): Distribution of axial pressure gradient $\frac{dp}{dx}$versus x for ϕ = 0.7, t = 0, λ = 10, k = 0.0005, a_0= 0.01, S = 0.1, D = 100.

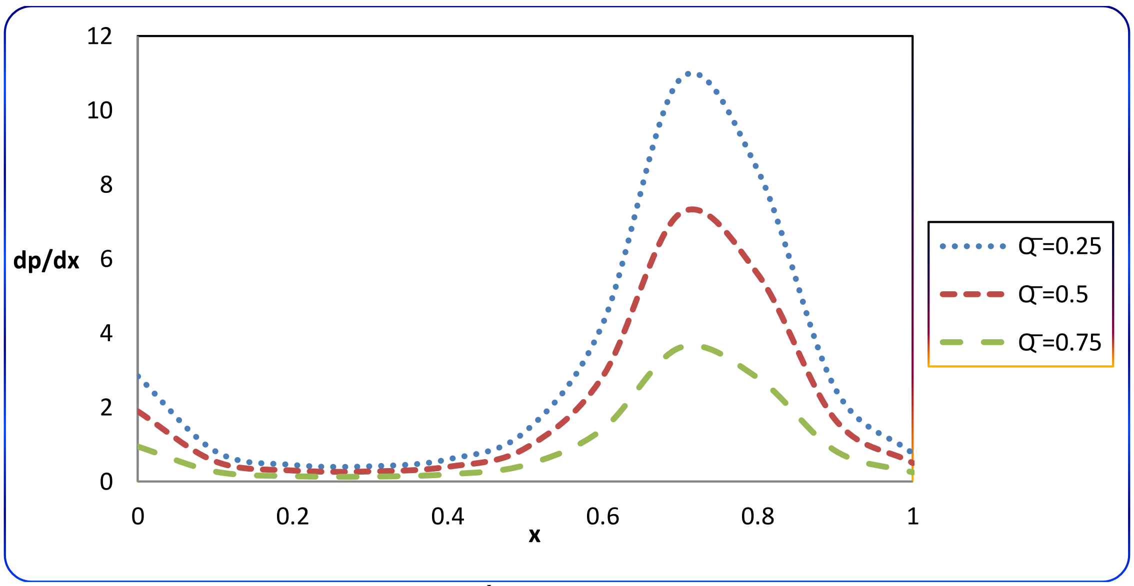

Figure (17): Distribution of axial pressure gradient $\frac{dp}{dx}$versus x for ϕ = 0.7, t = 0, λ = 10, k = 0.0005, a_0= 0.01, S = 0.1, D = 1000.

Conclusions

In this article, we have presented a mathematical model that describes a Peristaltic couple stress flow of blood through coaxial channel with effect of porous medium: blood flow study. The governing equations of the problem were solved analytically under assumptions of long wavelength approximation. A set of graphs were plotted in order to analyze the effects of various physical parameters on these solutions. The salient observations of the present study are listed below.

1. The axial velocity in increases with increase in couple stress parameter (S) and Porous parameter (D)
2. The axial pressure gradient increases with increase in couple stress parameter (S).
3. The magnitude of the pressure gradient increases with increase in couple stress parameter increases (See figures 8-14).

4. The axial pressure gradient is decreases with increase in averaged flow rate ($\bar{Q}$).
5. The magnitude of the pressure gradient decreases with increase in averaged flow rate ($\bar{Q}$). (See fig 15-17).

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