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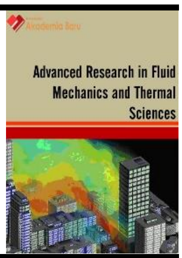

An Exploratory Approach to Study Electro-Osmotic of Non-Newtonian Bio-Bi-Phase Flow Due to Peristaltic Transport of Particulate Fluid

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ABSTRACT

The present article aims to probe the impacts of electro-magneto-hydrodynamics (EMHD) peristaltic flow of in-compressible, dusty, non-Newtonian fluid in a hose of predetermined dimension together with homogeneously scattered analogous rigid particles. In the presence of transversal static magnetic field, Navier-Stokes's equations are employed to design a flow problem for the particulate phase. Governing flow problem is simplified by approximation of long wavelength and zero Reynolds number. The analytical solution for both velocities (solid-liquid) and pressure rise is computed by using well known computational software Mathematica. Perturbation method is employed to extract analytical solution of the resulting ordinary differential equations. Impacts of different physical parameters, expansion in trapped bolus for fluid and particulate velocity profile by increasing Hartmann number are displayed and explained through graphs. Furthermore, a rise in skin friction is noticed with the rise in particle effect and electro-osmotic parameter. This study may have greater significance and viable applications to improve the quality of micro-fluidic devices.

1. Introduction

Fluid transport has fundamental importance in innovative world of fluid mechanics. Researchers are keenly interested in this special zealous area in response of its wider applications in medical equipment e.g., medical sensors, biological systems like blood flow, urine transport, sweating, biochips, micro pumps, industrial and engineering fields. One of the special phenomena of physiological flow can be observed in esophagus, ureter, chyme drive in the intestinal tract, sperm movement in male generative system and flowing of blood through arteries. This physiological special flow type is termed as Peristalsis. This peristaltic movement produced in the fluid by the contracting and relaxing muscular movement of the flexible tube-like structure containing fluid. This interesting flow mechanism works in living organisms as an inbuilt system while researchers have embraced with its man-made applications in biomedical engineering e.g., heart-lung machines, finger pumps, dialysis machine, and roller pump. Many significant uses of this flow procedure can be observed at larger scale e.g., transportation of slurries, fluid like sanitary, corrosive and noxious in nuclear industry.

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Practical application of this phenomenon in biochemical systems and industries is peristaltic pumping by means of finger and roller pumps to push corrosive or pure material by special care to prevent fluid adherence with internal surface of pump [1-5]. Study of this special aspect of fluid flow is initiated by Latham [6] to comprehend the peristaltic streams of hydrodynamic fluids with significant hypothetical and experimental soundings assuming different parameters i.e., low Reynolds number, long wavelength, small wave amplitude etc.

In recent time, too much progress has seen in the study of micro and nanofluidic. Nanotechnology along with peristaltic flow has brought modernization in present science and technology world. Inventions and applications like microelectronics, nuclear reactor coolant, hybrid power engines, space technology, fuel cells and pharmaceutical processes grinding are best descriptions of its technological importance. The theme “nanofluid” was principally familiarized by Choi [7] with probing about the improvement standard of thermal conducting ability of low or non-conducting fluids. investigated the peristaltic flow for the Jeffrey fluid model of chime in the small intestine using a magnetic field. Later workflow is added by Akbar *et al.,* [8,9]. They introduced the induced magnetic field environment in an asymmetric channel and gave numerical observations for peristaltic fluid flow. Stud *et al.,* [10] explored the blood flow with moving magnetic field to observe the influence of magnetic field. Human blood constitutes a suspension of red blood cells and can behave as an electronically conducting fluid. This philosophical idea was given by Srivastava and Agrawal [11]. Anwaruddin *et al.,* [12] considered peristaltic flow of blood in between flexible wall channel to construct a mathematical model for magnetic field effects by applying a wavelength approximation method. In biological context, fluid flow through curved type geometry of flexible and compliant ducts and granular tubes. Inspiring by this natural curved characteristic of peristaltic flow, number of investigations for peristaltic movement can be seen by researchers in compliant (flexible) walls channels/tubes [13,14]. Kumari *et al.,* [15] observed the peristaltic flow inside a channel with some inclination and wall effects and explained the magnetic field and slip behavior. Aly *et al.,* [16,17] encountered the slip effects for temperature, concentration and velocity of nanofluid with asymmetric wave production on walls of channel and extract analytical exact solution. Dramatical rise is noticed in the importance of multiphase flow from years. Reza-E-Rabbi *et al.,* [18] studied multiphase flow involving nano sized particles and analyzed the hydrodynamic flow behavior. Casson nanofluid flow over an elongating pane together with magnetohydrodynamics (MHD) has been elaborated for heat a mass transfer analysis [19]. Significant result-oriented work in the same sequence of heat and mass transfer analysis can be noticed in studies [20-27].

Studies associated with heat transmission and flow of particulate fluids in a channel are intensely advantageous in several engineering and industrial devices to ameliorate the designing and functioning purposes. Numerous very useful execution is discussed in, polymer technology, fluid droplet sprays, refining of crude oil in the petroleum industry and electrostatic precipitation [28-33]. In the presence of magnetic field acting in transverse direction, electrically conducting and particulate fluid flows are also revolutionized through various applications such as flow meters, pumps, generators and accelerators. Usually, the compact particles in such devices are dangled as soot in the conducting fluid due to combustion and corrosion processes. Investigations about the proven and practical significance of solid particles in efficient working principal of these devices attained much attention of researchers [34-36].

Micro-electric mechanical system is surprisingly greater development in mixed scientific industries due to its innovative applications e.g., Lab-on-a-chip. Ionized liquid flow in a microchannel subject to the conditions like tangential external electric field and stationary charged walls of channel is referred as electro-osmotic flow. The micro-pumps based on the mechanism of electro-osmosis has major constituent role in Lab-on-a-chip. The scientific innovation has been made in the microscale projects with the expansion in microfluidics devices, micro pumping and peristaltic micro pumping [37]. Without depending on mechanical parts, pulse free and plug-like flow production of electro-osmotic micro-pumps is its greater assistance [38]. Various important paybacks like liquid chromatography, fluid stirring and mixing, flow control in fluidic networks, fluid pumping etc. are based on the EMHD behavior of fluid are popular among researchers [39–41].

Interactions phenomenon amid the fluid and particle phase, particle-particle phase, and particle-wall introduce Solid liquid fluidized bed (SLFB) systems. Higher heat and mass transfer rates of SLFB systems raises their importance in industry and wide usage significance in chemicals, food industries, biochemical, mineral processing, and involving variety of applications such as ion exchange, water treatment, separation of minerals, sedimentation, adsorption, and crystallization. Shakhaoath *et al.,* [42] generated an investigation over liquid fluidized beds based on segregation and dispersion of binary particle species of different densities and uniform size. Comparative study and review of published work about SLFB was organized by Shakhaoath *et al.,* [43].

Innovative approaches of EMHD micro-pumps got huge attentions in current innovative world. Numerous authors have studied the effects of EMHD peristaltic flow of non-Newtonian incompressible dusty fluids [44,45]. However, bi-phase peristaltic motion of fluid under influence of an electromagnetic field has not been yet scrutinized. The current study is initiated in this sequence to make precise observations on the peristaltic flow of two-phase fluid and the impression of EMHD in a channel of finite length with the assumption of long wavelength. Governing flow problem is simplified by approximation of Long wavelength and zero Reynolds number. The analytical solution for both velocities (solid-liquid) and pressure rise is computed by using well known computational software Mathematica. Perturbation method is employed to extract analytical solution of the resulting ordinary differential equations. Next to literature review the propound study is furnished as: transport equations and flow analysis is stated in Section 2; solution methodologies are presented in Section 3. The justification of numerical and graphical outcomes is elaborated in Section 4. Finally, essential remarks are communicated in the endmost Section. The effect of all the physical parameters is drawn for the fluid phase velocity, the particulate phase velocity and pressure difference. The streamline graphs disclose the expansion in trapped bolus for fluid and particulate velocity profile by increasing Hartmann number. Furthermore, a rise in skin friction is noticed with the rise in particle effect and electro-osmotic parameter.

2. Formulation of the Problem

Consider an unsteady, incompressible and electrically conducting particle fluid suspension exhibiting a peristaltic movement along a channel of finite length. The two-dimensional incompressible fluid flow is subject to the conditions: electrokinetic body force is functional in the axial direction and a uniform magnetic field is acting in the transverse direction. The behaviour of fluid is considered electrically conducting due to the effect of electric and magnetic field (Figure 1). Mathematical representation of the geometrical model in Figure 1 is as

$$H(X,t) = a + b\sin\frac{2\pi}{\lambda}(X - ct) \tag{1}$$

The governing equations for fluid phase and particulate phase in terms of the Cartesian coordinate system (X, Y) are of the form.

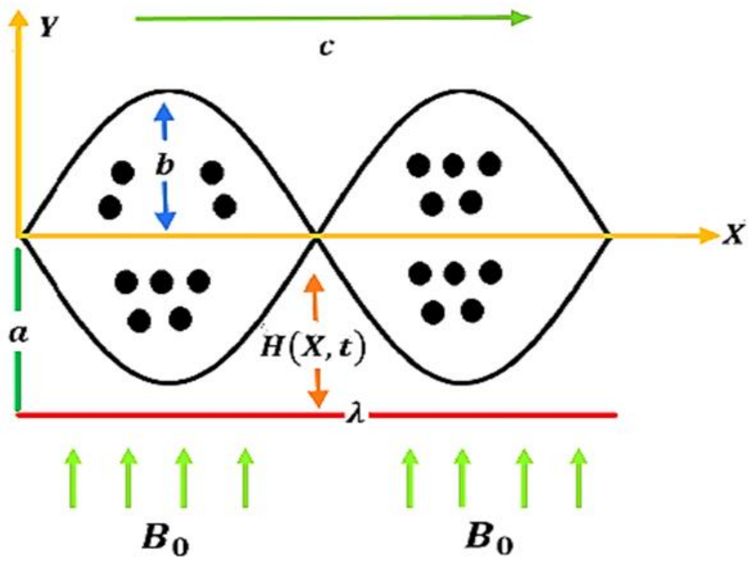

Fig. 1. Geometry of the problem

2.1 System of Equations for Fluid Phase

$$\frac{\partial U_f}{\partial X}+\frac{\partial V_f}{\partial Y}=0, \tag{2}$$

$$(1-C)\rho_f\left\{\frac{\partial U_f}{\partial t}+U_f\frac{\partial U_f}{\partial X}+V_f\frac{\partial U_f}{\partial Y}\right\}=-(1-C)\frac{\partial P}{\partial X}+(1-C)\mu_s\left(\frac{\partial^2 U_f}{\partial X^2}+\frac{\partial^2 U_f}{\partial Y^2}\right)+CS(U_p-U_f)+\bar{\rho}_e E_X+\vec{J}\times\vec{B}, \tag{3}$$

$$(1-C)\rho_f\left\{\frac{\partial V_f}{\partial t}+U_f\frac{\partial V_f}{\partial X}+V_f\frac{\partial V_f}{\partial Y}\right\}=-(1-C)\frac{\partial P}{\partial Y}+(1-C)\mu_s\left(\frac{\partial^2 V_f}{\partial X^2}+\frac{\partial^2 V_f}{\partial Y^2}\right)+\vec{\rho}_e E_Y+CS(V_p-V_f), \tag{4}$$

2.2 System of Equations for Particulate Phase

$$\frac{\partial U_p}{\partial X}+\frac{\partial V_p}{\partial Y}=0, \tag{5}$$

$$C\rho_p\left\{\frac{\partial U_p}{\partial t}+U_p\frac{\partial U_p}{\partial X}+V_p\frac{\partial U_p}{\partial Y}\right\}=-C\frac{\partial P}{\partial X}+CS(U_f-U_p), \tag{6}$$

$$C\rho_p\left\{\frac{\partial V_p}{\partial t}+U_p\frac{\partial V_p}{\partial X}+V_p\frac{\partial V_p}{\partial Y}\right\}=-C\frac{\partial P}{\partial Y}+CS(V_f-V_p) \tag{7}$$

3. Solution of the Problem

Using non-dimensional parameter

$$\left.\begin{aligned}&x=\frac{X}{\lambda},\ \mathrm{y}=\frac{Y}{d},\ u_{f,p}=\frac{U_{f,p}}{c},\ v_{f,p}=\frac{V_{f,p}}{c\delta},\ \delta=\frac{a}{\lambda},\ M_1=\frac{a^2SC}{\mu_s},\\&p=\frac{a^2}{\lambda c\mu_s}P,\ \mathrm{Re}=\frac{\rho ac}{\mu_s},\ \bar{E}=m^2U_{HS}\phi,\ M=\sqrt{\frac{B_0^2a^2}{\mu_s}}\end{aligned}\right\} \tag{8}$$

Using the Eq. (8), in Eq. (1)-(6), and taking the approximation of low Reynolds number and long wavelength after some simplification we get the resulting equation of fluid phase as

$$\frac{\partial p}{\partial x}=\frac{\partial^2 u_f}{\partial y^2}-\frac{m^2}{1-C}U_{HS}\phi+\frac{M_1}{1-C}(u_p-u_f)-\frac{Ha^2}{1-C}u_f, \tag{9}$$

$$\frac{\partial p}{\partial y}=0. \tag{10}$$

And for particulate phase

$$\frac{\partial p}{\partial x}=\frac{M_1}{C}(u_f-u_p), \tag{11}$$

$$\frac{\partial p}{\partial y}=0 \tag{12}$$

The Second order slip conditions are

$$u=-U_{slip}=-\left(A\frac{\partial u}{\partial y}+B\frac{\partial^2 u}{\partial y^2}\right)\text{ at y = 0,} \tag{13}$$
$$u=U_{slip}=A\frac{\partial u}{\partial y}+B\frac{\partial^2 u}{\partial y^2}\text{ at y = h,}$$

where $A=\frac{2}{3}\left(\frac{3-\alpha l^3}{\alpha}-\frac{3}{2}\frac{1-l^2}{k_n}\right)$ and $B=-\frac{1}{4}\left(l^4+\frac{2(1-l^2)}{{k_n}^2}\right)\frac{\lambda}{a^2}$.

Series solution for fluid and dust phase are

$$U_f=C_1\,Cosh\frac{Hay}{\sqrt{1-C}}+C_2\,Sinh\frac{Hay}{\sqrt{1-C}}-\frac{(1-C)}{Ha^2}(1-\frac{C}{1-C})\frac{\partial p}{\partial x}+\frac{(1-C)m^2U_{HS}}{m^2(1-C)-Ha^2}\phi \tag{14}$$

$$U_p=C_1\,Cosh\frac{Hay}{\sqrt{1-C}}+C_2\,Sinh\frac{Hay}{\sqrt{1-C}}-\frac{(1-C)}{Ha^2}(1-\frac{C}{1-C})\frac{\partial p}{\partial x}+\frac{(1-C)m^2U_{HS}}{m^2(1-C)-Ha^2}\phi-\frac{C}{M_1}\frac{\partial p}{\partial x} \tag{15}$$

where,

$$C_1=\frac{1}{1+\frac{BHa^2}{1-C}}\left(\frac{(1-C)\left(1-\frac{C}{1-C}\right)\frac{\partial p}{\partial x}}{Ha^2}-\frac{(1-C)m^2U_{HS}Sech[hm]}{-Ha^2+(1-C)m^2}-\frac{B(1-C)m^4U_{HS}Sech[hm]}{-Ha^2+(1-C)m^2}-\frac{\left(AHa^2\left(T_1+\frac{P_1}{Q_1}\right)\right)}{R_1}\right)$$

$$C_2=\frac{(1-C)\left(1-\frac{C}{1-C}\right)\frac{\partial p}{\partial x}}{Ha^2}-\frac{(1-C)m^2U_{HS}}{-Ha^2+(1-C)m^2}-\frac{B(1-C)m^4U_{HS}}{-Ha^2+(1-C)m^2}-P_2+\frac{Q_2}{R_2}$$

Here C_1 and C_2 are integration constants. To synopsize the volume of equation we have considered

$$T_1=\frac{(1-C)\left(1-\frac{C}{1-C}\right)}{Ha^2}+\frac{(1-C)m^2U_{HS}}{-Ha^2+(1-C)m^2}-\frac{(1-C)m^4U_{HS}}{-Ha^2+(1-C)m^2}-\frac{1}{Ha^2+\frac{BHa^2}{1-C}}(1-C)\Big(1-$$
$$\frac{C}{1-C}\Big)\frac{\partial p}{\partial x}\left(-Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right]\right)+\frac{BHa^2Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{1-C}+\frac{AHa^2Sinh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{\sqrt{1-C}}$$

$$P_1 = \left((1-C)m^2 U_{HS} Sech[hm] \left(-Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right] + \frac{BHa^2 Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{1-C} + \frac{AHa^2 Sinh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{\sqrt{1-C}} \right) \right)$$

$$Q_1 = \left(\left(1+\frac{BHa^2}{1-C}\right)(-Ha^2+(1-C)m^2) \right) + \frac{\left(B(1-C)m^4 U_{HS} Sech[hm] \left(-Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right] + \frac{BHa^2 Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{1-C} + \frac{AHa^2 Sinh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{\sqrt{1-C}} \right) \right)}{\left(\left(1+\frac{BHa^2}{1-C}\right)(-Ha^2+(1-C)m^2)\right) - \frac{A(1-C)m^3 U_{HS} Tan[hm]}{-Ha^2+(1-C)m^2}}$$

$$R_1 = \sqrt{1-C} \left(\frac{AHa^2 Sinh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{\sqrt{1-C}} - Sinh\left[\frac{hHa^2}{\sqrt{1-C}}\right] + \frac{BHa^2 Sinh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{1-C} - \frac{\left(AHa^2 \left(-Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right] + \frac{BHa^2 Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{1-C} + \frac{AHa^2 Sinh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{\sqrt{1-C}} \right) \right)}{\sqrt{1-C}\left(1+\frac{BHa^2}{1-C}\right)} \right)$$

$$P_2 = \frac{1}{Ha^2+\frac{BHa^2}{1-C}} (1-C)\left(1-\frac{C}{1-C}\right)\frac{\partial p}{\partial x}\left(-Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right] + \frac{BHa^2 Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{1-C} + \frac{AHa^2 Sinh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{\sqrt{1-C}} \right)$$

$$Q_2 = \left((1-C)m^2 U_{HS} Sech[hm] \left(-Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right] + \frac{BHa^2 Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{1-C} + \frac{AHa^2 Sinh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{\sqrt{1-C}} \right) \right)$$

$$R_2 = \left(\left(1+\frac{BHa^2}{1-C}\right)(-Ha^2+(1-C)m^2) \right) + \frac{\left(B(1-C)m^4 U_{HS} Sech[hm] \left(-Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right] + \frac{BHa^2 Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{1-C} + \frac{AHa^2 Sinh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{\sqrt{1-C}} \right) \right)}{\frac{\left(\left(1+\frac{BHa^2}{1-C}\right)(-Ha^2+(1-C)m^2) - \frac{A(1-C)m^3 U_{HS} Tan[hm]}{-Ha^2+(1-C)m^2}\right)}{\frac{\left(AHa^2 \left(-Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right] + \frac{BHa^2 Cosh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{1-C} + \frac{AHa^2 Sinh\left[\frac{hHa^2}{\sqrt{1-C}}\right]}{\sqrt{1-C}} \right) \right)}{\sqrt{1-C}\left(1+\frac{BHa^2}{1-C}\right)}}}$$

4. Results and Discussion

This section contains the graphical portrayal of different parameters sketched by computational software Mathematica and discussion of analytical solution. The solutions of velocity, pressure, streamlines for fluid and particulate phase are elaborated graphically through various pertinent parameters like Hartmann number (*Ha*), particle effect (*C*) and Electro-osmotic parameter (*m*) with second-order slip conditions. The computational software Mathematica has been used to visualize the performance of all the parameters through graphs.

Figure 2-4 represents the behaviour of velocity profiles of fluid phase and Figure 5-7 represents the behaviour of velocity profiles of particle-phase along with different parameters with the variations of time.

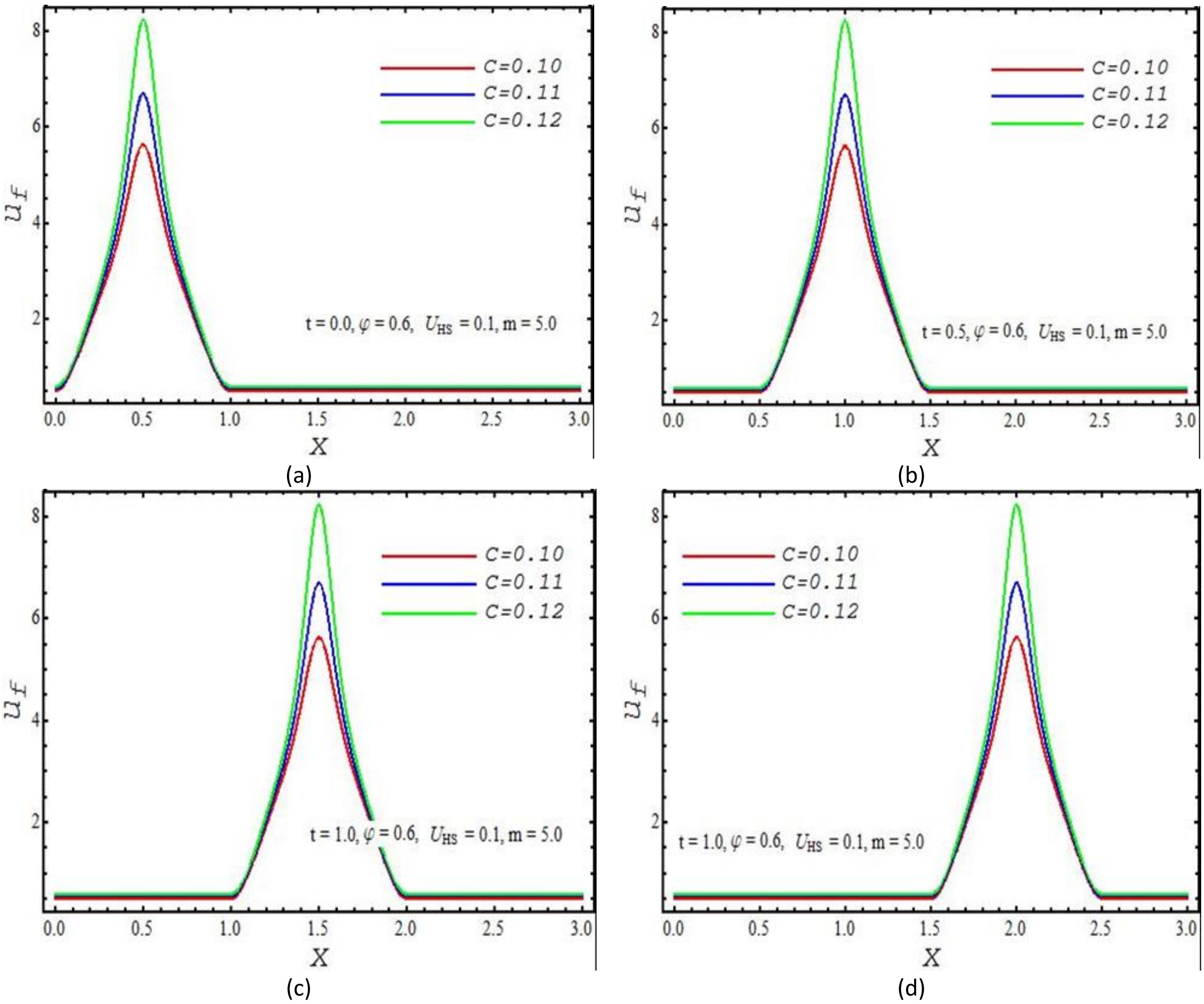

Fig. 2. Velocity for fluid phase at various values of C (a) t = 0, (b) t = 0.5, (c) t = 1.0, (d) t = 1.5, $\varphi = 0.6, U_{HS} = 0.1, m = 5$

Figure 2 declares that the velocity profile of the fluid phase shows the relationship between velocity and particle effect (*C*). It depicts that velocity of fluid phase decreases with the variations of particle effect (*C*) due to resistive drag force which is induced due to the presence of particles, whereas velocity profile of particulate phase shows opposite behaviour as shown in Figure 5. Figure 3 reveals that the velocity profile of the fluid phase increases with increase in Hartmann number due to the influence of Lorentz force which resists the flow. The velocity contour of the particulate phase demonstrates the opposite behaviour in Figure 6.

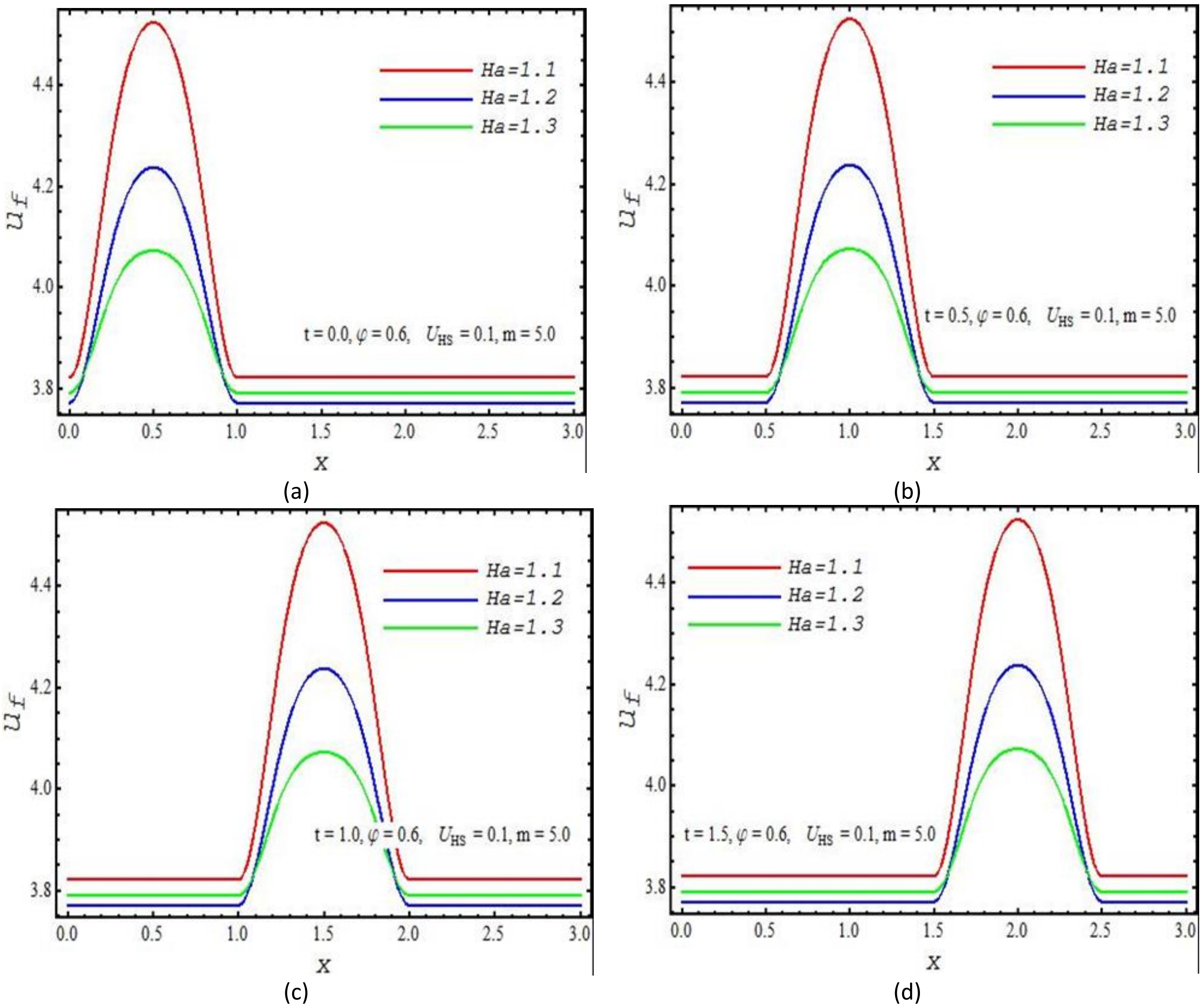

Fig. 3. Graph for velocity at various values of Ha. (a) t = 0, (b) t = 0.5, (c) t = 1.0, (d) t = 1.5, when $\varphi = 0.6, U_{HS} = 0.1, m = 5$

Figure 4 indicates that increase in electro-osmotic parameter (m) reflects a decline in velocity profile graph. The parameter (m) is inversely proportional to Debye length. The velocity profile of the particulate phase shows the opposite behaviour as displayed in Figure 7. There is no effect on the graphs even the variation of time. All graphs show same result at different time.

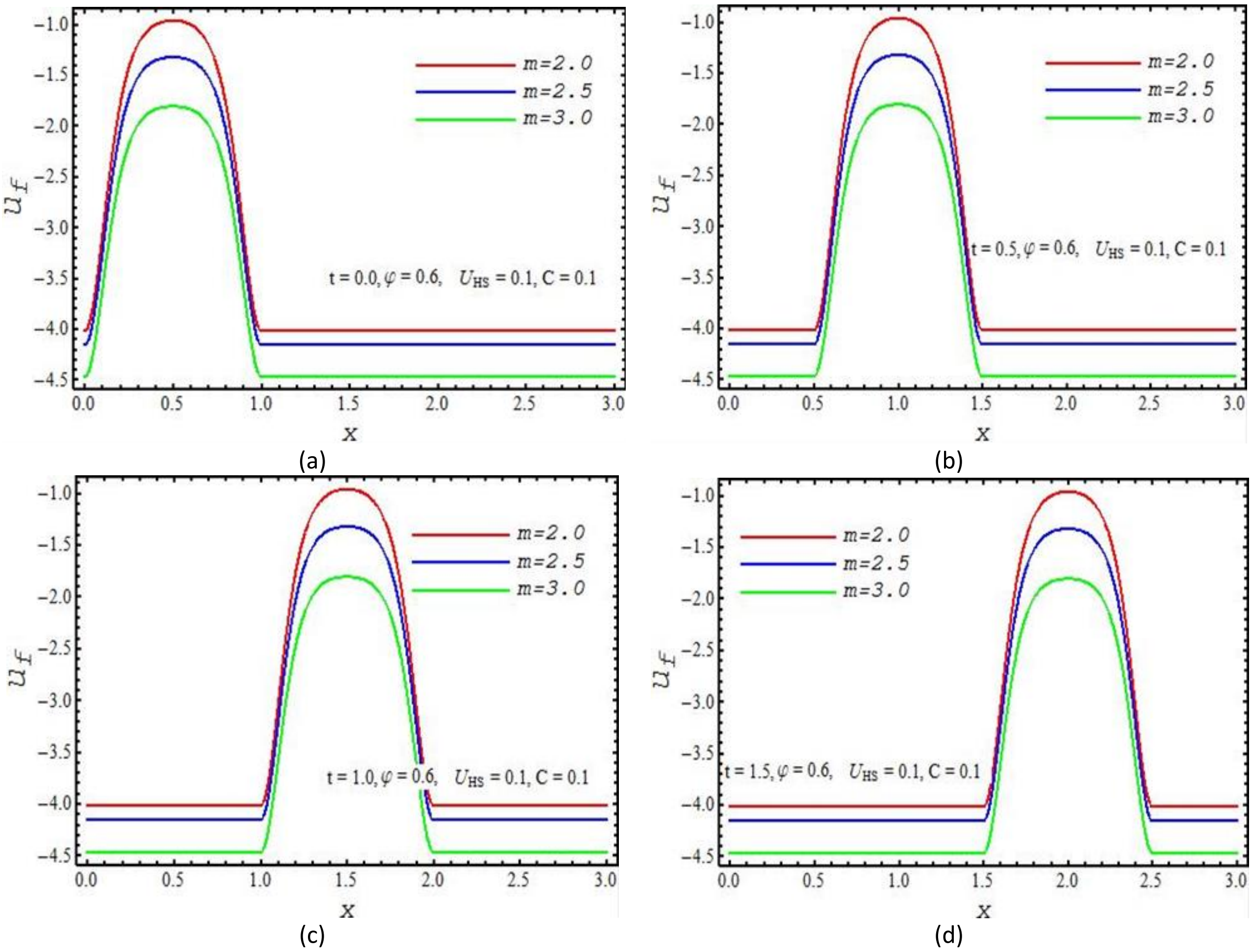

Fig. 4. For various values of m, the graph represents velocity for (a) t = 0, (b) t = 0.5, (c) t = 1.0, (d) t = 1.5, when $\varphi = 0.6, U_{HS} = 0.1, C = 0.1$

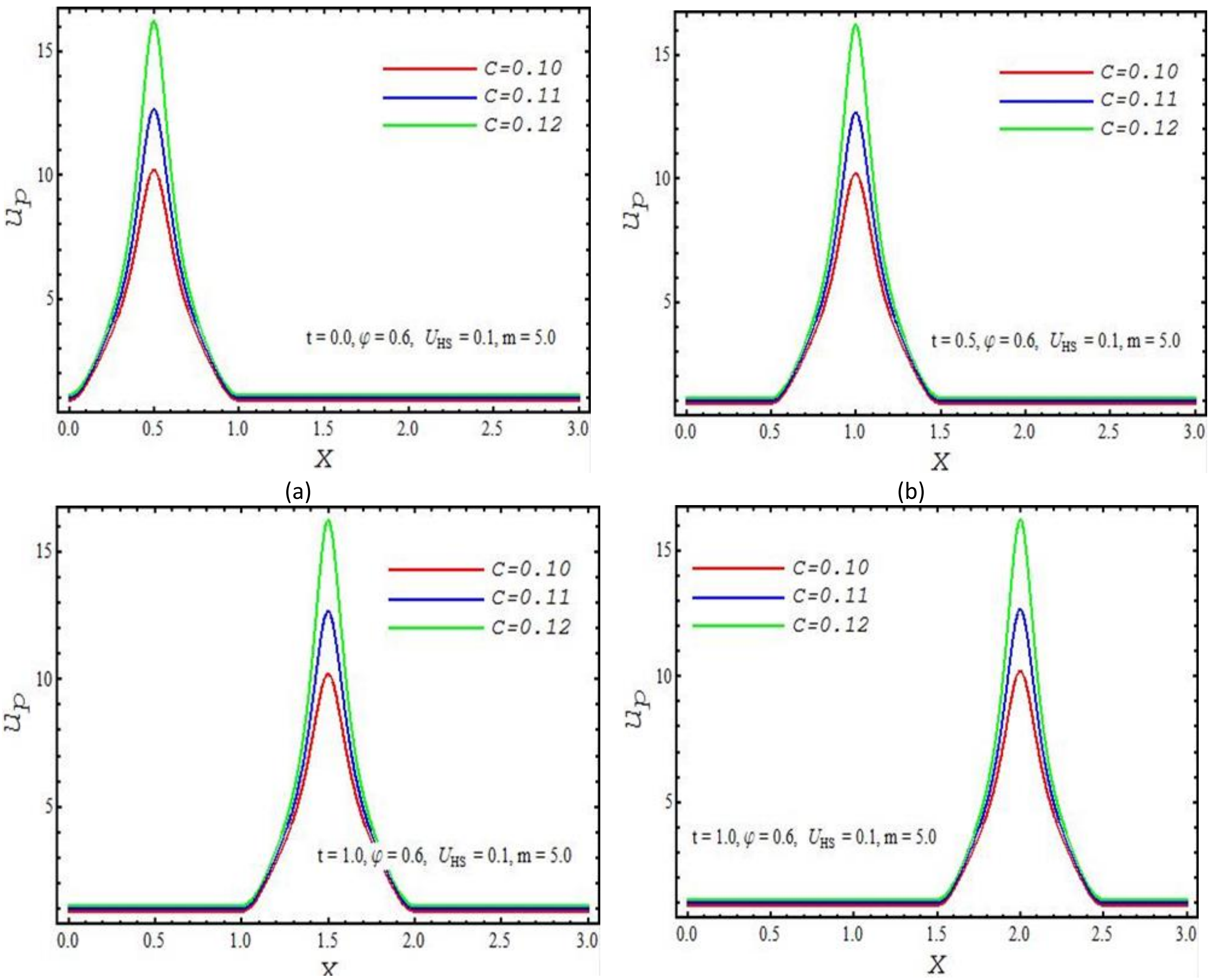

Fig. 5. Velocity graph for particulate phase at various values of C below (a) t = 0, (b) t = 0.5, (c) t = 1.0, (d) t = 1.5, when $\varphi = 0.6, U_{HS} = 0.1, m = 5$

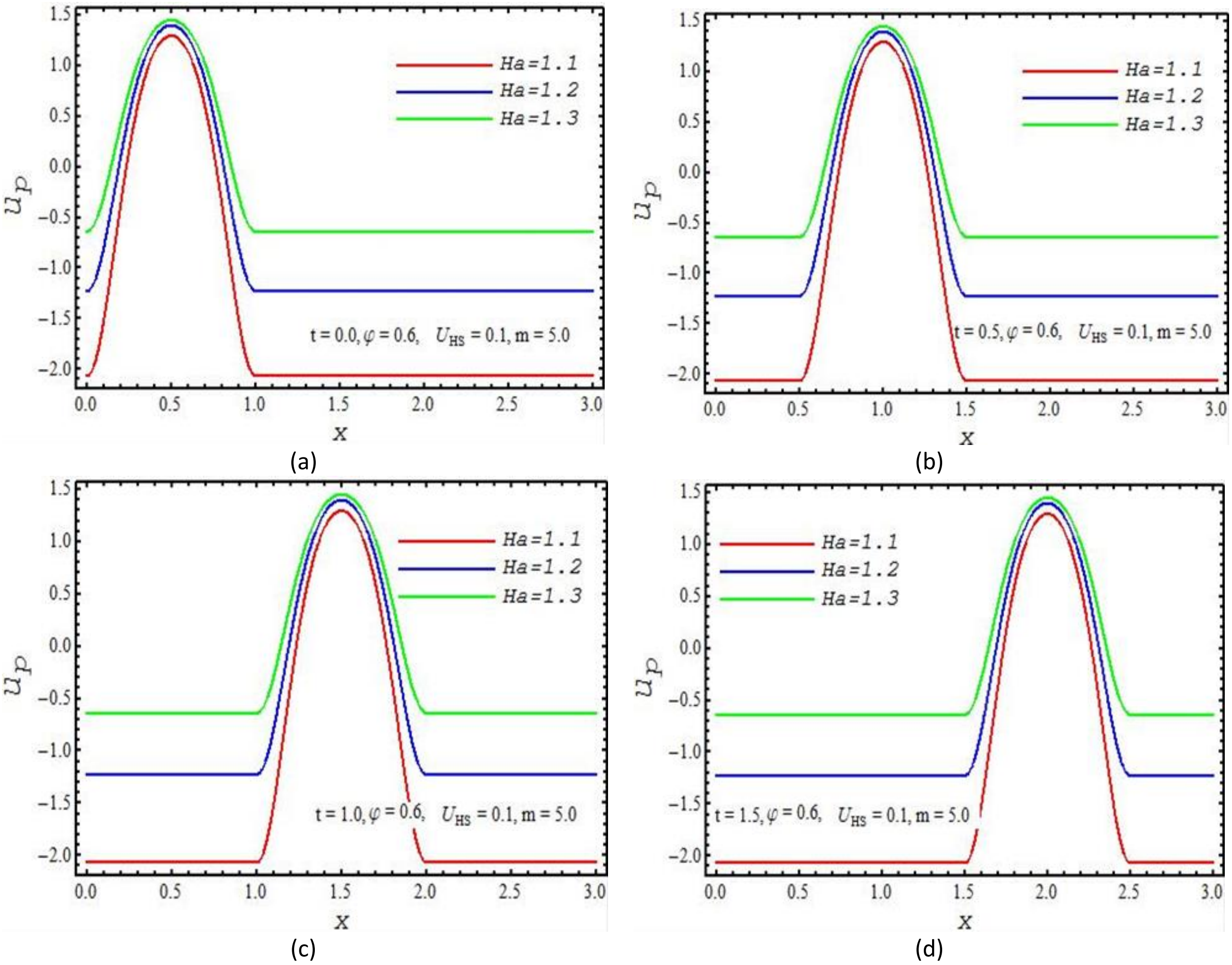

Fig. 6. Graph for velocity at particulate phase with various values of Ha (a) t = 0, (b) t = 0.5, (c) t = 1.0, (d) t = 1.5, when $\varphi = 0.6, U_{HS} = 0.1, m = 5$

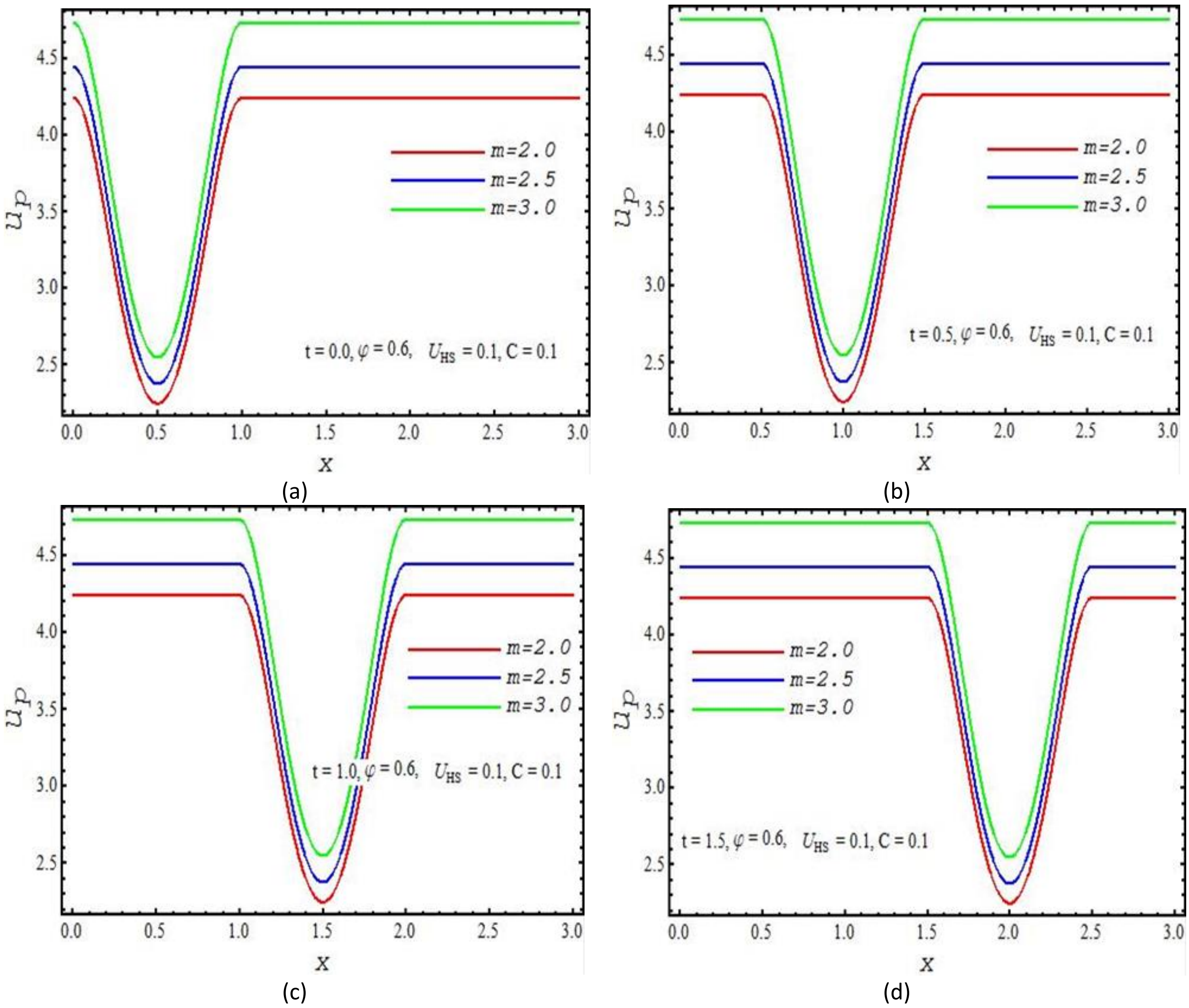

Fig. 7. Velocity representation for the particulate phase at various values of m (a) t = 0, (b) t = 0.5, (c) t = 1.0, (d) t = 1.5, when $\varphi = 0.6, U_{HS} = 0.1, C = 0.1$

Figure 8-10 represent the influence of the pressure gradient for different parameters with the variations of time. The relation between velocity and particle effect (C) is shown in Figure 8. A rise in pressure graph is noticed with the rise in values of particle effect (C). Similarly, Figure 9 and 10 shows the increase in pressure graphs with the increase of Hartmann number (Ha) and electro-osmotic parameter (m).

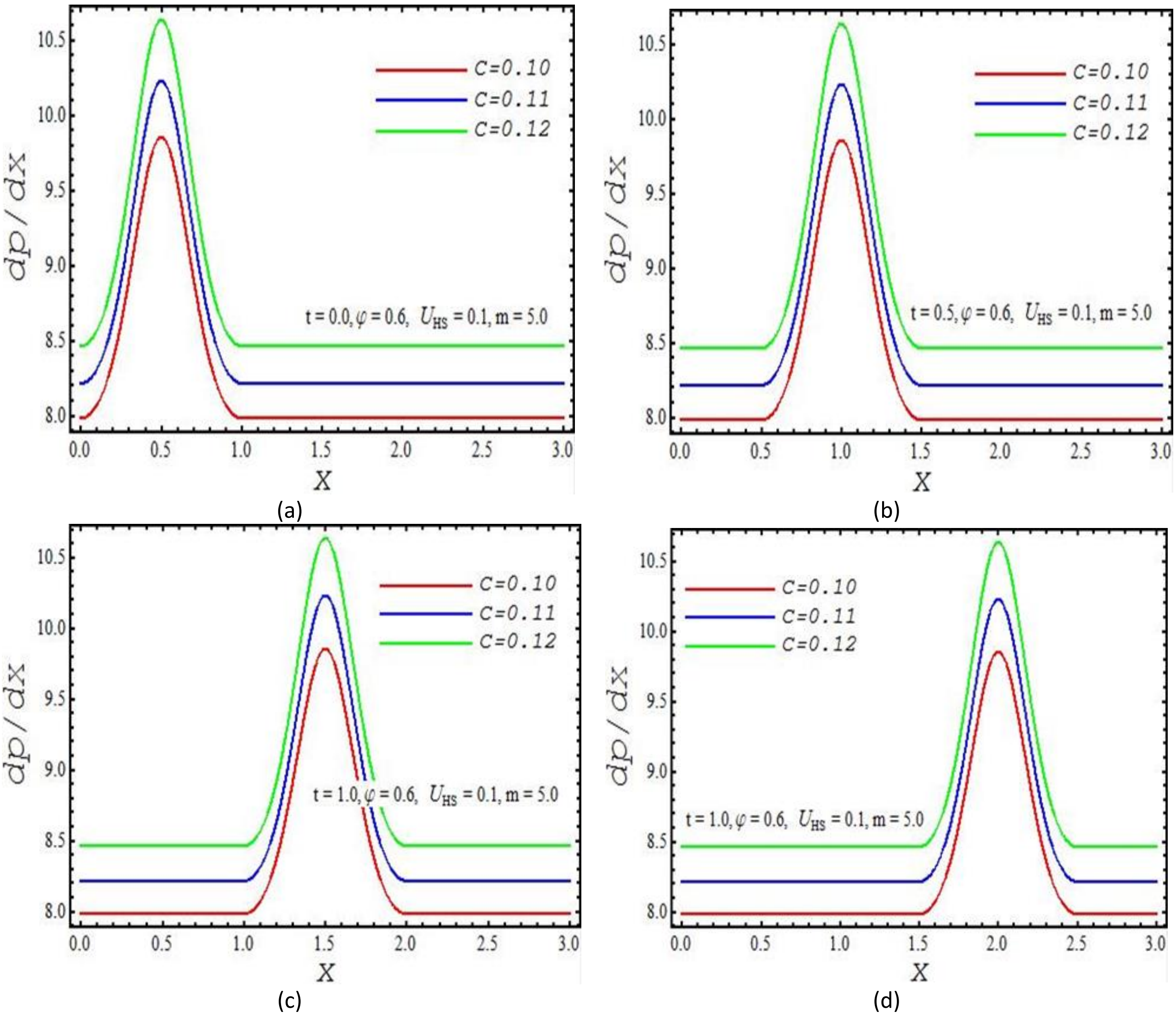

Fig. 8. Pressure gradient at various values of C for (a) t = 0, (b) t = 0.5, (c) t = 1.0, (d) t = 1.5, when $\varphi = 0.6, U_{HS} = 0.1, m = 5$

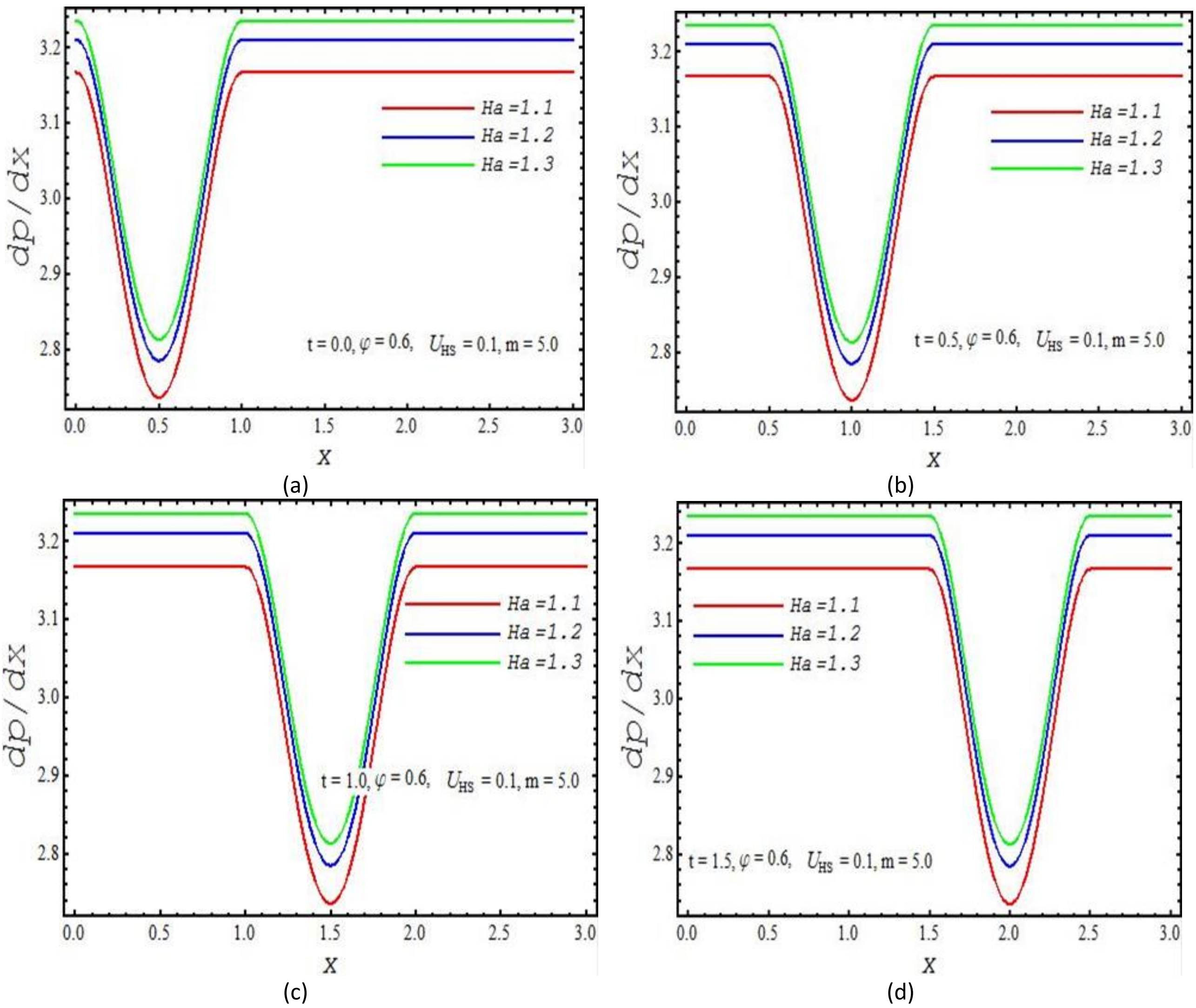

Fig. 9. Pressure gradient at different values of Ha in (a) t = 0, (b) t = 0.5, (c) t = 1.0, (d) t = 1.5, when $\varphi = 0.6, U_{HS} = 0.1, C = 0.1$

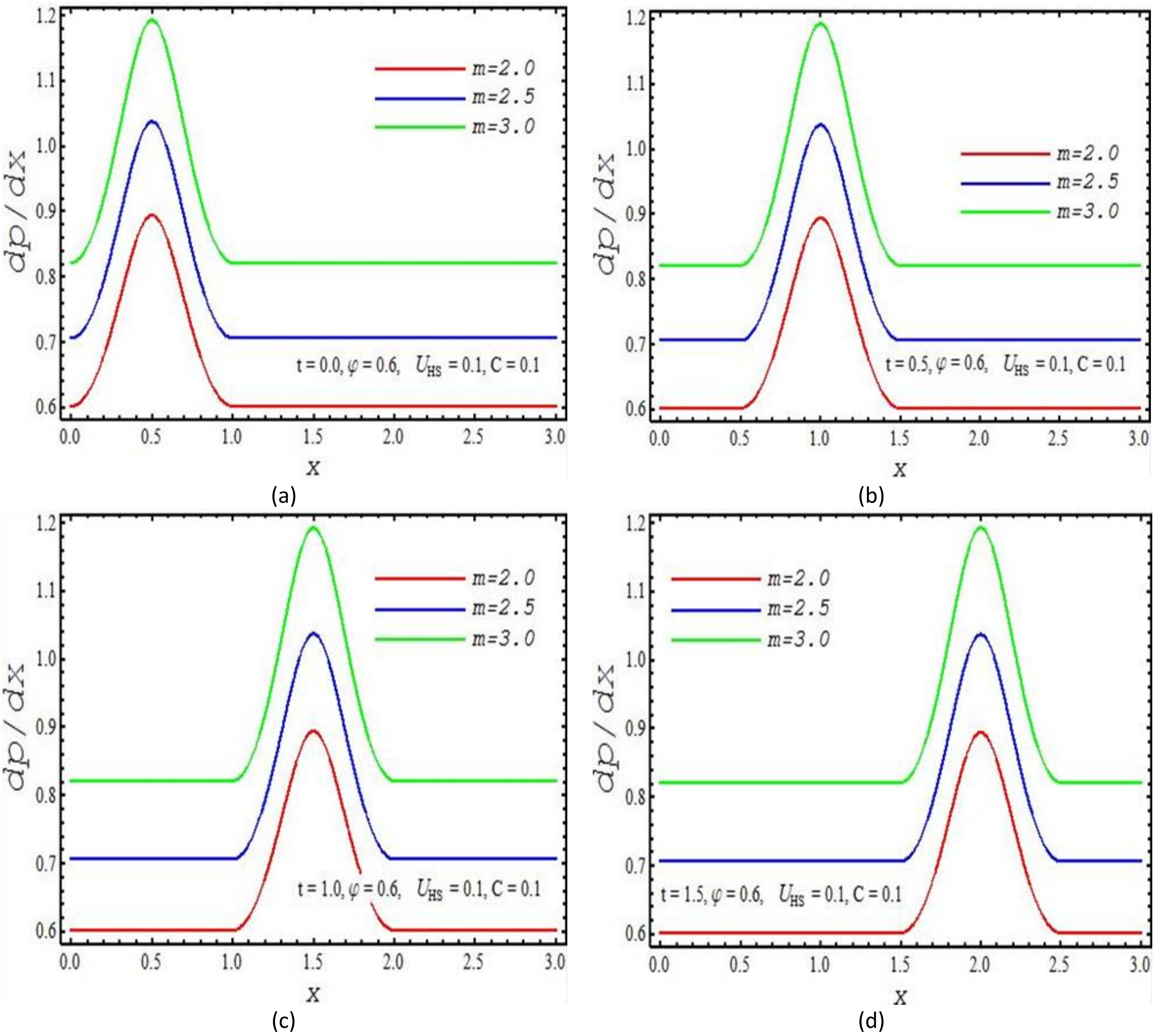

Fig. 10. Pressure gradient at various values of m below (a) t = 0, (b) t = 0.5, (c) t = 1.0, (d) t = 1.5, when $\varphi = 0.6, U_{HS} = 0.1, C = 0.1$

Figure 11 and 12 represents the role of skin friction with the variations of Hartmann number (*Ha*) along with different values of particle effect (*C*) and Electro-osmotic parameter (*m*) respectively. It can be seen from Figure 4-11 that by increasing the values of both particle effect (*C*) and Hartmann number (*Ha*), graph gradually increases. Graph of skin friction at different values of particle effect (*C*) starts from the same point and shows the same behaviour. Figure 12 indicates that by increasing the value of electro-osmotic (*m*), Hartmann number (*Ha*) is increased Skin friction graphs at different values of *m* starts from different points but shows the same trend.

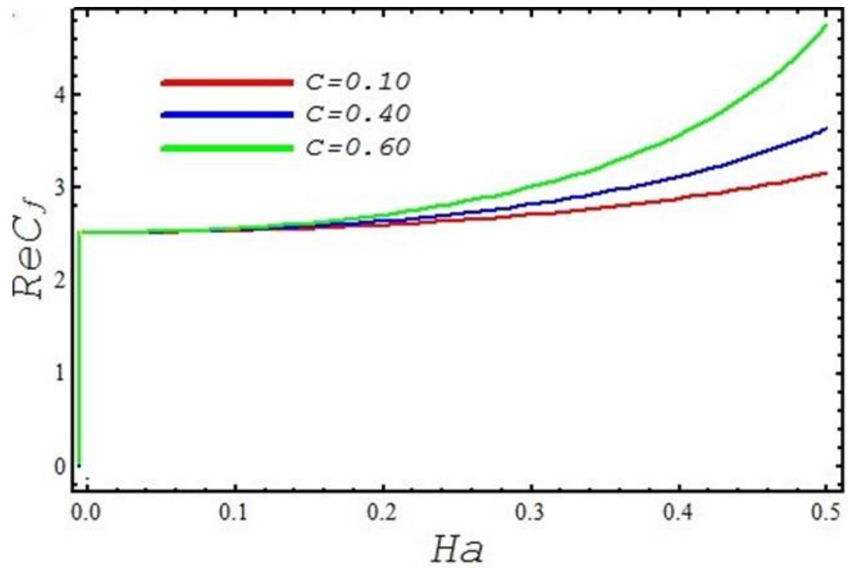

Fig. 11. Skin friction at various values of C, when $\varphi = 0.6, U_{HS} = 1, m = 5$

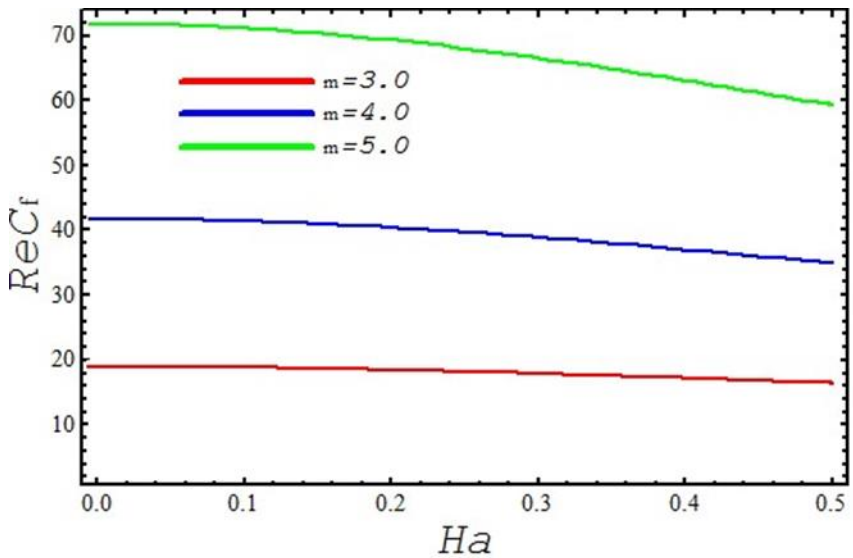

Fig. 12. Skin friction at various values of m, when $\varphi = 0.6, U_{HS} = 1, C = 0.1$

Figure 13 (a)-(d) and Figure 14 (a)-(d) shows the behaviour of streamlines by using the different values of Hartmann number (*Ha*) along with the fixed set of other parameters in the fluid and particulate phase. Closed streamlines circulating bolus of fluid is formed. In Figure 13 (a)-(d) of the fluid phase, the bolus forms in trapped geometry when Hartmann number (*Ha*) is low. It is observed that by increasing the value of Hartmann number (*Ha*) the trapped bolus starts expanding.

It can be seen that in Figure 14 (a)-(d) of the particulate phase, the trapped bolus comes with a small value of Hartmann number (*Ha*) and it starts expanding with increasing value of Hartmann number (*Ha*). The graphs disclose the expansion in trapped bolus for fluid and particulate velocity profile by increasing Hartmann number.

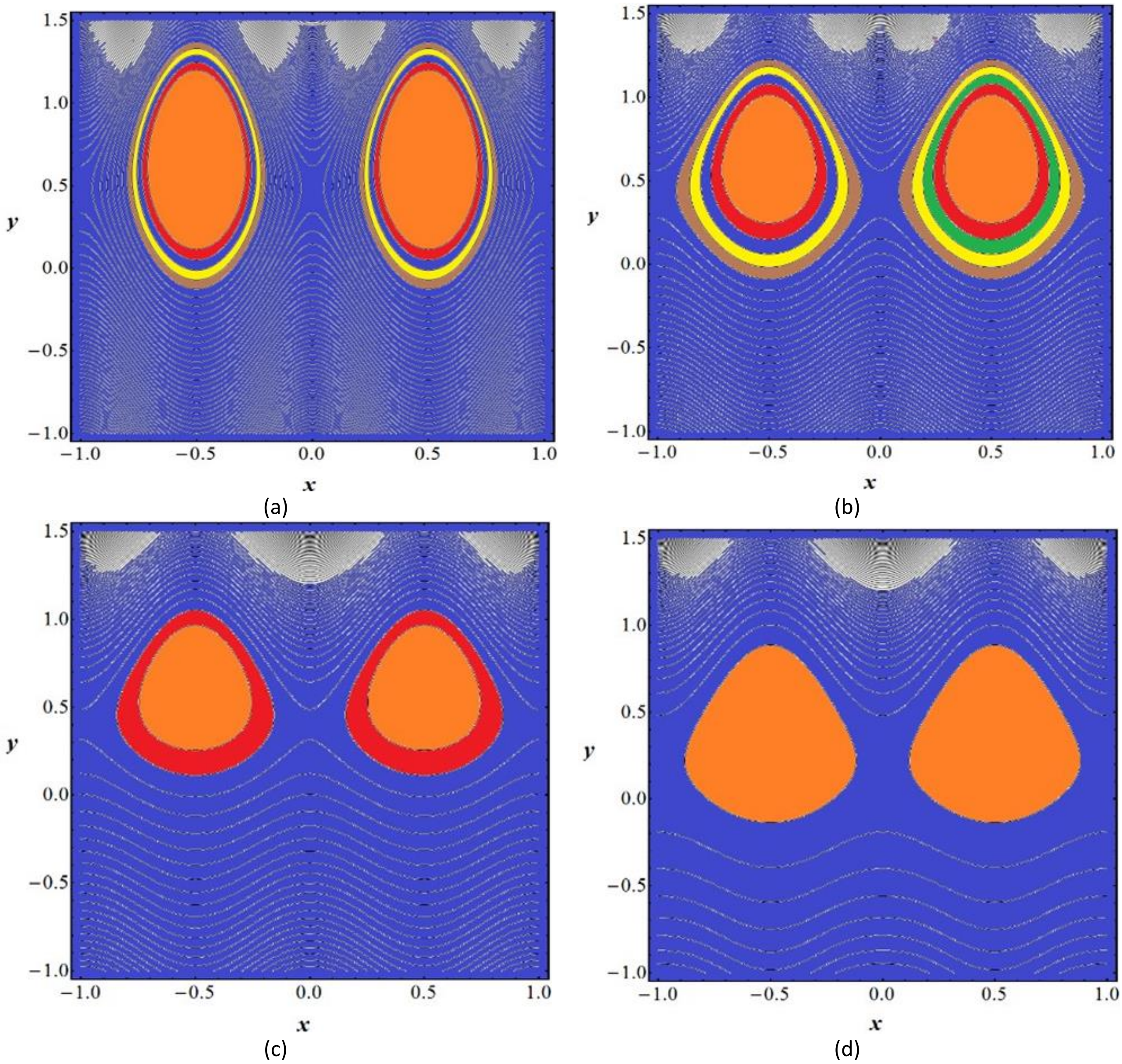

Fig. 13. Stream lines w.r.t u_f at various values of Ha, when $\varphi = 0.6, U_{HS} = 1, m = 5, C = 0.1$

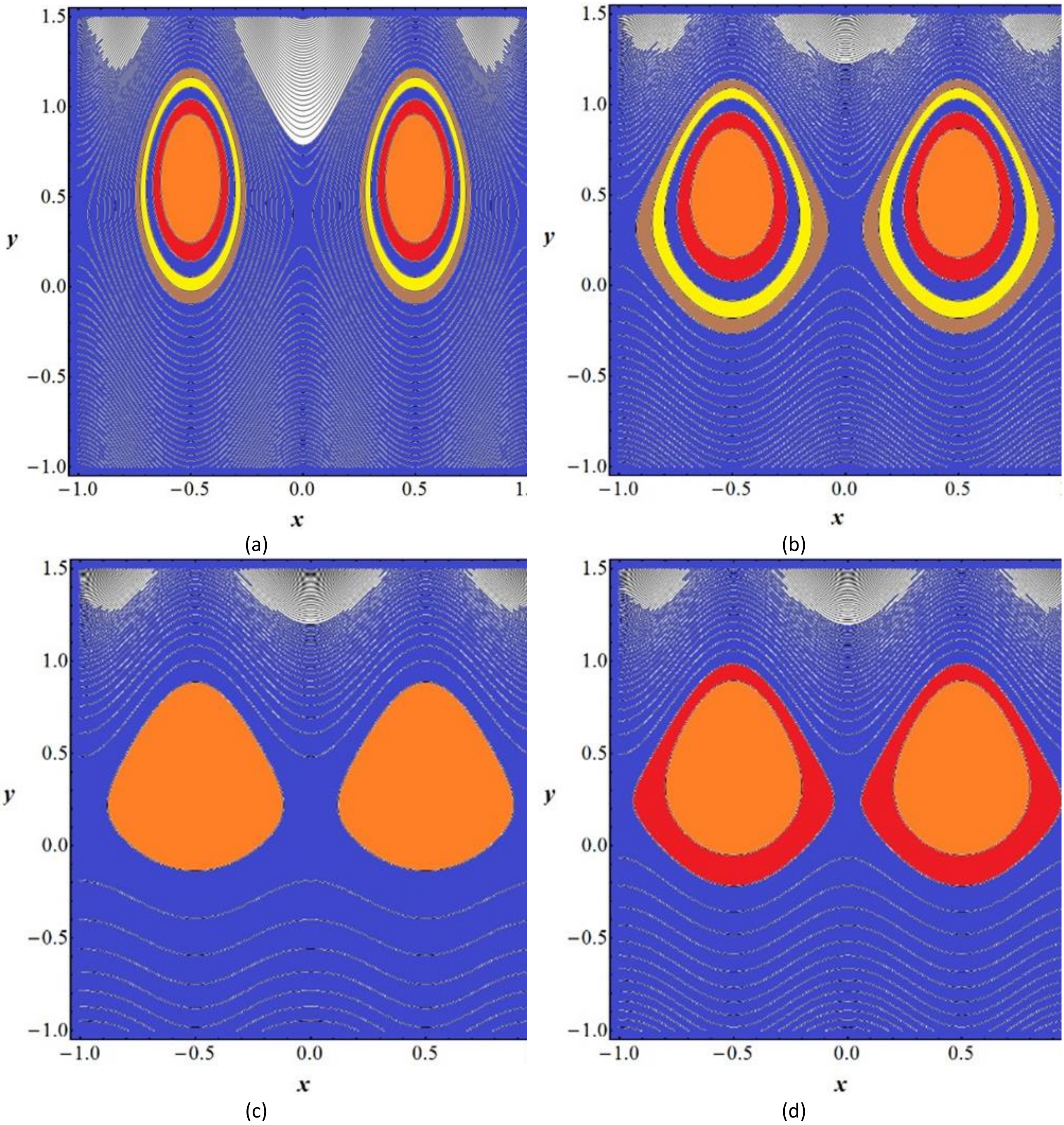

Fig. 14. Streamlines w.r.t u_p at various values of Ha, when $\varphi = 0.6, U_{HS} = 1, m = 5, C = 0.1$

5. Concluding Remarks

Effects of electro magneto-hydro-dynamics (EMHD) peristaltic flow of non-Newtonian incompressible particulate fluid containing identical rigid particles with uniform distribution in a channel of finite length (L) reveals by this study. Navier stokes equations and continuity equations describes the flow. The governing equations of fluid and particulate equations are solved with the assumption of low Reynolds number, long wavelength and considering the fluid to be un-steady, electrically-conducting and incompressible. Perturbation method is employed to extract analytical solution of the resulting ordinary differential equations. The effects of the Hartman number (*Ha*), Particle effect (*C*), and Electro-osmotic parameter (*m*) are scorched. A very significant conclusion that can be made on the basis of this study is that velocity is strongly affected with Joule heating parameter, electroosmotic parameter and thermophoresis parameter. A decline is observed in fluid velocity in contrast with the increase of electro-osmotic parameter (m), Hartmann number and particle effect while the particulate velocity shows the opposite behaviour. The rise in pressure gradient is witnessed by rising values of Hartmann number, particle effect and electro-osmotic parameter (m). The streamline graphs disclose the expansion in trapped bolus for fluid and particulate velocity profile by increasing Hartmann number. A rise in skin friction is noticed with the rise in particle effect and electro-osmotic parameter (m).

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Author Contributions

Sudheer Khan wrote the main manuscript text and performed mathematical modeling. Shu Wang provided guidance in preparing the figures and tables and reviewed the manuscript.

Competing interest

The author(s) declare no competing interests

Data Availability

The data that supports the findings of this study are available within the article

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