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RADIATION EFFECTS ON THE PERISTALTIC FLOW OF A JEFFREY FLUID THROUGH A POROUS MEDIUM IN A CHANNEL

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ABSTRACT

In this paper, the flow of a Jeffrey fluid through a porous medium in a channel with peristalsis has received minute attention. Hence, an attempt is made to study the peristaltic flow of a Jeffrey fluid through a porous medium in a symmetric channel under the assumptions of long wavelength. The expressions for the velocity and pressure gradient are obtained analytically. The effects of various pertinent parameters on the pumping characteristics and temperature field are studied in detail with the aid of graphs.

Keywords: *Jeffrey fluid; Porous medium; Peristaltic flow; Radiation.*

1. INTRODUCTION

The study of the mechanism of peristalsis in both mechanical and physiological situations has recently become the object of scientific research, since the first investigation of Latham [7]. Several theoretical and experimental attempts have been made to understand peristaltic action in different situations. A review of much of the early literature is presented in an article by Jaffrin and Shapiro [5]. A summary of most of the experimental and theoretical investigations reported with details of the geometry, fluid Reynolds number, wavelength parameter wave amplitude parameter and wave shape has been given by Srivastava and Srivastava [14].

Flow through a porous medium has been of considerable interest in recent years particularly among geophysical fluid dynamicists. Examples of natural porous media are beach sand, stand stone, limestone, rye bread, wood, the human lung, bile duct, gall bladder with stones and in small blood vessels. Flow through a porous medium has been studied by a number of workers employing Darcy's law Scheidegger [13]. Some studies about this point have been made by Varshney [17] and Raptis and Perdikis [11]. The first study of peristaltic flow through a porous medium is presented by Elsehawey *et al.* [2]. Elsehawey *et al.* [3] studied peristaltic motion of a generalized Newtonian fluid through a porous medium. Non-linear peristaltic transport through a porous medium in an inclined planar channel has studied by Mekheimer [9] taking the gravity effect on pumping characteristics. Subba Reddy and Nadhamuni Reddy [15] have studied the peristaltic flow of a non-Newtonian fluid through a porous medium in a tube with variable viscosity using Adomian decomposition method.

Heat transfer analysis can be used to obtain information about the properties of tissues. For example, the flow of blood can be evaluated using a dilution technique. In this procedure, heat is either injected or generated locally and the thermal clearance is monitored. With knowledge of initial thermal conditions and the thermal clearance rate, it is possible to estimate blood flow rates. A review of thermal dilution techniques can be found elsewhere Bowman [1]. Understanding of bio-heat transport is important in the beneficial applications of heat and cold for medical treatment. Recent advances in the application of heat (hyperthermia), radiation (laser therapy), and coldness (cryosurgery), as means to destroy undesirable tissues, such as cancer, have stimulated much interest in the study of thermal modeling in tissue. In the case of hyperthermia, it is noted that tissue can be destroyed when heated to 42 – 45^o C (Field and Franconi [4]). Vajravelu *et al.* [16] have studied the peristaltic flow of a Newtonian fluid in a vertical porous annulus

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with heat transfer. The effect of heat transfer on the peristaltic flow of a Newtonian fluid in a vertical annulus under the effect of magnetic field was analyzed by Mekheimer and Elmaboud [10]. The influence of wall properties in the MHD peristaltic transport of a Newtonian fluid through a porous medium with heat transfer was studied by Kothandapani and Srinivas [6]. Influence of magnetic field and heat transfer on peristaltic flow of Jeffrey fluid through a porous medium in an asymmetric channel was studied by Vasudev *et al.* [18]. Mahmoud *et al.* [8] have investigated the effect of a heat transfer on the peristaltic transport of a Jeffrey fluid through a porous medium with magnetic field. Ravindranath Reddy *et al.* [12] have investigated influence of heat transfer on peristaltic flow of Jeffrey fluid through a porous medium in an inclined asymmetric channel.

However, the flow of a Jeffrey fluid through a porous medium in a channel with peristalsis has received minute attention. Hence, an attempt is made to study the peristaltic flow of a Jeffrey fluid through a porous medium in a symmetric channel under the assumptions of long wavelength. The expressions for the velocity and pressure gradient are obtained analytically. The effects of various pertinent parameters on the pumping characteristics and temperature field are studied in detail with the support of graphs.

2. MATHEMATICAL FORMULATION

We Consider an incompressible Jeffrey fluid confined in a two-dimensional infinite symmetric channel through porous medium. We employ a rectangular coordinate system with parallel and normal to the channel walls. The symmetry in the channel is induced by assuming the peristaltic wave train on the walls to have different amplitudes and phases due to the variation of channel.

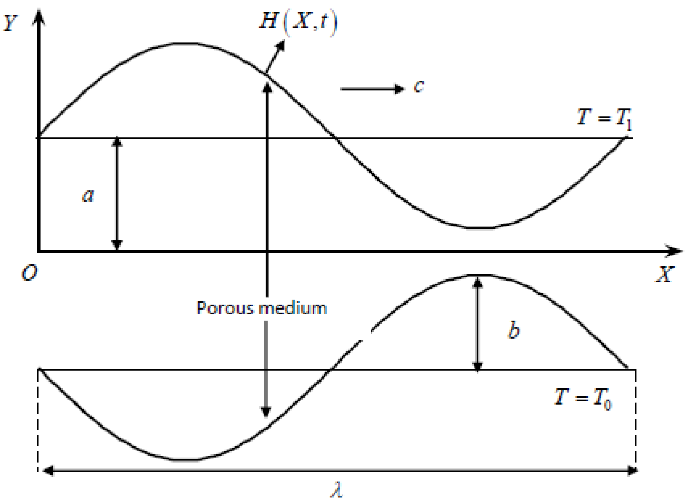

Fig. 1: The Physical Model

The shape of the symmetric channel wall is:

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

Here a and b are the amplitudes of the waves, λ is the wavelength.

The constitutive equations for an incompressible Jeffrey fluid are:

$$I_0 = -pI + S \tag{2.2}$$

$$S = \frac{\mu}{1+\lambda_1}(\dot{\gamma} + \lambda_2 \ddot{\gamma}) \tag{2.3}$$

where I and S Cauchy stress tensor and extra stress tensor, respectively, p is the pressure, I is the identity tensor, μ is dynamic viscosity, λ_1 is the ratio of relaxation to retardation times λ_2 is the retardation time, $\dot{\gamma}$ is the shear rate and dots over the quantities indicate differentiation with respect to time.

In laboratory frame, the equations governing two-dimensional motion of an incompressible MHD Jeffrey fluid through a porous medium:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{2.4}$$

$$\rho\left(\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y}\right) = -\frac{\partial p}{\partial X} + \frac{\partial}{\partial X}(S_{XX}) + \frac{\partial}{\partial Y}(S_{XY}) - \sigma H_0^2 U - \frac{\mu}{k_0}U \tag{2.5}$$

$$\rho\left(\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y}\right) = -\frac{\partial P}{\partial Y} + \frac{\partial}{\partial X}(S_{XY}) + \frac{\partial}{\partial Y}(S_{YY}) - \frac{\mu}{k_0}V \tag{2.6}$$

$$\zeta\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \frac{k}{\rho}\nabla^2 T + \nu\left(2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right) + 4\frac{\alpha^2}{\rho c_p}(T - T_0) \tag{2.7}$$

where U, V the velocity components in the laboratory frame are $(X,\ Y)$ ρ is the density, p is the pressure and σ is the electrical conductivity of the fluid, ζ is a specific heat at constant volume, T is the temperature of the fluid, k is the thermal conductivity of the fluid, μ is the kinematic viscosity, k_0 is the permeability of the porous medium, α is the coefficient of linear thermal expansion of the fluid and

$$S_{XX} = \frac{2\mu}{1+\lambda_1}\left(1 + \lambda_2\left[U\frac{\partial}{\partial X} + V\frac{\partial}{\partial Y}\right]\right)\frac{\partial U}{\partial X} \tag{2.8}$$

$$S_{YY} = \frac{2\mu}{1+\lambda_1}\left(1 + \lambda_2\left[U\frac{\partial}{\partial X} + V\frac{\partial}{\partial Y}\right]\right)\frac{\partial V}{\partial Y} \tag{2.9}$$

$$S_{XY} = \frac{\mu}{1+\lambda_1}\left(1 + \lambda_2\left[U\frac{\partial}{\partial X} + V\frac{\partial}{\partial Y}\right]\right)\left(\frac{\partial U}{\partial Y} - \frac{\partial V}{\partial X}\right) \tag{2.10}$$

We shall carry out this investigation in a coordinate system moving with the wave speed, in which the boundary shape is stationary. The coordinates and velocities in the laboratory frame (X, Y), and the wave frame (x, y), are related by:

$$x = X - ct, y = Y, u = U - c, v = V, p(x) = P(x,t),$$

where u, v the velocity components in the laboratory frame are (X, Y), p is the pressure and P fixed frame references.

Introducing the non-dimensional parameters and variables

$$\bar{x} = \frac{x}{\lambda}, \bar{y} = \frac{y}{a_1}, \bar{u} = \frac{u}{c}, \bar{v} = \frac{v}{c\delta}, \bar{S} = \frac{a_1}{\mu c}S, \bar{p} = \frac{pa_1^2}{\mu c\lambda}, \bar{t} = \frac{ct}{\lambda}, h = \frac{H}{a},$$

$$\delta = \frac{a}{\lambda}, Re = \frac{\rho ac}{\mu},\ \phi = \frac{b}{a}, \theta = \frac{T-T_0}{T_1-T_0}, Pr = \frac{\rho v\zeta}{k}, Ec = \frac{c^2}{\zeta(T_1-T_0)}$$

Using non-dimensional variables and parameters in Eqs. (2.4) - (2.6) we get

$$\delta\frac{\partial u}{\partial x} + \delta\frac{\partial v}{\partial y} = 0 \tag{2.11}$$

$$Re\,\delta\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \delta\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} - \frac{1}{Da}u - \frac{1}{k}u \tag{2.12}$$

$$Re\delta^3\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \delta^2\frac{\partial S_{xy}}{\partial x} + \frac{\partial S_{yy}}{\partial y} - \frac{\delta^2}{k}v \tag{2.13}$$

$$Re\delta\left[u\frac{\partial\theta}{\partial x} + v\frac{\partial\theta}{\partial y}\right] = \frac{1}{Pr}\left(\delta^2\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2}\right) + Ec\begin{bmatrix} 4\delta^2\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y}\right)^2 \\ +\delta^4\left(\frac{\partial v}{\partial x}\right)^2 + 2\delta^2\frac{\partial u}{\partial y}\frac{\partial v}{\partial x}\end{bmatrix} + R^2\theta \tag{2.14}$$

where $R^2 = \frac{4\alpha^2 d^2}{k}$ is the radiation parameter, $Da = \frac{k}{a^2}$ is the Darcy number, $Pr = \frac{\rho v\zeta}{k}$ is the Prandtl number, $Ec = \frac{c^2}{\zeta(T_1-T_0)}$ is the Eckert number,

$$S_{xx} = \frac{2\delta}{1+\lambda_1}\left(1 + \frac{\delta c\lambda_2}{d_1}\left[u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y}\right]\right)\frac{\partial U}{\partial x}$$

$$S_{xy} = \frac{1}{1+\lambda_1}\left(1 + \frac{\delta c\lambda_2}{d_1}\left[\frac{\partial u}{\partial y}\frac{\partial}{\partial x} - \frac{\partial}{\partial y}\frac{\partial u}{\partial x}\right]\right)\left(\frac{\partial u}{\partial y} + \delta^2\frac{\partial v}{\partial x}\right)$$

$$S_{yy} = \frac{2\delta}{1+\lambda_1}\left(1 + \frac{\delta c\lambda_1}{d_1}\left[\frac{\partial u}{\partial y}\frac{\partial}{\partial x} - \frac{\partial u}{\partial x}\frac{\partial}{\partial y}\right]\right)\frac{\partial^2 u}{\partial xy}$$

Under lubrication approach (i.e., $\delta \ll 1$and $Re \to 0$), the Equations (2.12) - (2.14) become:

$$0 = -\frac{\partial p}{\partial x} + \frac{1}{1+\lambda_1}\frac{\partial^2 u}{\partial y^2} - \frac{1}{Da}(u+1) \tag{2.15}$$

$$0 = -\frac{\partial p}{\partial y} \tag{2.16}$$

$$\frac{d^2\theta}{dy^2} + R^2 Pr\theta = -PrEc\left(\frac{\partial u}{\partial y}\right)^2 \tag{2.17}$$

The corresponding boundary conditions are

$$u = -1 \quad \text{at} \quad y = h \tag{2.18}$$

$$\frac{\partial u}{\partial y} = 0 \quad \text{at} \quad y = 0 \tag{2.19}$$

$$\frac{\partial\theta}{\partial y} = 0 \quad \text{at} \quad y = 0 \tag{2.20}$$

$$\theta = 1 \quad \text{at} \quad y = h \tag{2.21}$$

From Eq. (2.15) and (2.16), we write Eq. (2.15) as

$$0 = -\frac{dp}{dx} + \frac{1}{1+\lambda_1}\frac{\partial^2 u}{\partial y^2} - \frac{1}{Da}(u+1) \tag{2.22}$$

The volume flux q through each cross section in the wave frame is given by

$$q = \int_0^h u\,dy \tag{2.23}$$

The instantaneous volume flow rate $Q(X,t)$ in the laboratory frame between the centre line and the wall is

$$Q(X,t) = \int_0^H UdY = \int_0^h (u+1)dy = q + h \tag{2.24}$$

The average volume flow rate $\bar{Q}$ over one wave period $\left(T = \frac{\lambda}{c}\right)$ of the peristaltic wave is defined as

$$\bar{Q} = \frac{1}{T}\int_0^T Q(X,t)\,dt = q + 1 \tag{2.25}$$

3. SOLUTION

Solving Eq. (2.22) subject to the boundary conditions (2.18) and (2.19), we get

$$u = \left(\frac{1+\lambda_1}{N^2}\right)\frac{\partial p}{\partial x}\left[\frac{coshNy}{coshNh} - 1\right] - 1 \tag{3.1}$$

where $N = \sqrt{\frac{1+\lambda_1}{Da}}$.

Using the Eq. (3.1) and solving the Eq. (2.17) subject to the boundary conditions (2.20) and (2.21), we get

$$\theta = \left[1 + PrE\left(\frac{1+\lambda}{N}\right)^2\left(\frac{\partial p}{\partial x}\right)^2\frac{1}{2cosh^2Nh}\left[\frac{cosh2Nh}{4N^2+\alpha_1^2} + \frac{1}{\alpha_1^2}\right]\frac{cos\alpha_1 y}{cos\alpha_1 h}\right]$$
$$-PrE\left(\frac{1+\lambda}{N}\right)^2\left(\frac{1}{4N^2+\alpha_1^2}\right)\left(\frac{\partial p}{\partial x}\right)^2\frac{cosh2Ny}{2cosh^2Nh} + PrE\left(\frac{1+\lambda}{N}\right)^2\left(\frac{\partial p}{\partial x}\right)^2\frac{1}{\alpha_1^2 2cosh^2Nh} \tag{3.2}$$

where $\alpha_1 = iR\sqrt{Pr}$.

The volume flux q through each cross section in the wave frame is given by

$$q = \int_0^h u\,dy = \left(\frac{1+\lambda}{N^3}\right)\frac{\partial p}{\partial x}[tanhNh - Nh] - h \tag{3.3}$$

From Eq. (3.3), we have

$$\frac{dp}{dx} = \frac{(q+h)N^3}{(1+\lambda_1)[tanhNh - Nh]} \tag{3.4}$$

The heat transfer coefficient at the upper wall is defined by

$$z = \frac{\partial\theta}{\partial y}.\frac{\partial h}{\partial x}\bigg|_{y=h}$$
$$= -\alpha_1 tan\alpha_1 h - p_r E\frac{(q+h)^2N^4}{(tanhNh-Nh)^2 2cosh^2Nh}\left[\alpha_1 tan\alpha_1 h\left(\frac{cosh2Nh}{4N^2+\alpha_1^2} + \frac{1}{\alpha_1^2}\right) + \frac{4sinh2Nh}{4N^2+\alpha_1^2}\right] \tag{3.5}$$

4. DISCUSSIONS OF THE RESULT

Fig. 2 depicts the variation of axial pressure gradient $\frac{dp}{dx}$ with $\lambda_1$for $\phi = 0.5$ and $Da = 0.1$. It is found that, the axial pressure gradient decreases on increasing the material parameter λ_1.

Fig. 3 shows the variation of axial pressure gradient $\frac{dp}{dx}$ with Da for $\phi = 0.5$ and $\lambda_1 = 0.3$. It is noticed that, the axial pressure gradient decreases with increasing Darcy number Da.

Fig. 4 illustrates the variation of axial pressure gradient $\frac{dp}{dx}$ with $\phi$for $\lambda_1 = 0.3$ and $Da = 0.1$. It is noticed that, the axial pressure gradient increases with an increase in amplitude ratio ϕ.

Fig. 5 depicts the variation of pressure rise Δp with $\bar{Q}$ for different values of λ_1 with $\phi = 0.5$ and $Da = 0.1$. It is found that, the time-averaged flow rate $\bar{Q}$ decreases in both the pumping $(\Delta p > 0)$ and the free-pumping$(\Delta p = 0)$ regions with increasing λ_1, while it increases in the co-pumping $(\Delta p < 0)$ region with increasing λ_1.

Fig. 6 illustrates the variation of pressure rise Δp with $\bar{Q}$ for different values of Da with $\phi = 0.5$ and $\lambda_1 = 0.3$. It is observed that, the time-averaged flow rate $\bar{Q}$ decreases in the pumping region with increasing Da, while it increases in both the free-pumping and the co-pumping regions with increasing Da.

Fig. 7 shows the variation of pressure rise Δp with $\bar{Q}$ for different values of ϕ with $\lambda_1 = 0.3$ and $Da = 0.1$. It is noted that, the time-averaged flow rate $\bar{Q}$ increases in both the pumping and the free-pumping regions with increasing ϕ, while it decreases in the co-pumping region with increasing ϕ for chosen $\Delta p(< 0)$.

Fig. 8 depicts the temperature profiles for different values of λ_1 with $\phi = 0.5, Da = 0.1,\ \bar{Q} = -1, Pr = 0.7, Ec = 0.1$, $R = 1$ and $x = 0.1$. It is found that, the temperature θ decreases with increasing material parameter λ_1.

Fig. 9 shows the temperature profiles for different values of Da with $\phi = 0.5, \lambda_1 = 0.3,\ \bar{Q} = -1,\ \ Pr = 0.7, Ec = 0.1,$ $R = 1$ and $x = 0.1$. It is found that, the temperature θ increases with increasing Darcy number Da.

Fig. 10 shows the temperature profiles for different values of ϕ with $\lambda_1 = 0.3, Da = 0.1,\ \bar{Q} = -1,\ Pr = 0.7,$ $Ec = 0.1,\ R = 1$ and $x = 0.1$. It is found that, the temperature θ decreases with increasing amplitude ratio ϕ.

Fig. 11 depicts the temperature profiles for different values of Pr with $\phi = 0.5,\ Da = 0.1,\ \bar{Q} = -1,\ \lambda_1 = 0.3,$ $Ec = 0.1,\ R = 1$ and $x = 0.1$. It is found that, the temperature θ increases with increasing Prandtl number Pr.

Fig. 12 illustrates the temperature profiles for different values of Ec with $\phi = 0.5, Da = 0.1,\ \bar{Q} = -1, \lambda_1 = 0.3,$ $Pr = 0.7,\ R = 1$ and $x = 0.1$. It is found that, the temperature θ increases with increasing Eckert number Ec.

Fig. 13 shows the temperature profiles for different values of R with $\phi = 0.5, Da = 0.1,\ \bar{Q} = -1, \lambda_1 = 0.3,\ Ec = 0.1,$ $Pr = 0.7$ and $x = 0.1$. It is found that, the temperature θ decreases with increasing α_1.

Table-1shows the heat transfer coefficient Z at the upper wall $y = h$ for $x = 0.1$ and $\bar{Q} = -1$. It is observed that the heat transfer coefficient Z increases with increasing λ_1, Pr, ϕ and R, while it decreases with increasing Da and Ec.

5. CONCLUSIONS

In this paper, we studied the radiation effects on the peristaltic flow of a Jeffrey fluid through a porous medium in a channel under the assumptions of low Reynolds number and long wavelength approximations. A closed form solutions are obtained for the velocity, temperature and the pressure gradient. It is found that, the axial pressure gradient and the time averaged volume flow rate decreases with increasing λ_1 and Da, while they increases with increasing ϕ. The temperature increases with increasing the parameters Da, Pr and Ec, while it decreases with increasing the parameters λ_1, ϕ and R.

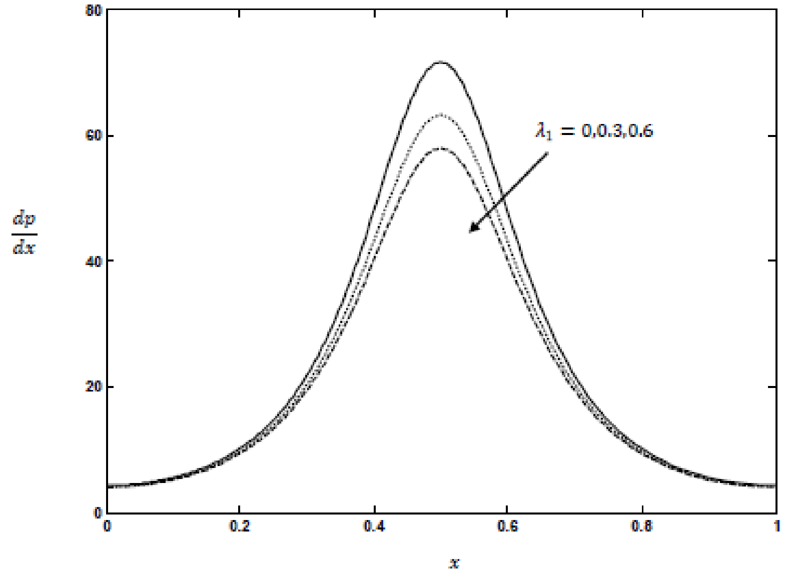

Fig. 2: The variation of axial pressure gradient $\frac{dp}{dx}$ with $\lambda_1$for $\phi = 0.5$ and $Da = 0.1$.

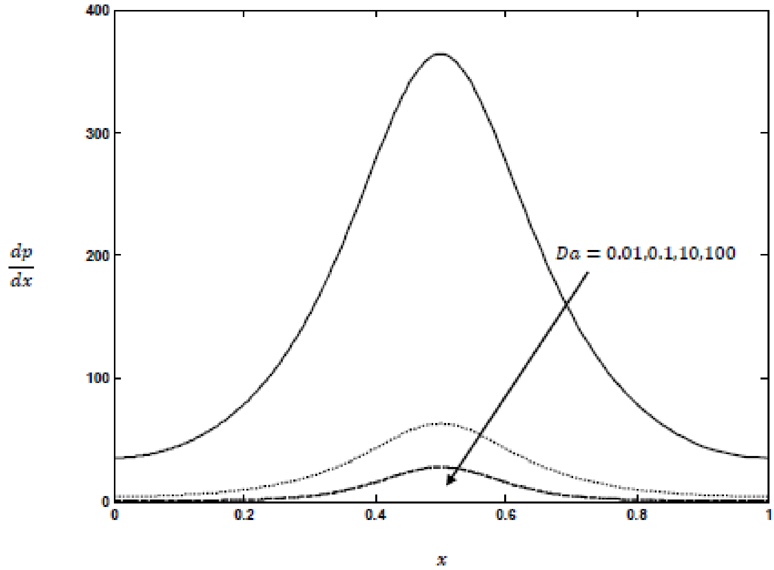

Fig. 3: The variation of axial pressure gradient $\frac{dp}{dx}$ with Da for $\phi = 0.5$ and $\lambda_1 = 0.3$.

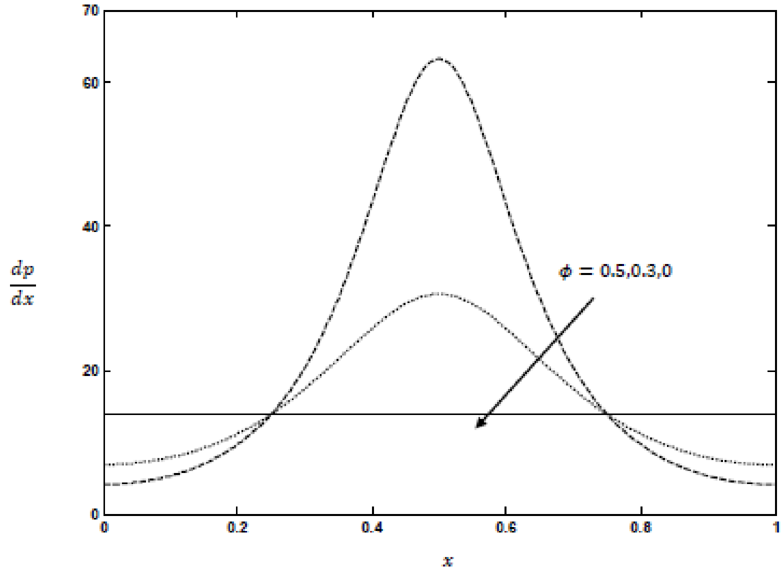

Fig. 4: The variation of axial pressure gradient $\frac{dp}{dx}$ with $\phi$for $\lambda_1 = 0.3$ and $Da = 0.1$.

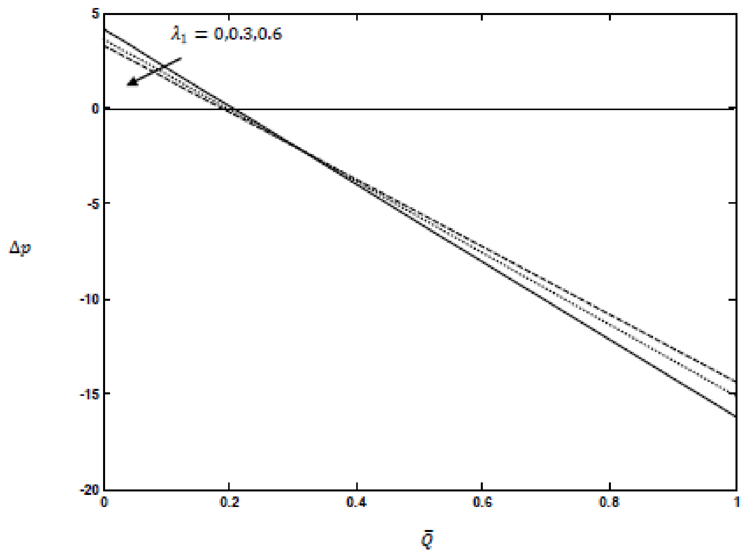

Fig. 5: The variation of pressure rise Δp with $\bar{Q}$ for different values ofλ_1 with $\phi = 0.5$ and $Da = 0.1$.

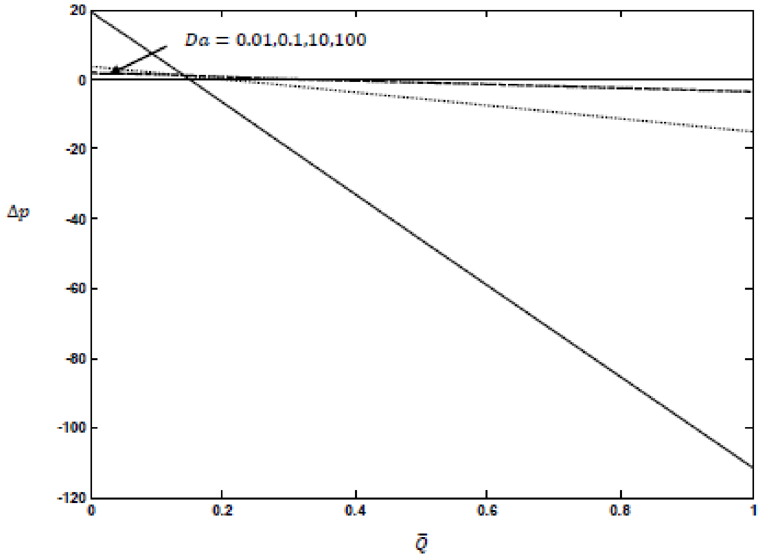

Fig. 6: The variation of pressure rise Δp with $\bar{Q}$ for different values of Da with $\phi = 0.5$ and $\lambda_1 = 0.3$.

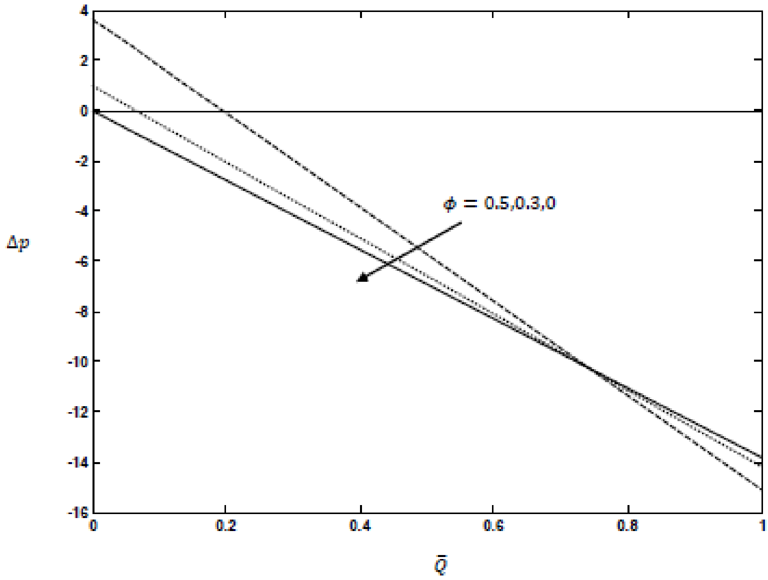

Fig. 7: The variation of pressure rise Δp with $\bar{Q}$ for different values of ϕ with $\lambda_1 = 0.3$ and $Da = 0.1$.

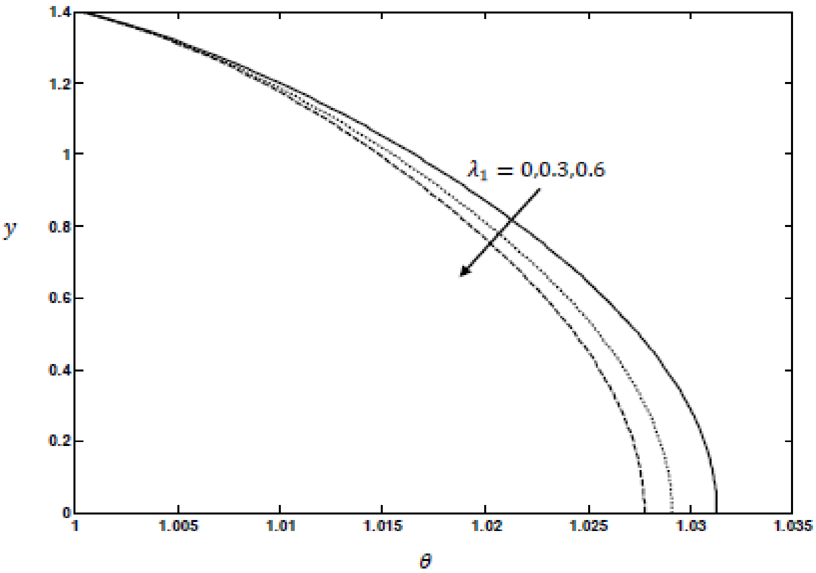

Fig. 8: Temperature profiles for different values of λ_1 with $\phi = 0.5, Da = 0.1, \bar{Q} = -1,\ Pr = 0.7,\ Ec = 0.1,\ R = 1$ and $x = 0.1$.

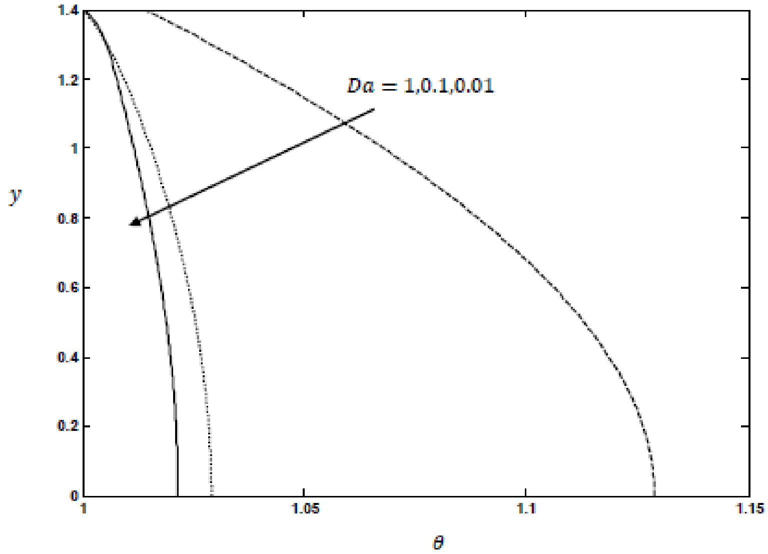

Fig. 9: Temperature profiles for different values of Da with $\phi = 0.5, \lambda_1 = 0.3, \bar{Q} = -1,\ Pr = 0.7, Ec = 0.1,\ R = 1$ and $x = 0.1$.

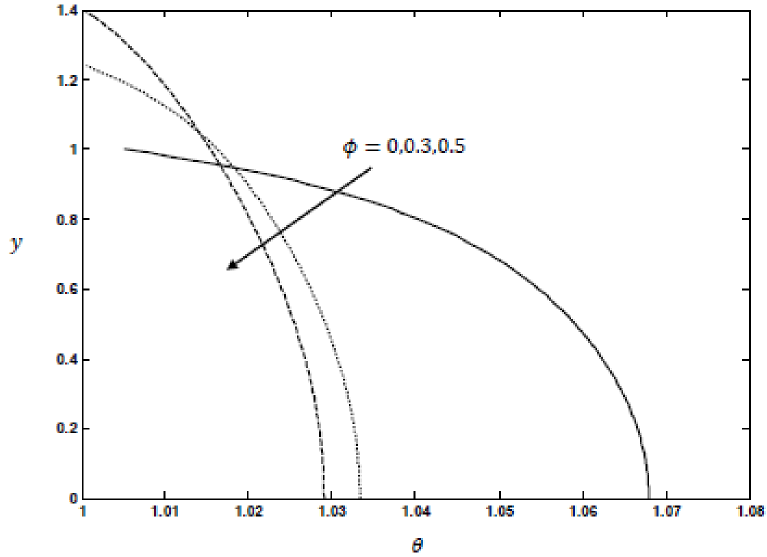

Fig. 10: Temperature profiles for different values of ϕ with $\lambda_1 = 0.3, Da = 0.1, \bar{Q} = -1,\ Pr = 0.7, Ec = 0.1,\ R = 1$ and $x = 0.1$.

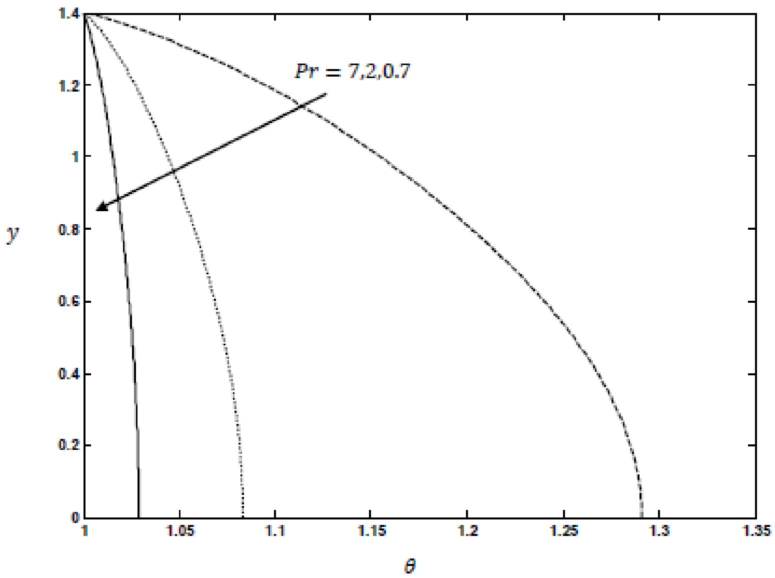

Fig. 11: Temperature profiles for different values of Pr with $\phi = 0.5,\ Da = 0.1, \bar{Q} = -1,\ \lambda_1 = 0.3, Ec = 0.1,\ R = 1$ and $x = 0.1$.

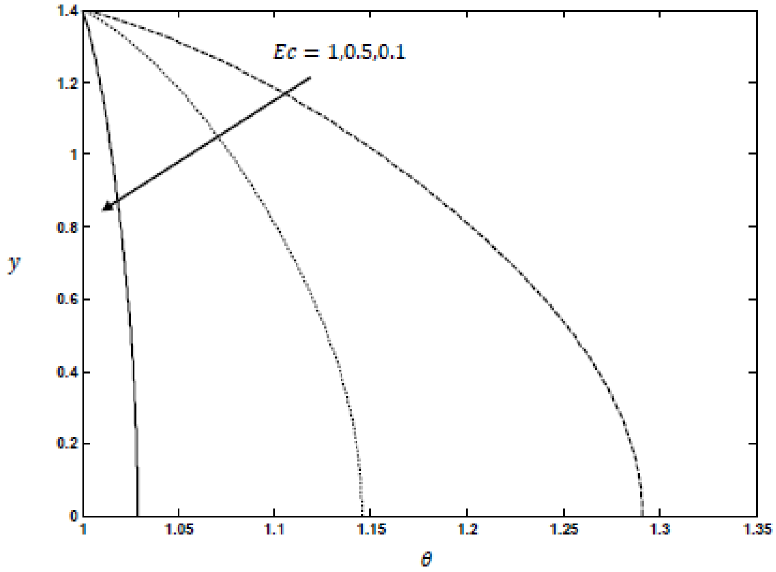

Fig. 12: Temperature profiles for different values of Ec with $\phi = 0.5, Da = 0.1, \bar{Q} = -1,\ \lambda_1 = 0.3,\ Pr = 0.7,\ R = 1$ and $x = 0.1$.

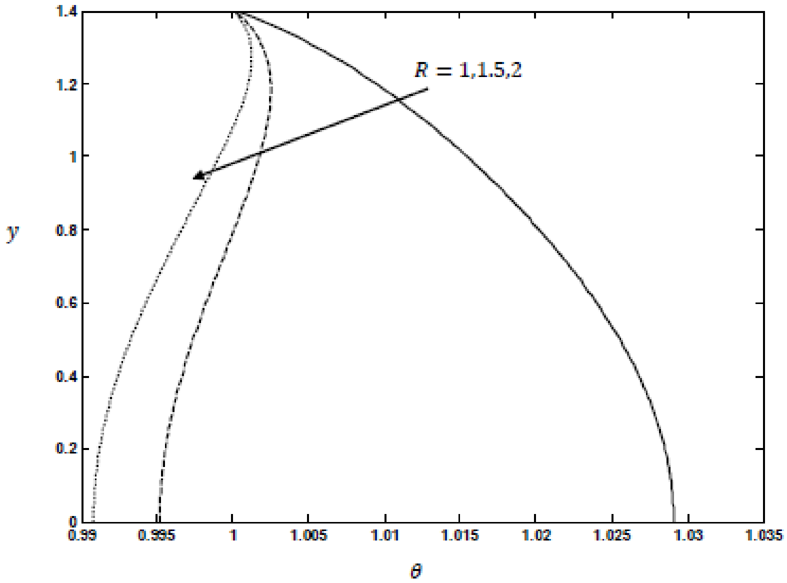

Fig. 13: Temperature profiles for different values of R with $\phi = 0.5, Da = 0.1, \bar{Q} = -1, \lambda_1 = 0.3,\ Ec = 0.1,\ Pr = 0.7$ and $x = 0.1$.

Table-1: The heat transfer coefficient Z at the upper wall $y = h$ for $x = 0.1$and $\bar{Q} = -1$.

λ_1	Da	Pr	Ec	ϕ	R	$\boldsymbol{Z}$
0.3	0.1	0.7	0.1	0.5	1	0.6358
0.5	0.1	0.7	0.1	0.5	1	0.6369
0.3	1	0.7	0.1	0.5	1	0.5293
0.3	0.1	1	0.1	0.5	1	0.8214
0.3	0.1	0.7	0.5	0.5	1	0.5214
0.3	0.1	0.7	0.1	0.6	1	0.6577
0.3	0.1	0.7	0.1	0.5	2	1.6086

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