Influence of Varying Temperature and Concentration on Magnetohydrodynamics Peristaltic Transport for Jeffrey Fluid with a Nanoparticles Phenomenon through a Rectangular Porous Duct

Dheia G. Salih Al-Khafajy

Department of Mathematics, College of Science, University of Al-Qadisiyah, Diwaniya, Iraq.
E-mail: dheia.salih@qu.edu.iq
ORCID ID: https://orcid.org/0000-0001-7848-8243

Received 18/9/2019, Accepted 27/4/2020, Published Online First 11/1/2021

Abstract:
A mathematical model constructed to study the combined effects of the concentration and the thermodiffusion on the nanoparticles of a Jeffrey fluid with a magnetic field effect the process of containing waves in a three-dimensional rectangular porous medium canal. Using the HPM to solve the nonlinear and coupled partial differential equations. Numerical results were obtained for temperature distribution, nanoparticles concentration, velocity, pressure rise, pressure gradient, friction force and stream function. Through the graphs, it was found that the velocity of fluid rises with the increase of a mean rate of volume flow and a magnetic parameter, while the velocity goes down with the increasing a Darcy number and lateral walls. Also, the velocity behaves strangely under the influence of the Brownian motion parameter and local nanoparticle Grashof number effect.

Key words: Homotopy perturbation method (HPM), Jeffrey fluid, Magnetohydrodynamics (MHD), Nanoparticles, Peristaltic flow.

Introduction:
The Peristaltic flow is a mechanics for pumped fluids into tubes when the wave-out of the contraction zone or expansion spreads along an expandable and shrinking tube containing fluid. The peristalses have very important applications in many industries and physiological systems. They include the transfer of urine and food through the urinary tract and digestive system respectively, blood circulation through blood movement, the menstrual movement for the egg in the fallopian tube. The major industrial application for this phenomenon is the design of rotary pumps used in pumping fluids without contamination due to contact with pumping munitions (1). Furthermore, the peristaltic movement study has acquired many applications, for example, ship movements, mud transport, sensitive or corrosive liquids, healthy fluids, and harmful fluids in the nuclear industry. In (2) Kothandapani and Srinivas analyzed the effect of a magnetic field in the peristaltic transport for a Jeffrey fluid in an asymmetric canal and discussed the problem in wave frame moved at a stable axial velocity under the approximations of low Reynolds number and long wavelength. The influence of wall properties and heat transfer on the peristaltic transport of a Jeffrey fluid through a porous medium in the magnetic field has been investigated by Al-Khafajy and Abdulhadi in (3). The effect of lateral walls on peristaltic flow in a rectangular duct has been investigated by (4). They noted that the uterine cross-section of the uterus may be preferably approximated by a tube than a rectangular section of a two-dimensional canal. Nadeem et al. (5) analyzed a "mathematical model for the peristaltic flow of Jeffrey fluid with nanoparticles phenomenon through a rectangular duct".

Nanotechnology has basic and important applications in the modern industry in nano-size exhibit unmatched physical and chemical properties. Gasoline, oil, ethylene glycol and water are common examples of essential fluids used for liquid nanoparticles. Nano-fluids make a huge contribution to heat transfer such as fuel cells, microelectronics, hybrid engines, refrigerators, nuclear reactor radiators, space technology and many other cases. Suitable to the spacious thermal properties, nanofluid has attracted the consideration.
of researchers to the fabrication of heat transfer fluids in hotness exchangers, in plants and in auto cooling chillers. In literature, many researchers and industrialists are studied nanofluid and their applications, (6-11). Nadeem and Maraj (6) described the mathematical analysis for peristaltic flow of a nanofluid in a curved channel with compliant walls. Hayat et al. (7) investigated the flow of MHD from a saturated porous space of Williamson fluid. The effect of thermal radiation on unstable free heat flow (MHD) for the rotation of Jeffrey nanofluid that passes through the porous medium was studied in (8). In (9) Latha and Kumar described the mathematical analysis for peristaltic flow of a non-Newtonian (Jeffrey) incompressible fluid with the concentration of nanoparticles in a cross-section of a normal rectangular three-dimensional channel (4).

The flow is generated by the propagation of sinusoidal waves along the axial direction of the transverse channel, that is 

\[ V = (U,0,W) \]

velocity of the nanofluid problem has the following form:

\[
\frac{\partial U}{\partial x} + \frac{\partial W}{\partial z} = 0 \quad \text{... (2)}
\]

\[
\rho_f \left( \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + W \frac{\partial U}{\partial z} \right) = -\frac{\partial p}{\partial x} + \frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} + \frac{\partial S_{xz}}{\partial z} + \rho_f g \alpha_f (\bar{T} - T_0) + \rho_f g \alpha_f (\bar{C} - C_0) \frac{\mu}{k} U - a B_0^2 U \quad \text{... (3)}
\]

\[
0 = -\frac{\partial p}{\partial y} + \frac{\partial S_{yy}}{\partial x} + \frac{\partial S_{xy}}{\partial y} + \frac{\partial S_{yz}}{\partial z} \quad \text{... (4)}
\]

Figure 1. Schematic diagram for peristaltic flow in a rectangular duct

The peristaltic waves on the walls as represented (4):

\[ Z = \mp H(X,t) = \mp a \mp b \cos \left( \frac{2\pi}{L} (X - ct) \right) \quad \text{... (1)} \]

whereas \( a \) and \( b \) are wave amplitudes, \( t \) is time and \( X \) is the wave propagation direction.

The walls are still parallel to XZ-plane that is unobstructed and not subject to any wave movement. Assuming that the side speed is zero as there is no change in the lateral direction of the transverse channel, that is 

\[ V = (U,0,W) \]

The governing equations in three-dimensional for flow
\[ \rho f \left( \frac{\partial u}{\partial t} + U \frac{\partial u}{\partial x} + W \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial x} + \frac{\partial s_{XX}}{\partial x} + \frac{\partial s_{YY}}{\partial y} + \frac{\partial s_{ZZ}}{\partial z} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (5) \]

\[ \frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} + W \frac{\partial T}{\partial z} = \kappa \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \tau \left( \frac{\partial C_B}{\partial x} + \frac{\partial C_B}{\partial y} + \frac{\partial C_B}{\partial z} \right) \quad (6) \]

\[ \left( \frac{\partial^2 \beta}{\partial y^2} \right)^2 + \left( \frac{\partial^2 \beta}{\partial z^2} \right)^2 \right) \right) \quad (7) \]

where \( U \) is the component of the velocity in X-direction, \( W \) is the component of the velocity in Z-direction, \( T \) is the temperature, \( C \) is the concentration of the fluid, \( \kappa \) is the thermal diffusivity, \( \tau \) is the ratio of relaxation to retardation times, \( \gamma \) is the shear rate, \( \lambda \) is the retardation time and \( \mu \) is the viscosity of the fluid.

To analyze the flow of the \((x, y, z)\) current wave frame with the constant velocity \( c \) away from the \((X, Y, Z)\) fixed frame by the transference
\[ x = X - ct, \quad y = Y, \quad z = Z, \quad u = U - c, \quad w = W, \quad p(x, z) = P(X, Z, T), \quad T = \tilde{T}, \quad C = \tilde{C} \quad (9) \]

Introducing the following dimensionless transformations for facilitating the governing equations of the motion, as follows:
\[ \theta = \frac{\alpha}{\alpha} \frac{\beta}{\alpha} \frac{\gamma}{\alpha} \frac{\lambda}{\alpha} \]

where \( \alpha, \beta, \gamma, \lambda \) represent the Reynolds number, the Schmidt number, the Brownian motion parameter, the thermophoresis parameter, local nanoparticle Grashof number, local temperature Grashof number, Prandtl number, Darcy number and the magnetic parameter.

Compensate equations (10) into equations (1)-(9), and using the assumption of long-wavelength \( \delta \ll 1 \) and low Reynolds number, lead to simplifying the equations to the following form:
\[ \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0 \quad (11) \]

\[ \beta^2 \frac{\partial^2 u}{\partial y^2} + \frac{\partial u}{\partial z} \right) + \left( 1 + \alpha \right) \left( \frac{1}{\alpha} + \frac{M^2}{\alpha} \right) u = \frac{\partial u}{\partial x} \quad (12) \]

\[ \frac{\partial p}{\partial x} = 0, \quad \frac{\partial p}{\partial y} = 0 \quad (13) \]

\[ \beta^2 \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial \theta}{\partial z} + \frac{\partial \theta}{\partial z} \right) \right) + \left( 1 + \alpha \right) \left( \frac{1}{\alpha} + \frac{M^2}{\alpha} \right) \]

\[ \frac{\partial \theta}{\partial x} \quad (14) \]

\[ \frac{\partial^2 \Omega}{\partial y^2} + \frac{\partial^2 \Omega}{\partial z^2} \right) \right) - \frac{\partial \theta}{\partial z} \quad (15) \]

The boundaries of the channel will obtain the dimensionless form as follows:
\[ z = \mp h(x) = \mp \mp \mp \mp \cos 2nx \quad (16) \]

The corresponding boundary conditions are:
\[ u = -1 \text{ at } y = \mp 1, \quad u = -1 \text{ at } z = \mp h(x), \quad \ldots \quad (17) \]
here as $V = \frac{\partial^2}{\partial z^2}$. Choosing the following preliminary estimates

$$\bar{u}_0(y, z) = \frac{1}{\beta}(1 - y^2)(z^2 - h^2) - 1, \quad \ldots \quad (23)$$

$$\bar{\theta}_0 = \bar{\theta}_0 = \beta^2(z^2 - h^2) + \frac{h - z}{2h}. \quad \ldots \quad (24)$$

Let us define

$$v(x, y, z) = v_0 + r v_1 + r^2 v_2 + \ldots$$

$$\Theta(x, y, z) = \Theta_0 + r \Theta_1 + r^2 \Theta_2 + \ldots$$

$$\Phi(x, y, z) = \Phi_0 + r \Phi_1 + r^2 \Phi_2 + \ldots \quad \ldots \quad (25)$$

Replacing the equations (25) into equations (20)–(22) and then the similar forces are compared with $r$, the following problems are produced with corresponding boundary conditions, i.e.

For $r^0$:

$$\mathcal{C} - \mathcal{C}[u_0] - \mathcal{C}[\bar{u}_0] = 0, \quad \text{with} \quad v_0 = -1 \text{ at } y = \mp 1, \quad v_0 = -1 \text{ at } z = \mp h(x), \quad \mathcal{C}[\Theta_0] - \mathcal{C}[\bar{\theta}_0] = 0, \quad \text{with} \quad \Theta_0 = a_1 \text{ at } y = 1, \quad \Theta_0 = b_1 \text{ at } y = -1, \quad \Theta_0 = 0 \text{ at } z = h(x), \quad \Theta_0 = 1 \text{ at } z = -h(x), \quad \mathcal{C}[\Phi_0] - \mathcal{C}[\bar{\Phi}_0] = 0, \quad \text{with} \quad \Phi_0 = a_2 \text{ at } y = 1, \quad \Phi_0 = b_2 \text{ at } y = -1, \quad \Phi_0 = 0 \text{ at } z = h(x), \quad \Phi_0 = 1 \text{ at } z = -h(x).$$

For $r^1$:

$$\frac{\partial^2 v_1}{\partial x^2} + \frac{\partial^2 v_1}{\partial y^2} + \frac{\partial^2 v_1}{\partial z^2} - (1 + \lambda_1) \left( \left( \frac{1}{Da} + M^2 \right) v_1 + \frac{\partial \theta_1}{\partial z} \right) = 0,$$

$$\frac{\partial^2 \theta_1}{\partial x^2} + \frac{\partial^2 \theta_1}{\partial y^2} + \frac{\partial^2 \theta_1}{\partial z^2} - (1 + \lambda_1) \left( \left( \frac{1}{Da} + M^2 \right) v_1 - G_r \theta_1 - B_r \theta_1 \right) = 0,$$

$$\frac{\partial^2 \phi_1}{\partial x^2} + \frac{\partial^2 \phi_1}{\partial y^2} + \frac{\partial^2 \phi_1}{\partial z^2} - (1 + \lambda_1) \left( \left( \frac{1}{Da} + M^2 \right) v_1 - G_r \theta_1 - B_r \theta_1 \right) = 0,$$

$$\frac{\partial^2 \phi_1}{\partial x^2} + \frac{\partial^2 \phi_1}{\partial y^2} + \frac{\partial^2 \phi_1}{\partial z^2} - (1 + \lambda_1) \left( \left( \frac{1}{Da} + M^2 \right) v_1 - G_r \theta_1 - B_r \theta_1 \right) = 0.$$
The volumetric flow rate q is
\[ q = \int_0^{f(x)} \int_0^z u(x, y, z) \, dy \, dz \quad \ldots \quad (29) \]

The dimensionless friction force \( F \) at the wall per wavelength is given by:
\[ F = \int_0^1 h \left( -\frac{dp}{dx} \right) dx \quad \ldots \quad (33) \]

The average volume flow rate over one period \( T = \frac{1}{c} \) of the peristaltic wave is
\[ Q = \int_0^{f(x)} \int_0^1 (u(x, y, z) + 1) \, dy \, dz = q + h(x) \quad \ldots \quad (30) \]

From solving equation (30) after compensating the equation (29), the pressure gradient is obtained;

\[ \Omega = \beta^2 (z^2 - h^2) + \frac{h - z}{2h} = \frac{\beta^2 (N_t + N_b)}{N_b} (z^2 - h^2) - \frac{N_t}{76h^2 \beta^2 N_b} [76h^6 \beta^6 + (1 + 96h^4 \beta^4 + 256h^6 \beta^3)] (N_t + N_b) + \frac{N_t}{48h^2 \beta^2 N_b} [48h^3 \beta^3 z^2 + (N_t + N_b) (4h^2 \beta^2 z - 1)^4] \]
\[ \ldots \quad (28) \]

Numerical integration of the pressure gradient along one wave, gives us a pressure rise \( \Delta p \) formula, i.e.,
\[ \Delta p = \int_0^1 \left( \frac{dp}{dx} \right) dx \quad \ldots \quad (32) \]

The pressure rise \( \Delta p \) is defined as the speed of the fluid in the walls \( T = \frac{1}{c} \) as particular at the boundary conditions. Figure 2, illustrates the influence of the parameters \( \Phi \) and \( N_t \) on the velocity distribution function \( u \) vs. \( z \). It is found that the average flow rate \( u \) rising up with the increasing \( \Phi \), when \( |z| < 1 \), while \( u \) increases with increasing of \( N_t \), when \( z \in (-1,0.4) \cup (0.5,1) \), and \( u \) decreases with increasing \( N_t \), when \( -0.4 \leq z < 0.5 \). Figure 3, shows the behavior of \( u \) under the variation of \( Q \) and \( N_b \), one can depict here that \( u \) increases with the increasing of \( Q \), while \( u \) increases with the increasing of \( N_b \), when \( -1 < z < 0.5 \) and \( u \) decreases with increasing \( N_b \), when \( 0.5 < z < 1 \). Figure 4, contains the velocity profile behavior under the difference of \( M \) and \( B_r \), it is aforesaid that the maximum height at \( z = 0 \), the speed of the fluid begins to increase and tends to be fixed in the walls \( T = \frac{1}{c} \). Figure 2, illustrates the effect of the parameters \( \Phi \) and \( N_t \) on the velocity profile \( u \) vs. \( z \). It is found that the velocity profile \( u \) rising up with the increasing of \( \Phi \). Add to that, \( u \) goes down with the increasing \( G_r \), when \( -0.5 < z < 0.5 \), and \( u \) increases with increasing \( B_r \), when \( z \in (-1,0.35) \cup (0.55,1) \). Finally, Fig. 6 shows the velocity profile behavior under the variation of \( Q \) and \( Da \). It is previously mentioned that the velocity profile goes down with the increasing effects of both the parameters. This appears to increase the extent of the side walls either by increasing the height of vertical or by reducing the horizontal distance of the walls, resulting in a decrease in fluid velocity.

Results and Discussions:

Analytical solutions are acquired for momentum equation, energy equation and neutralizing the concentration of nano-particles with the help of homotopy perturbation technique up to the third order deformation. Discussed graphically all solutions obtained under variations of different parameters relevant in this section. The effects of side walls (aspect ratio \( \beta \)), amplitude ratio \( \Phi \), thermophoresis parameter \( N_t \), average flow rate \( Q \), Brownian movement parameter \( N_b \), magnetic parameter \( M \), local nanoparticle Grashof number \( B_r \), Jeffrey fluid number \( \lambda_3 \), local temperature Grashof number \( G_r \) and Darcy number \( Da \) on the velocity \( u \), temperature \( \theta \), nano-particles concentration \( \theta \), pressure rise \( \Delta p \), pressure gradient \( \frac{dp}{dx} \) and friction force \( F \) are presented by sketching graphs for three and two dimensions. The phenomenon of a trapped bolus is also incorporated by drawing streamlines for various physical parameters.

Based on equation (26), Figs. 2 - 6, illustrate the effect of the parameters \( \Phi \), \( N_t \), \( N_b \), \( Q \), \( M \), \( B_r \), \( \lambda_3 \), \( G_r \), \( Da \) and \( \beta \) on the velocity. It is found that the velocity profile \( u \), achieves its maximum height at \( z = 0 \), the speed of the fluid begins to increase and tends to be fixed in the walls \( T = \frac{1}{c} \) as particular at the boundary conditions. Figure 2, illustrates the influence of the parameters \( \Phi \) and \( N_t \) on the velocity distribution function \( u \) vs. \( z \). It is found that the velocity profile \( u \) rising up with the increasing \( \Phi \), when \( |z| < 1 \), while \( u \) increases with increasing of \( N_t \), when \( z \in (-1,0.4) \cup (0.5,1) \), and \( u \) decreases with increasing \( N_t \), when \( -0.4 < z < 0.5 \). Figure 3, shows the behavior of \( u \) under the variation of \( Q \) and \( N_b \), one can depict here that \( u \) increases with the increasing of \( Q \), while \( u \) increases with the increasing of \( N_b \), when \( -1 < z < 0.5 \) and \( u \) decreases with increasing \( N_b \), when \( 0.5 < z < 1 \). Figure 4, contains the velocity profile behavior under the difference of \( M \) and \( B_r \), it is aforesaid that the velocity profile rises with the increase of parameter \( M \). The effect of the \( B_r \) parameter is similar to the parameter effect \( N_t \) on the velocity profile increases, where \( u \) increases with the increasing of \( B_r \), when \( z \in (-1,0.5) \cup (0.5,1) \), and \( u \) decreases with increasing \( B_r \), when \( |z| \leq 0.5 \). Figure 5, illustrates the effects of the parameters \( \lambda_3 \) and \( G_r \) on the velocity distribution function \( u \) vs. \( z \). It is found that the velocity profile \( u \) rising up with the increasing of \( \lambda_3 \). Add to that, \( u \) goes down with the increasing \( G_r \), when \( -0.5 < z < 0.5 \), and \( u \) increases with increasing \( B_r \), when \( z \in (-1,0.35) \cup (0.55,1) \). Finally, Fig. 6 shows the velocity profile behavior under the variation of \( Q \) and \( Da \). It is previously mentioned that the velocity profile goes down with the increasing effects of both the parameters. This appears to increase the extent of the side walls either by increasing the height of vertical or by reducing the horizontal distance of the walls, resulting in a decrease in fluid velocity.
Figure 2. Velocity distribution for various values of $\phi$ and $N_t$ with $x = 0, N_b = 0.5, Q = 1, B_r = 0.5, \lambda_1 = 0.6, G_r = 0.5, \beta = 1.5, Da = 0.9, M = 1.1$.

Figure 3. Velocity distribution for various values of $Q$ and $N_b$ with $x = 0, \phi = 0.15, N_t = 0.5, B_r = 0.5, \lambda_1 = 0.6, G_r = 0.5, \beta = 1.5, Da = 0.9, M = 1.1$.

Figure 4. Velocity distribution for various values of $M$ and $B_r$ with $x = 0, \phi = 0.15, N_b = 0.5, N_t = 0.5, Q = 1, \lambda_1 = 0.6, G_r = 0.5, \beta = 1.5, Da = 0.9$. 

284
Figure 5. Velocity distribution for various values of $\lambda_1$ and $G_r$ with $x = 0, \emptyset = 0.15, N_t = 0.5, N_b = 0.5, B_r = 0.5, Q = 1, \beta = 1.5, Da = 0.9, M = 1.1$.

Figure 6. Velocity distribution for various values of $Da$ and $\beta$ with $x = 0, \emptyset = 0.15, N_t = 0.5, N_b = 0.5, B_r = 0.5, Q = 1, G_r = 0.5, \lambda_1 = 0.6, M = 1.1$.

Based on equation (27), Fig. 7, illustrates the effect of the parameters $\emptyset, \beta, N_b$ and $N_t$ on the temperature distribution function $\theta$. The graph for temperature curve along with the variations of the amplitude ratio $\emptyset$ and the lateral wall $\beta$ with the other constant parameters are explained in (a). It is mentioned earlier that the velocity profile goes down with the increasing effects of both the parameters. Also, it is important to note that the temperature curve gives linear demeanor at $\beta = 0.3$ while for the large values of the side walls, the bending begins and gets its maximum curvature near $z = -0.1$ and disappears at $z = h(x)$ to meet the physical quality at the walls. In (b), the temperature curve is a reduced function of $N_b$ and $N_t$ in the region $-1.2 < z < -0.3$, while in $-0.3 < z < 1.2$, it shows opposite variation.

Figure 7. Temperature distribution $\theta$ vs. $z$ with $x = 0, y = 1$, for (a) different values of $\emptyset$ and $\beta$ at $N_t = 0.5, N_b = 0.5$, (b) different values of $N_t$ and $N_b$ at $\emptyset = 0.2, \beta = 0.5$.

Based on equation (28), Fig. 8 illustrate the effect of the parameters $\emptyset, \beta, N_b$ and $N_t$ on the nanoparticles concentration $\Omega$. The influence of the amplitude ratio $\emptyset$ and the lateral walls $\beta$ on $\Omega$ can be measured from (a), the behavior of the concentration is almost similar to the behavior of temperature with variation $\emptyset$ and $\beta$. Whilst, it depicts that the concentration of nanoparticles is
directly proportional to the difference of \( N_b \) but inversely related to \( N_t \), view (b). From the figures below, observed the movement from \( h(x) \) to 0, the curves are declined, but as proceed, those begin to rise and get stable in \( h(x) \).

![Graphs showing temperature distribution](image)

**Figure 8.** Temperature distribution \( \Omega \) vs. \( z \) with \( x = 0, y = 1, \varnothing = 0.2, \lambda_1 = 1 \), for (a) different values of \( \beta \) at \( N_t = 0.5, N_b = 0.5 \), (b) different values of \( N_t \) and \( N_b \) at \( \beta = 0.5 \).

Based on equation (31), Fig. 9 illustrates the influence of the parameters \( \emptyset, N_t, N_b, M, B_r, G_r, \alpha, D \) and \( \beta \) on the pressure gradient \( \frac{dp}{dx} \) vs. \( x \). The effects of the parameters \( M \) and \( N_b \) on the pressure gradient are explained in (a). It is found that \( \frac{dp}{dx} \) rises with the increasing \( M \), while \( \frac{dp}{dx} \) goes down with the increasing \( N_b \), and \( \frac{dp}{dx} \) rises with the increasing \( M \), otherwise. Furthermore, if \( M = 1, \frac{dp}{dx} \geq 0 \) when \( 0.3 \leq x \leq 0.65 \) at \( N_b = 0.3, \frac{dp}{dx} \geq 0 \) when \( 0.32 \leq x \leq 0.68 \) at \( N_b = 0.4 \) and \( \frac{dp}{dx} \geq 0 \) when \( 0.3 \leq x \leq 0.7 \) at \( N_b = 0.5 \), otherwise \( \frac{dp}{dx} \leq 0 \). Also, observed that, if \( M = 1, \frac{dp}{dx} \geq 0 \) when \( 0.33 \leq x \leq 0.67 \) at \( N_b = 0.3, \frac{dp}{dx} \geq 0 \) when \( 0.31 \leq x \leq 0.69 \) at \( N_b = 0.4 \) and \( \frac{dp}{dx} \geq 0 \) when \( 0.3 \leq x \leq 0.7 \) at \( N_b = 0.5 \), otherwise \( \frac{dp}{dx} \leq 0 \). The influence of \( \beta \) and \( N_t \) on the pressure gradient can be noted from (b), it is mentioned here that \( \frac{dp}{dx} \) goes down with the increasing effects of both the parameters \( \beta \) and \( N_t \). Noted that, at \( \beta = 1.3, \frac{dp}{dx} \geq 0 \), while if \( \beta = 1.5, \frac{dp}{dx} \geq 0 \) when \( 0.23 \leq x \leq 0.77 \) at \( N_t = 0.4, \frac{dp}{dx} \geq 0 \) when \( 0.26 \leq x \leq 0.74 \) at \( N_t = 0.5, \frac{dp}{dx} \geq 0 \) when \( 0.28 \leq x \leq 0.72 \) at \( N_t = 0.6 \) and \( \frac{dp}{dx} \leq 0 \) otherwise. The influence of the parameters \( \emptyset \) and \( \alpha, D \) on the pressure is direct, while in the negative region the effect is reversed. Finally (d), contains the behavior pattern of pressure gradient under the change of \( B_r \) and \( G_r \). It is found that the pressure gradient goes down with the increasing effects of both parameters. Furthermore, if \( B_r = 0.3, \frac{dp}{dx} \geq 0 \) when \( 0.1 \leq x \leq 0.9 \) at \( G_r = 0.4 \) and \( \frac{dp}{dx} \geq 0 \) when \( 0.2 \leq x \leq 0.8 \) at \( G_r = 0.5 \), otherwise \( \frac{dp}{dx} \leq 0 \), while if \( B_r = 0.5, \frac{dp}{dx} \geq 0 \) when \( 0.32 \leq x \leq 0.68 \) at \( G_r = 0.3 \), \( \frac{dp}{dx} \geq 0 \) when \( 0.28 \leq x \leq 0.72 \) at \( G_r = 0.4 \) and \( \frac{dp}{dx} \geq 0 \) when \( 0.2 \leq x \leq 0.8 \) at \( G_r = 0.5 \), otherwise \( \frac{dp}{dx} \leq 0 \).
Figure 9. pressure gradient vs. z with Q = 1, 𝜆₁ = 1, for (a) different values of Nb and M at Φ = 0.15, Nt = 0.5, Br = 0.5, Gr = 0.4, 𝛽 = 1.5, Da = 0.9, (b) different values of 𝛽 and Nt at Φ = 0.15, Nb = 0.5, Nt = 0.5, Br = 0.5, Da = 0.9, M = 1.1, (c) different values of Φ and Da at Nt = 0.5, Nb = 0.5, Br = 0.5, Gr = 0.4, 𝛽 = 1.5, M = 1.2, (d) different values of Br and Gr at Φ = 0.15, Nt = 0.5, Nb = 0.5, 𝛽 = 1.5, Da = 0.9, M = 1.2.

Based on equation (32), Figs. 10 and 11, illustrates the effect of the parameters Br, 𝜆1, Gr, M, Nb, Da, Nt and 𝛽 on the pressure rise Δp vs. Φ and Q, respectively. Figure 10, illustrate the effect of the parameters Br, 𝜆1, Gr, M, Nb, Da, Nt and 𝛽 on the pressure rise vs. Φ. The behavior of Δp vs. Φ, under the variation of Br and 𝜆1 are explained in (a). One can depict here that Δp rises with the increasing 𝜆1, while Δp rises with the increasing Br when 0<Φ<0.4 and Δp goes down with the increasing Br when 0.5<Φ<1. Observed in (b), the influence of the parameters Gr and M on the pressure rise Δp vs. Φ. One can depict here that Δp goes down with the increasing M, while if M=1.2, Δp increases with the increasing of Gr, and if M=1. The behavior of Δp vs. Φ, under the variation of Nt and Gr is explained in (d). One can depict here that Δp goes down with the increasing Nt. Furthermore, observed that the pressure rise function is generally increasing in (d), notice that at 𝛽=1.3 the function is increasing at the beginning and when it reaches the almost middle of the distance (Φ=0.45) it begins to decrease.
Figure 10. pressure rise $\Delta p$ vs. $\phi$, at $Q = 1$ for (a) different values of $B_r$ and $\lambda_1$ at $G_r = 0.4$, $M = 1.2$, $N_b = 0.5$, $N_t = 0.5$, $Da = 0.9$, $\beta = 1.5$, (b) different values of $G_r$ and $M$ at $B_r = 0.5$, $\lambda_1 = 1$, $N_b = 0.5$, $N_t = 0.5$, $Da = 0.9$, $\beta = 1.5$, (c) different values of $N_b$ and $Da$ at $B_r = 0.5$, $\lambda_1 = 1$, $G_r = 0.4$, $M = 1.2$, $N_t = 0.5$, $\beta = 1.5$, (d) different values of $N_t$ and $\beta$ at $B_r = 0.5$, $\lambda_1 = 1$, $N_b = 0.5$, $G_r = 0.4$, $M = 1.2$, $Da = 0.9$.

Figure 11 illustrates the effect of the parameters $B_r$, $\lambda_1$, $G_r$, $M$, $N_b$, $Da$, $N_t$ and $\beta$ on the pressure rise $\Delta p$ vs. $Q$. In (a) observed the influence of $B_r$ and $\lambda_1$ on the pressure rise $\Delta p$ vs. $Q$. One can depict here that $\Delta p$ goes down with the increasing $B_r$, while if $B_r=0.4$, $\Delta p$ increases with increasing of $\lambda_1$ when $0<Q<0.1$, and $\Delta p$ decreases with the increasing $\lambda_1$ when $0.1<\lambda<1$, if $B_r=0.5$, $\Delta p$ increases with increasing of $\lambda_1$ when $0<\lambda<0.15$, and $\Delta p$ decreases with the increasing $\lambda_1$ when $0.15<\lambda<1$, and if $B_r=0.6$, $\Delta p$ increases with increasing of $\lambda_1$ when $0<\lambda<0.2$, and $\Delta p$ decreases with the increasing $\lambda_1$ when $0.2<\lambda<1$. Furthermore, if $B_r=0.4$ obtaining $\Delta p < 0$ when $Q < 0.1$, if $B_r=0.5$ obtaining $\Delta p < 0$ when $Q < 0.15$, and if $B_r=0.6$ obtaining $\Delta p < 0$ when $Q < 0.2$, otherwise $\Delta p > 0$. Observed in (b), the behavior of $\Delta p$ vs. $Q$, under the variation of $G_r$ and $M$. Observed here that $\Delta p$ goes down with the increasing $G_r$, while if $G_r=0.3$, $\Delta p$ increases with increasing of $M$ when $0<Q<0.3$, and $\Delta p$ decreases with the increasing $M$ when $0.3<Q<1$, if $G_r=0.5$, $\Delta p$ increases with increasing of $M$ when $0<Q<0.5$, and $\Delta p$ decreases with the increasing $M$ when $0.5<Q<1$, and if $G_r=0.7$, $\Delta p$ increases with increasing of $M$ when $0<Q<0.6$, and $\Delta p$ decreases with the increasing $M$ when $0.6<Q<1$. Furthermore, at $M=1.1$, if $G_r=0.3$ obtain the $\Delta p < 0$ when $Q < 0.15$, if $G_r=0.5$ obtain the $\Delta p < 0$ when $Q < 0.25$, and if $G_r=0.7$ obtain the $\Delta p < 0$ when $Q < 0.3$, otherwise $\Delta p > 0$. While at $M=1.2$, if $G_r=0.3$ then $\Delta p < 0$ when $Q < 0.1$, if $G_r=0.5$ then $\Delta p < 0$ when $Q < 0.175$, and if $G_r=0.7$ then $\Delta p < 0$ when $Q < 0.25$, otherwise $\Delta p > 0$. In (c), observed that $\Delta p$ rising up with the increasing of $N_b$, while if $N_b=0.3$, $\Delta p$ decreases with increasing of $Da$ when $0<Q<0.4$, and $\Delta p$ increases with the increasing $Da$ when $0.4<Q<1$, if $N_b=0.5$, $\Delta p$ decreases with increasing of $Da$ when $0.4<Q<0.25$, and $\Delta p$ increases with the increasing $Da$ when $0.25<Q<1$, if $N_b=0.7$. $\Delta p$ decreases with increasing of $Da$ when $0<Q<0.2$, and $\Delta p$ increases with the increasing $Da$ when $0.2<Q<1$. Furthermore, at $Da=0.8$, if $N_b=0.3$ obtain $\Delta p < 0$ when $Q < 0.2$, if $N_b=0.5$ obtain $\Delta p < 0$ when $Q < 0.1$, and if $N_b=0.7$ obtain $\Delta p < 0$ when $Q < 0.1$, otherwise $\Delta p > 0$. While at $Da=1.1$, if $N_b=0.3$ then $\Delta p < 0$ when $Q < 0.275$, if $N_b=0.5$ then $\Delta p < 0$ when $Q < 0.2$, and if $N_b=0.7$ obtain $\Delta p < 0$ when $Q < 0.15$, otherwise $\Delta p > 0$. Observed in (d), that $\Delta p$ goes down with the increasing of both parameters $N_t$ and $\beta$. Furthermore, at $\beta=1.3$, if $N_t=0.3$ have $\Delta p > 0$, if $N_t=0.5$ then $\Delta p < 0$ when $Q < 0.05$, and if $N_t=0.7$ then $\Delta p < 0$ when $Q < 0.1$, otherwise $\Delta p > 0$. While at $\beta=1.5$, if $N_t=0.3$ obtain $\Delta p < 0$ when $Q < 0.1$, if $N_t=0.5$ have $\Delta p < 0$ when $Q < 0.15$, and if $N_t=0.7$ then $\Delta p < 0$ when $Q < 0.2$, otherwise $\Delta p > 0$. 

288
Figure 11. Pressure rise $\Delta p$ vs. $Q$, at $\phi = 0.15$ for (a) different values of $B_r$ and $\lambda_1$ at $G_r = 0.4, M = 1.2, N_b = 0.5, N_t = 0.5, Da = 0.9, \beta = 1.5$, (b) different values of $G_r$ and $M$ at $B_r = 0.5, \lambda_1 = 1, N_b = 0.5, N_t = 0.5, Da = 0.9, \beta = 1.5$, (c) different values of $N_b$ and $Da$ at $B_r = 0.5, \lambda_1 = 1, G_r = 0.4, M = 1.2, N_t = 0.5, \beta = 1.5$, (d) different values of $N_t$ and $\beta$ at $B_r = 0.5, \lambda_1 = 1, N_b = 0.5, G_r = 0.4, M = 1.2, Da = 0.9$.

Based on equation (33), Figs. 12 and 13 illustrate the effect of the parameters $B_r, \lambda_1, G_r, M, N_b, Da, N_t$ and $\beta$ on the friction force $F$ vs. $\phi$ and $Q$, respectively. Figure 12 illustrates the effect of the parameters $B_r, \lambda_1, G_r, M, N_b, Da, N_t$ and $\beta$ on the friction force $F$ vs. $\phi$. Observed that the distribution of friction force gives an inverse behavior compared to the distribution of pressure rise versus the amplitude ratio factor. Also, observed that the distribution of friction force gives an inverse behavior compared to the distribution of pressure rise versus the average flow rate $Q$ in Fig. 13.
Figure 12. Friction force $F$ vs. $\phi$, at $Q = 1$ for (a) different values of $B_r$ and $\lambda_1$ at $G_r = 0.4, M = 1.2, N_b = 0.5, N_t = 0.5$, $D\alpha = 0.9, \beta = 1.5$, (b) different values of $G_r$ and $M$ at $B_r = 0.5, \lambda_1 = 1, N_b = 0.5, N_t = 0.5, D\alpha = 0.9, \beta = 1.5$, (c) different values of $N_b$ and $D\alpha$ at $B_r = 0.5, \lambda_1 = 1, G_r = 0.4, M = 1.2, N_t = 0.5, \beta = 1.5$, (d) different values of $N_t$ and $\beta$ at $B_r = 0.5, \lambda_1 = 1, N_b = 0.5, G_r = 0.4, M = 1.2, D\alpha = 0.9$.

Figure 13. Friction force $F$ vs. $Q$, at $\phi = 0.15$ for (a) different values of $B_r$ and $\lambda_1$ at $G_r = 0.4, M = 1.2, N_b = 0.5, N_t = 0.5$, $D\alpha = 0.9, \beta = 1.5$, (b) different values of $G_r$ and $M$ at $B_r = 0.5, \lambda_1 = 1, N_b = 0.5, N_t = 0.5, D\alpha = 0.9, \beta = 1.5$, (c) different values of $N_b$ and $D\alpha$ at $B_r = 0.5, \lambda_1 = 1, G_r = 0.4, M = 1.2, N_t = 0.5, \beta = 1.5$, (d) different values of $N_t$ and $\beta$ at $B_r = 0.5, \lambda_1 = 1, N_b = 0.5, G_r = 0.4, M = 1.2, D\alpha = 0.9$.

**Trapping phenomena:**

The effects of $\phi, \lambda_1, \beta, B_r, G_r, N_t, N_b, Q, M$ and $D\alpha$ on trapping bolus can be seen through Figs. 14 – 23. Figure 14 shows that the size of the trapped bolus grows and increases with the increasing of $\phi$, the effect of $\lambda_1$ on trapping bolus is similar to the effect of $\phi$ on trapping bolus which can be seen in Fig. 15. The effect of lateral walls on trapping bolus is analyzed in Fig. 16. It can be deduced that the size of the trapped bolus in the channel is contracted and decreases when $\beta$ increases, also at $\beta = 1.535$ the upper bolus disappears while at $\beta = 1.5545$ the lower bolus is disappeared. Figures 17 and 18 show that the size of the trapped bolus shrinks and decreases with the increases of $B_r$ and $G_r$, respectively. The effect of thermophoresis parameter $N_t$ on trapping bolus is analyzed in Fig. 19. It can be deduced that the size of the trapped bolus in the channel shrinks and decreases when $N_t$ increases. While in Fig. 20 one can notice that the effect of the Brownian
motion parameter $N_b$ on trapping is inversion of effect of $N_t$ on the trapped bolus. The effect of $Q$ on the trapping is analyzed in Fig. 21, note that the dose size increases and expands with an increased $Q$. The effect of $M$ on trapping analogous to effect $Q$ on trapping, Observe that in Fig. 22. And the effect of $Da$ on trapping bolus is analyzed in Fig. 23. It can be deduced that the size of the trapped bolus in the channel is contracted and decreases when $Da$ increases, also at $Da= 1.191$ the upper bolus disappears while at $Da= 1.241$ the lower bolus disappears.

Figure 14. Streamlines for different values of $\varnothing$ at $y = 1, Q = 0.1, G_r = 0.3, M = 1.2, N_b = 0.5, N_t = 0.9, Da = 0.9, B_r = 0.3, \lambda_1 = 0.6, \beta = 1.2$ for: (a) $\varnothing=0.15$, (b) $\varnothing=0.16$ and (c) $\varnothing=0.17$.

Figure 15. Streamlines for different values of $\lambda_1$ at $y = 1, Q = 0.1, G_r = 0.3, M = 1.2, N_b = 0.5, N_t = 0.9, Da = 0.9, B_r = 0.3, \varnothing = 0.15, \beta = 1.2$ for: (a) $\lambda_1=0.6$, (b) $\lambda_1=0.7$ and (c) $\lambda_1=0.8$.

Figure 16. Streamlines for different values of $\beta$ at $y = 1, Q = 0.1, G_r = 0.3, M = 1.2, N_b = 0.5, N_t = 0.9, Da = 0.9, B_r = 0.3, \varnothing = 0.15, \lambda_1 = 0.6$ for: (a) $\beta=1.2$, (b) $\beta=1.3$ and (c) $\beta=1.53$. 

291
Figure 17. Streamlines for different values of $B_r$ at $y = 1, Q = 0.1, G_r = 0.3, M = 1.2, N_b = 0.5, N_t = 0.9, D\alpha = 0.9, \varnothing = 0.15, \lambda_1 = 0.6, \beta = 1.2$ for: (a) $B_r=0.2$, (b) $B_r=0.3$ and (c) $B_r=0.5$.

Figure 18. Streamlines for different values of $G_r$ at $y = 1, Q = 0.1, B_r = 0.2, M = 1.2, N_b = 0.5, N_t = 0.9, D\alpha = 0.9, \varnothing = 0.15, \lambda_1 = 0.6, \beta = 1.2$ for: (a) $G_r=0.6$, (b) $G_r=0.7$ and (c) $G_r=1$.

Figure 19. Streamlines for different values of $N_t$ at $y = 1, Q = 0.1, B_r = 0.2, M = 1.2, N_b = 0.5, G_r = 0.3, D\alpha = 0.9, \varnothing = 0.15, \lambda_1 = 0.6, \beta = 1.2$ for: (a) $N_t=1$, (b) $N_t=1.5$ and (c) $N_t=2$.

Figure 20. Streamlines for different values of $N_b$ at $y = 1, Q = 0.1, B_r = 0.2, M = 1.2, N_t = 0.5, G_r = 0.3, D\alpha = 0.9, \varnothing = 0.15, \lambda_1 = 0.6, \beta = 1.2$ for: (a) $N_b=1$, (b) $N_b=1.5$ and (c) $N_b=2$. 

292
Figure 21. Streamlines for different values of $Q$ at $y = 1, B_r = 0.2, M = 1.2, N_b = 0.5, N_t = 0.5, G_r = 0.3, Da = 0.9, \varnothing = 0.15, \lambda_1 = 0.6, \beta = 1.2$ for: (a) $Q=0.1$, (b) $Q=0.125$ and (c) $Q=0.15$.

Figure 22. Streamlines for different values of $M$ at $y = 1, Q = 0.1, B_r = 0.2, N_b = 0.5, N_t = 0.5, G_r = 0.3, Da = 0.9, \varnothing = 0.15, \lambda_1 = 0.6, \beta = 1.2$ for: (a) $M=1.2$, (b) $M=1.3$ and (c) $M=1.4$.

Figure 23. Streamlines for different values of $Da$ at $y = 1, Q = 0.1, B_r = 0.2, N_b = 0.5, N_t = 0.5, G_r = 0.3, M = 1.2, \varnothing = 0.15, \lambda_1 = 0.6, \beta = 1.2$ for: (a) $Da=0.8$, (b) $Da=0.9$ and (c) $Da=1.19$.

Concluding remarks:
The peristaltic flow of a nanofluid for Jeffrey fluid is deemed in a cross-section of rectangular porous medium duct to portray the mathematical results under convection is the phenomenon of heat transfer and the concentration of nanoparticles with the magnetic field. Current analysis can serve as a model that may help to understand the mechanism of physiological flows in a loop for fluids acting like nanofluids. From the mechanic’s point of view, it is interesting to note how the peristaltic movement of the applied pressure gradient is affected. The exact expressions for axial velocity of the fluid, axial pressure gradient, pressure rise and stream function are obtained analytically. All governing equations are designed under the long wavelength approximation and the number of Reynolds negligible. The flow is measured in a reference frame moving at constant speed $c$ along the axial direction of the canal. Analytical results were obtained using the HPM and all physical parameters affecting the phenomenon were discussed. The main findings can be summarized as follows:

1- The velocity is an increasing function vs. $\varnothing, Q, \lambda_1$ and $M$, respectively, but decreasing...
function vs. $Da$ and $\beta$ both for two and three dimensional analysis.

2- The velocity is a decreasing function vs. $N_b, G_r$ and $B_r$, respectively, when $-0.5 < z < 0.5$, while the function is an increasing function when $z \in (-1,-0.5) \cup (0.5,1)$.

3- The velocity is an increasing function vs. $N_b$ when $-0.5 < z < 0.5$, while the function is a decreasing when $z \in (-1,-0.5) \cup (0.5,1)$.

4- The temperature distribution is changing inversely vs. $\varnothing$ and $\beta$, respectively. And the discussion previously mentioned that temperature curves decrease with increases in $N_b$ and $N_t$ when $-1 < z < 0$ while increases when $0 < z < 1$, respectively.

5- The nanoparticles concentration rising up with the increase of $N_b$, while it reveals opposite relation with $\varnothing, N_t$ and $\beta$.

6- The pressure gradient profile displays direct relation with $Q$ and $N_b$, while reverses variation with $\lambda_1, N_t, B_r, \beta$ and $G_r$. Also, the pressure gradient profile directs with $Da$ and reverses with $M$ in middle part of the canal, whilst in the both sides the fact is reversed. Furthermore the pressure gradient is positive in middle part of the canal, whilst negative on both sides of the canal.

7- The peristaltic pumping rate increases vs. $\varnothing$ with the increase in $N_b, \lambda_1, G_r, Da$ and $\beta$, while decreases with the increase in $B_r, N_t$ and $M$, respectively. Moreover, observed that the relationship between the pressure rise function and the amplitude ratio parameter is a parabola.

8- The peristaltic pumping rate decreases vs. the flux $Q$, with the increase in $N_b, B_r, G_r$ and $\beta$, respectively, while increases with the increases of in $N_b$. Moreover, observed that the relationship between the pressure rise function and the flux is a linear. Also, it is concluded that peristaltic retrograde pumping ($\Delta p<0$) occurs when $0<Q<0.2$, free pumping ($\Delta p=0$) occurs near $Q=0.2$ and peristaltic pumping region ($\Delta p>0$) occurs when $Q>0.2$.

9- The size of the trapped bolus is growing and increasing with the increasing of $\varnothing, N_b, \lambda_1, Q$ and $M$, respectively, while the trapped bolus is contracting and decreasing with increasing in $\beta, N_t, B_r, G_r$ and $Da$. In general, the size of trapped bolus in upper half is greater than of lower half.

Author's declaration:

- Conflicts of Interest: None.

- I hereby confirm that all the Figures and Tables in the manuscript are mine. Besides, the Figures and images, which are not mine, have been given the permission for re-publication attached with the manuscript.

- Ethical Clearance: The project was approved by the local ethical committee in University of Al-Qadisiyah.

References:


تأثير تباين درجة الحرارة والتركيز على الانتقال الممغنطي للهيدروديناميكا الممغنطة لمانع جيفرى مع ظاهرة الجسيمات النانوية خلال قناة مسامية مستطيلة

ضياء غازي صالح الخفاجي
قسم الرياضيات، كلية العلوم، جامعة القادسية، الديوانية، العراق.

الخلاصة:
تم إنشاء نموذج رياضي لدراسة الآثار المشتركة للتوازن والانتشار الحراري على الجسيمات النانوية لمانع جيفرى مع تأثير المجال المغناطيسي على عملية اتخاذ الأمواج في قناة متوازنة مسامية مستطيلة ثلاثية الأبعاد. استخدمنا تقنية الاضطراب الهوموتوبي لحل المعادلات التفاضلية الجزئية الاختزالية. تم الحصول على نتائج عددية لتوزيع درجة الحرارة، تركز الجسيمات النانوية، السرعة، ارتفاع الضغط، تدرج الضغط، قوة الاحتكاك وذات الدفق. من خلال الرسوم البيانية، وجدت أن سرعة المائع مباشرة مع معدل متوازن لتوزيع الدفع المحرك والملزمة المغناطيسية بينما تكون عكسية مع عدد دارسي والجدران الجانبية. أيضا، تتصرف السرعة بشكل غريب تحت تأثير معلمة الحركة البراونية وتأثير عدد كراشوف النانوي المحلي. 

الكلمات المفتاحية: طريقة الاضطراب الهوموتوبي (HPM)، مائع جيفرى، مجال مغناطيسي هيدروديناميكي، جسيمات نانوية، تدفق متعجي.