

**MHD TWO-PHASE FLOW AND HEAT TRANSFER BETWEEN
TWO PARALLEL POROUS WALLS IN A ROTATING SYSTEM**

Abstract

The equations describing the two-phase magnetohydrodynamic steady flow and heat transfer through a horizontal channel consists of two parallel porous walls subject to the action of uniform magnetic field, applied in the direction normal to the plane of flow/axis of rotation are written down, assuming that the magnetic Reynolds number is small. Also, it is assumed that the fluids in the two regions are incompressible, immiscible and electrically conducting, having different viscosities, thermal and electrical conductivities. Further, assumed that the transport properties of the two fluids are constant having constant bounding wall temperatures. With these assumptions, the resulting governing differential equations are solved analytically, using the prescribed conditions and obtained the exact solutions for the velocity and temperature distributions. Also, their corresponding numerical calculations for various sets of values of the governing parameters involved are obtained to represent them graphically and are discussed. We observe that the effect of increasing suction number is to increase the temperature in both phases. Also, as the suction number increases, there is a significant change in the primary velocity at the upper region but is insignificant in the lower region.

Key words: Two-Phase flows, Magnetohydrodynamics, Heat transfer, Rotating fluids, porous walls.

1. Introduction

The simplest case of multiphase flows is the two-phase flows, which are of great practical concern in a large number of engineering disciplines, including the chemical, petroleum and various power generating industries. For instance, questions concerning nuclear-reactor safety have led to a demand for an understanding of the detailed phase-distribution mechanisms involved in two-phase flows. Also, one of the more interesting and potentially useful phenomena associated with the simultaneous, horizontal pipeline flow of two incompressible fluids is the fact that the pressure gradient and power requirement necessary for the flow of the more viscous phase at a

39 given rate may be substantially reduced by the presence of the less viscous phase. The
40 most common practical example in which this effect is evident is the pipeline flow of
41 petroleum and water. Numerous studies dealing with both the experimental and
42 theoretical aspects of the two-phase classical hydrodynamic problems have been
43 under taken in the past and made available in literature during the several decades by
44 various investigators [1-10]. But, rigorous formulation of the two-phase flow
45 conservation equations, such as mass, momentum and energy has for some time been
46 a challenge, and the inclusion of both electric and magnetic fields into this theory has
47 not been carried out properly. The difficulty in the formulation of conservation
48 equations is associated with the presence of a large number of interfaces and the
49 apparent random nature of the flow field.

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51 But the requirement of modern technology has stimulated interest in
52 magnetohydrodynamic two-phase flow studies more closely, which involve the
53 interaction of several phenomena. As the theoretical and organizing experimental
54 results for predicting design parameters of two-phase flows are becoming
55 increasingly important because of their widespread applications in industry in relation
56 to various energy conversion systems. In particular, the development of conceptual
57 design for fusion reactors and liquid metal magnetohydrodynamic rotating power
58 generators, demands an accurate and reliable knowledge of the heat transfer and
59 thermohydraulic mechanisms of two-phase flow in presence of an applied magnetic
60 field. Transportation and extraction of the products of oil are other obvious
61 applications using a two-phase system to obtain increased flow rates in an
62 electromagnetic pump from the possibility of reducing the power required to pump oil
63 in a pipe line by suitable addition of water (see Shail [11]). Consequently, extensive
64 publications dealing with both the experimental and theoretical aspects of the

65 two-phase flow systems with or without considering the heat transfer problems
66 associated with MHD generators as the generator channels are significantly
67 influenced by the presence of magnetic field have appeared in the literature during the
68 past, studied by various investigators notably, Shercliff [12], Saito et al [13], Dobran
69 [14], Malashetty and Umavathi [15], Chauhan and Rastogi[16, 17].

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71 Besides these studies, Lohrasbi and Sahai [18] have studied the MHD heat
72 transfer aspects in two-phase flow with the fluid in one phase being electrically
73 conducting. Then Malashetty and Leela [19] have carried out a theoretical study on
74 Magnetohydrodynamic heat transfer in two- fluid flow for short circuit case.
75 Subsequently, in 1992 they [20] have analyzed the problem of magnetohydrodynamic
76 heat transfer in two-phase flow by assuming that the fluid in both regions to be
77 electrically conducting for the open circuit case. However, the use of liquid metals as
78 heat transfer agents and as working fluid in a rotating MHD power generator and
79 nuclear reactor technology has created a growing interest in the behaviour of liquid
80 metal flows and in particular the nature of interaction with magnetic and electric
81 fields. Moreover, the interaction with coriolis forces between the conducting and the
82 magnetic field radically modifies the MHD two-phase flow.

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84 On the other hand, numerous studies involving heat transport phenomena from
85 both symmetrical and asymmetrical surfaces under the action of rigid rotation where
86 the electromagnetic and coriolis forces often significantly affect the heat transport
87 rates in case of single-phase flow have been reported in the literature during the last
88 several decades. But, in case of two-phase flow, with the exception of few papers
89 discussed above, this substantial effort has not contributed significantly in the
90 literature either toward the understanding of the physical process involved or toward
91 helping the designer in providing him with design information and criteria of

92 sufficient accuracy, reliability and geometry.

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94 Hence, the purpose of this study is to provide a rigorous mechanistic basis for
95 the theoretical description of MHD two-phase flow driven by a constant pressure
96 gradient and associated heat transfer in a horizontal channel consists of two parallel
97 porous walls under the action of uniform strong magnetic field, applied in the
98 direction normal to the plane of flow subjected to a constant suction applied normal to
99 both walls. With these assumptions and considering that the magnetic Reynolds
100 number is small, the resulting governing linear differential equations are solved
101 analytically, using the prescribed boundary and interface conditions to obtain the
102 exact solutions for velocity and temperature distributions. Also, their corresponding
103 numerical results for various sets of values of the governing parameters are obtained
104 to represent them graphically and are discussed in detail.

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106 The presentation of a two-phase MHD flow model in a rotating frame of
107 reference, with porous boundaries subject to normal suction is timely in view of the
108 recent interest in liquid metal flow in MHD power rotating generators, in proper
109 design of cooling blanket in a magnetically confined plasma fusion reactors/thermo
110 nuclear reactors, also this study would provide guidance for the investigation of
111 boundary layer behaviors along porous walls with fluid injection or suction.

112 **2. Formulation of the problem**

113 A steady magnetohydrodynamic two-phase flow driven by a common constant
114 pressure gradient ($-\partial p/\partial x$) in a horizontal channel ($y = h_1$ and $y = -h_2$) consists of
115 two parallel porous walls, infinite in extent along x- and z-directions subject to the
116 uniform suction v_0 applied normal to both walls(i.e., in the y- direction) is considered.
117 A constant magnetic field of strength B_0 is applied in the y-direction. The whole
118 system is rotated with an angular velocity Ω about an axis perpendicular to their

119 planes i.e., y-axis. Fig. 1, illustrates the physical model and coordinate system. Also,
 120 assumed that, the regions $0 \leq y \leq h_1$ and $-h_2 \leq y \leq 0$ are occupied by two different
 121 immiscible electrically conducting, incompressible fluids having different viscosities,
 122 thermal and electrical conductivities. The interface between the two immiscible fluids
 123 is assumed to be flat, stress free and undisturbed. The boundaries of the channel are
 124 rigid. And the channel width is assumed to be very large in comparison with the
 125 channel height. The two bounding walls are maintained at constant temperature T_w .
 126 Further, it is to be assumed that the magnetic Reynolds number is small, so that the
 127 externally applied magnetic field is undisturbed by the flow, namely, the induced
 128 magnetic field is small when compared with the applied field, hence is negligible.
 129 With these assumptions, the governing equations of motion, energy and the
 130 corresponding boundary and interface conditions can be formulated as follows for the
 131 two-dimensional steady state problem.

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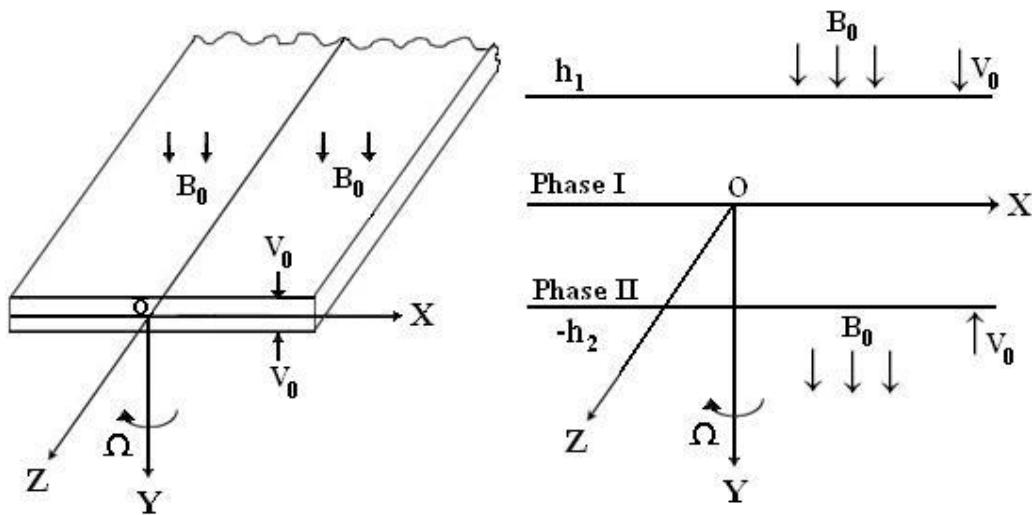


Figure 1. Physical model and coordinate system.

3. Governing equations with boundary and interface conditions and Mathematical analysis of the problem.

With the above assumptions, the governing equations of motion and energy as in Malashetty and Leela [20] and Raju and Murty [21] for both phases in a rotating frame of reference are

$$\mu_i \frac{d^2 u_i}{dy^2} - \frac{dp}{dx} - \sigma_i (B_0^2 u_i + B_0 E_0) = 2\rho\Omega w_i - \rho v_0 \frac{du_i}{dy} \quad (1)$$

$$\mu_i \frac{d^2 w_i}{dy^2} - \sigma_i B_0^2 w_i = -2\rho\Omega u_i - \rho v_0 \frac{dw_i}{dy} \quad (2)$$

$$K_i \frac{d^2 T_i}{dy^2} + K_i \frac{\rho v_0}{\mu_i} \frac{dT_i}{dy} + \mu_i \left[\left(\frac{du_i}{dy} \right)^2 + \left(\frac{dw_i}{dy} \right)^2 \right] + \sigma_i [E_0 + B_0 \mu_i + B_0 w_i]^2 = 0 \quad (3)$$

where T_i is the temperature, u_i and w_i are the primary and secondary velocity components along x and z directions respectively. The no slip condition requires that the velocity must vanish at the wall. In addition the fluid velocity, shear stress, temperature and heat flux must be continuous across the interface.

The boundary and interface conditions are

$$u_1(h_1) = 0, w_1(h_1) = 0, u_2(-h_2) = 0, w_2(-h_2) = 0, u_1(0) = u_2(0), w_1(0) = w_2(0). \quad (4)$$

$$\mu_1 \frac{du_1}{dy} = \mu_2 \frac{du_2}{dy} \text{ at } y=0, \quad \mu_1 \frac{dw_1}{dy} = \mu_2 \frac{dw_2}{dy} \text{ at } y=0. \quad (5)$$

$$T_1(h_1) = T_w, T_2(-h_2) = T_w, T_1(0) = T_2(0), K_1 \frac{dT_1}{dy} = K_2 \frac{dT_2}{dy} \text{ at } y=0. \quad (6)$$

In making these equations dimensionless, the following transformations are used:

$$u_i^* = u_i / \bar{u}_1, w_i^* = w_i / \bar{u}_1, y_i^* = y_i / h_i, \theta_i = K_1 (T_i - T_w) / (\bar{u}_1^2 \mu_1), \alpha = \mu_1 / \mu_2, \beta = K_1 / K_2$$

$$h = \frac{h_2}{h_1}, \sigma = \frac{\sigma_2}{\sigma_1}, P = \frac{h_1^2}{(u_1 \mu_1)} \left[-\frac{dp}{dx} \right], M = B_0 h_1 \sqrt{\frac{\sigma_1}{\mu_1}}, K = h_i \sqrt{\frac{\Omega}{\nu}}, R_e = \frac{E_0}{B_0 u_1}, \lambda = \frac{h_i v_0}{\nu}.$$

164 With the above non dimensional quantities, the governing equations (1), (2) and (3)

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167 Phase-I

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$$169 \quad \frac{d^2 u_1}{dy^2} + P - M^2 (R_e + u_1) = 2K^2 w_1 - \lambda \frac{du_1}{dy}. \quad (7)$$

$$170 \quad \frac{d^2 w_1}{dy^2} - M^2 w_1 = -2K^2 u_1 - \lambda \frac{dw_1}{dy}. \quad (8)$$

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$$172 \quad \frac{d^2 \theta_1}{dy^2} + \lambda \frac{d\theta_1}{dy} + \left(\frac{du_1}{dy} \right)^2 + \left(\frac{dw_1}{dy} \right)^2 + M^2 (R_e + u_1 + w_1)^2 = 0. \quad (9)$$

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174 Phase-II

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$$176 \quad \frac{d^2 u_2}{dy^2} + Ph^2 \alpha - \alpha \sigma h^2 M^2 (R_e + u_2) = 2K^2 w_2 - \lambda \frac{du_2}{dy}. \quad (10)$$

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$$178 \quad \frac{d^2 w_2}{dy^2} - \alpha \sigma h^2 M^2 w_2 = -2K^2 u_2 - \lambda \frac{dw_2}{dy}. \quad (11)$$

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$$180 \quad \frac{d^2 \theta_2}{dy^2} + \lambda \frac{d\theta_2}{dy} + \frac{\beta}{\alpha} \left[\left(\frac{du_2}{dy} \right)^2 + \left(\frac{dw_2}{dy} \right)^2 \right] + \beta \sigma h^2 M^2 (R_e + u_2 + w_2)^2 = 0. \quad (12)$$

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182 Boundary and interface conditions are

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$$184 \quad u_1(+1) = 0, w_1(+1) = 0, u_2(-1) = 0, w_2(-1) = 0, \quad (13)$$

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$$186 \quad u_1(0) = u_2(0), w_1(0) = w_2(0), \quad (14)$$

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$$188 \quad \frac{du_1}{dy} = \frac{1}{\alpha h} \frac{du_2}{dy}, \frac{dw_1}{dy} = \frac{1}{\alpha h} \frac{dw_2}{dy} \quad \text{at } y = 0, \quad (15)$$

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$$190 \quad \theta_1(+1) = 0, \theta_2(-1) = 0, \theta_1(0) = \theta_2(0), \frac{d\theta_1}{dy} = \frac{1}{\beta h} \frac{d\theta_2}{dy} \quad \text{at } y = 0. \quad (16)$$

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4. Solutions of the problem

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The governing equations of momentum and the energy are to be solved analytically subject to the boundary and interface conditions for the velocity and temperature distributions. Hence the exact solutions of the governing differential equations (7), (8) and (10), (11) using the boundary and interface conditions (13) to (15) for the primary and secondary velocities u_1 , u_2 and w_1 , w_2 respectively in the two regions are obtained as:

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$$u_1 = \frac{1}{2} \left((C_{12} \cosh C_1 y + C_{13} \sinh C_1 y + C_{17} \cosh C_{16} y + C_{18} \sinh C_{16} y) e^{\frac{-\lambda y}{2}} + A_2 + A_{10} \right), \quad (17)$$

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$$w_1 = A_{50} \left((C_{12} \cosh C_1 y + C_{13} \sinh C_1 y - C_{17} \cosh C_{16} y - C_{18} \sinh C_{16} y) e^{\frac{-\lambda y}{2}} + A_2 - A_{10} \right), \quad (18)$$

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$$u_2 = \frac{1}{2} \left((C_{14} \cosh C_2 y + C_{15} \sinh C_2 y + C_{20} \cosh C_{19} y + C_{21} \sinh C_{19} y) e^{\frac{-\lambda y}{2}} + A_4 + A_{16} \right), \quad (19)$$

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$$w_2 = A_{50} \left((C_{14} \cosh C_2 y + C_{15} \sinh C_2 y - C_{20} \cosh C_{19} y - C_{21} \sinh C_{19} y) e^{\frac{-\lambda y}{2}} + A_4 - A_{16} \right). \quad (20)$$

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Further, to solve the non-dimensional energy equations (9) and (12) for temperature distributions, we use the solutions (17) to (20), as already obtained above for u_1 , u_2 , w_1 and w_2 along with the boundary and interface conditions (16). So the solutions for the temperature distributions θ_1 and θ_2 in two regions are obtained as

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$$\begin{aligned} \theta_1 = & D_{39} e^{D_{25} y} + D_{40} e^{-D_{26} y} + D_{41} e^{D_{27} y} + D_{42} e^{-D_{28} y} + D_{43} e^{D_{29} y} + D_{44} e^{-D_{30} y} \\ & + D_{45} e^{D_{31} y} + D_{46} e^{-D_{32} y} + D_{47} e^{D_{34} y} + D_{48} e^{-D_{35} y} + D_{49} e^{D_{36} y} \\ & + D_{50} e^{-D_{37} y} + D_{33} e^{-\lambda y} + D_{38} y^2 + F_{51} y + F_{52}, \end{aligned} \quad (21)$$

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$$\begin{aligned} \theta_2 = & F_{32} e^{F_{11} y} + F_{33} e^{F_{22} y} + F_{34} e^{2F_{11} y} + F_{35} e^{2F_{22} y} + F_{36} e^{F_{55} y} + F_{37} e^{F_{66} y} \\ & + F_{38} e^{2F_{55} y} + F_{39} e^{2F_{66} y} + F_{40} e^{F_{99} y} + F_{41} e^{F_{1010} y} + F_{42} e^{F_{1111} y} \\ & + F_{43} e^{F_{1212} y} + F_{44} e^{F_{1313} y} + F_{45} e^{F_{1414} y} - \frac{F_{23}}{2} y^2 + F_{53} y + F_{54}. \end{aligned} \quad (22)$$

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The constants appearing in equations (17) to (22) are not given for the sake of brevity. The numerical computations of the velocity and temperature distributions in both the

regions are performed for different sets of values of governing parameters involved in the study and these results are presented graphically. While computing the results, the value of P is fixed at 2.

5. Results and discussion

The problem of magnetohydrodynamic two-phase flow and heat transfer in a horizontal channel consisting of two parallel porous walls in a rotating system, assuming that the magnetic Reynolds number is small is investigated analytically. The resulting differential equations are solved analytically to obtain exact solutions for the primary and secondary velocity distributions, such as u_1 , u_2 and w_1 , w_2 respectively in the two regions. Consequently, closed form solutions for temperature distributions, namely, θ_1 and θ_2 in both the regions are determined by making use of the, already obtained solutions of velocity distributions. The graphs for the velocity and temperature distributions are shown in figures 2-13.

The effect of suction number λ is shown in figures 2, 3 and 10. We found that, as λ increases u_1 decreases everywhere except near the center of the channel. While, u_2 first decreases and then increases near the channel center line, but it increases below the channel center line as λ increases. Also it is observed that, as λ increases, w_2 increases but w_1 increases except at the upper wall. The effect of λ is felt more on u_2 and w_2 . From fig. 10, it is noticed that θ_1 and θ_2 increase for increasing values of λ . The effect of varying the electrical conductivity ratio σ is represented in figures 4, 5 and 11. It is observed that, as σ increases, u_1 , u_2 and w_1 , w_2 also increase. But as σ increases, θ decreases. It is noticed that, the effect of this ratio is more pronounced on temperature compared to the velocity. From figures 6 and 7, it is found that, the effect of increasing M is to increase u_1 and to decrease w_1 , where as to increase both u_2 and w_2 . From fig. 12, it is observed that, as M increases (up to 8), θ_1 and θ_2 also increase, but if M increases further (>8), θ_2 decreases and θ_1 increases.

252 The effect of α is shown in figures 8, 9 and 13. The effect of α is felt more on
253 u_2 and w_2 . As α increase u_1 , u_2 and w_1 , w_2 also increase. For small values of α , the
254 fluid in the lower region is more viscous compared to the upper region and this
255 increased shear stress in lower region retorted the flow in this region and this effect is
256 carried over to the upper region through the interface conditions. From fig. 13, it is
257 found that, the effect of increasing α is to decrease θ_1 and θ_2 . For small α , it is
258 observed that, the temperature in the two regions increase with decreasing values of α ,
259 this is because, more heat is added to the fluid due to viscous heating.

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6. Conclusions

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Hence, we conclude that, as the suction number increases, there is a significant
264 change in the primary velocity at the upper region but is insignificant in the lower
265 region. While as this number increases, the primary velocity first increases up to the
266 middle, there after decreases but the secondary velocity increases. Also, as suction
267 number increases, there is an increase of temperature in the two regions. Also, it is
268 found that, the effect of viscosity ratio of the two fluids in the two regions is more
269 pronounced on temperature when compared to the velocities. As the electrical
270 conductivity ratio increases, both the primary and secondary velocities in the two
271 regions also increase but temperature decreases. The effect of increasing Hartmann
272 number is to increase the primary velocity and to decrease the secondary velocity in
273 the upper region where as to increase both velocities in the lower region. With full
274 understanding of the process involved in this study bearing this simple geometry, it is
275 hoped that, more understanding can be gained of similar phenomena in complex
276 geometries, so that correlations can eventually be regarded by analytical models and
277 experimental studies.

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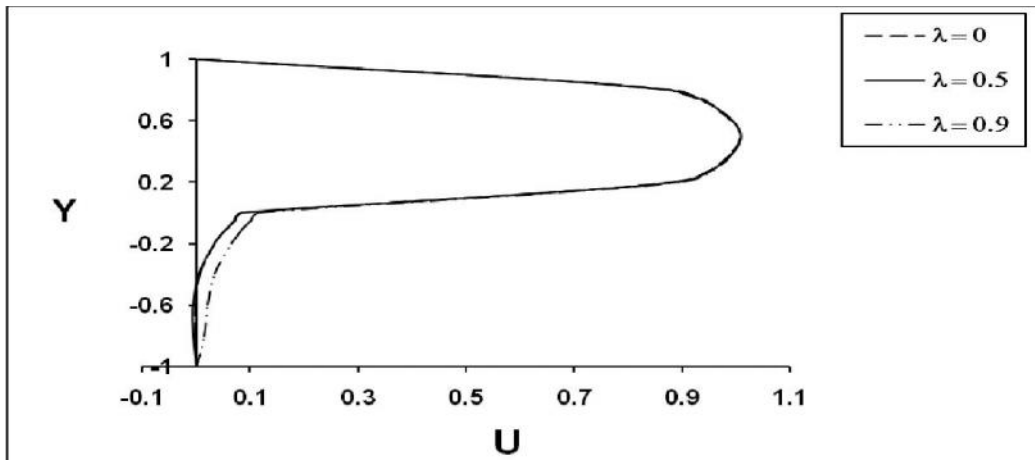


Fig. 2 Primary velocity profiles for different λ , $K=2$, $\alpha=0.333$, $\beta=1$, $\sigma=0.2$, $h=0.1$, $M=10$, $Re=-1$, $P=2$

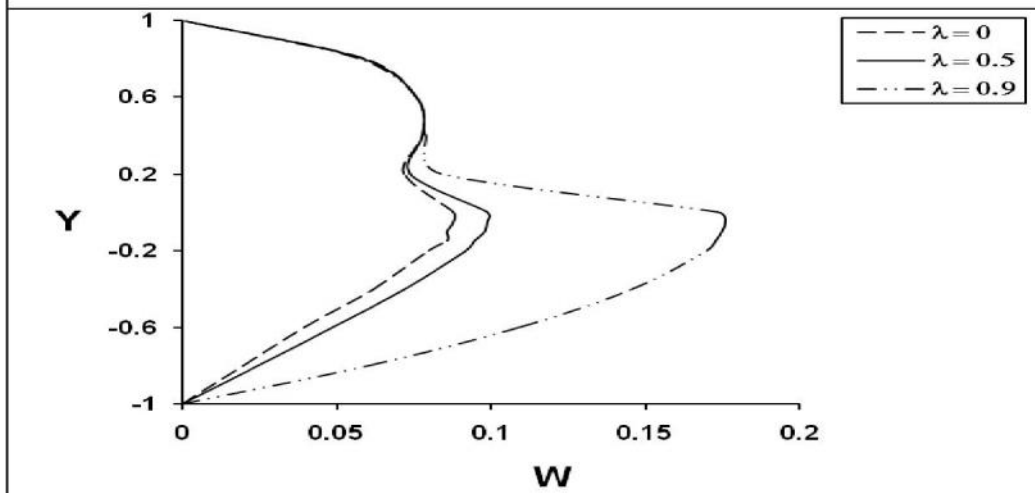


Fig.3 Secondary velocity profiles for different λ , $K=2$, $\alpha=0.333$, $\beta=1$, $\sigma=0.2$, $h=0.1$, $M=10$, $Re=-1$, $P=2$

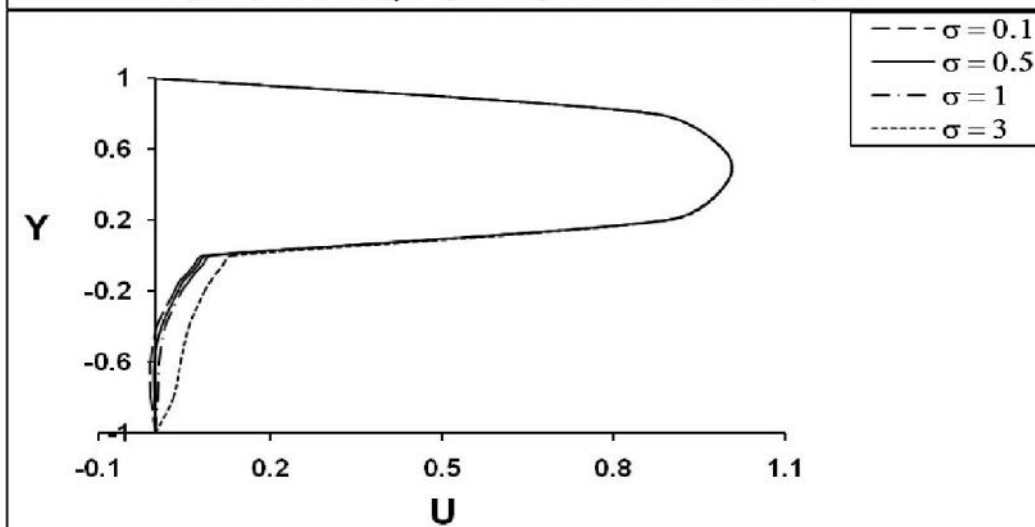


Fig. 4 Primary velocity profiles for different σ , $\lambda=0.5$, $K=2$, $\alpha=0.333$, $\beta=1$, $h=0.1$, $M=10$, $Re=-1$, $P=2$

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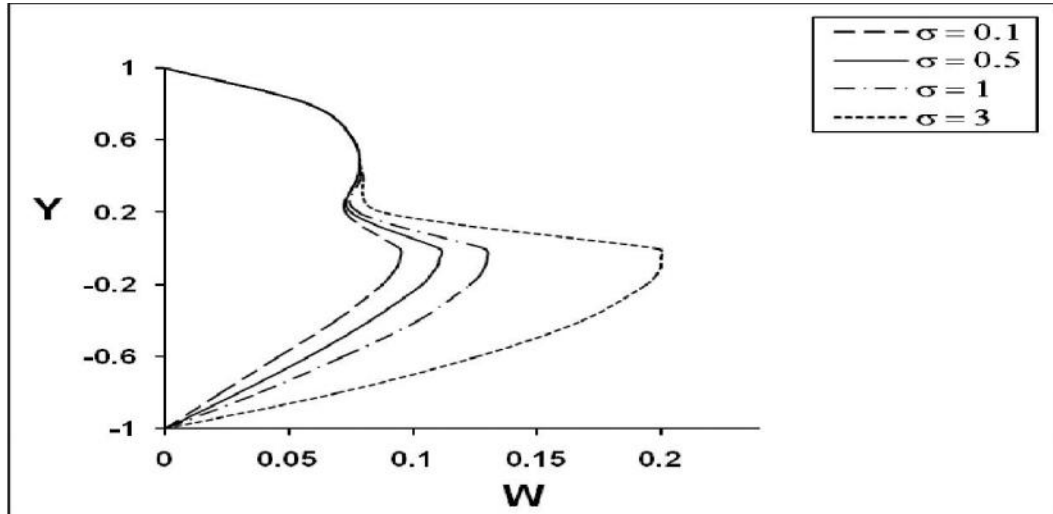


Fig. 5 Secondary velocity profiles for different $\sigma, \lambda=0.5, K=2, \alpha=0.333, \beta=1, h=0.1, M=10, Re=-1, P=2$

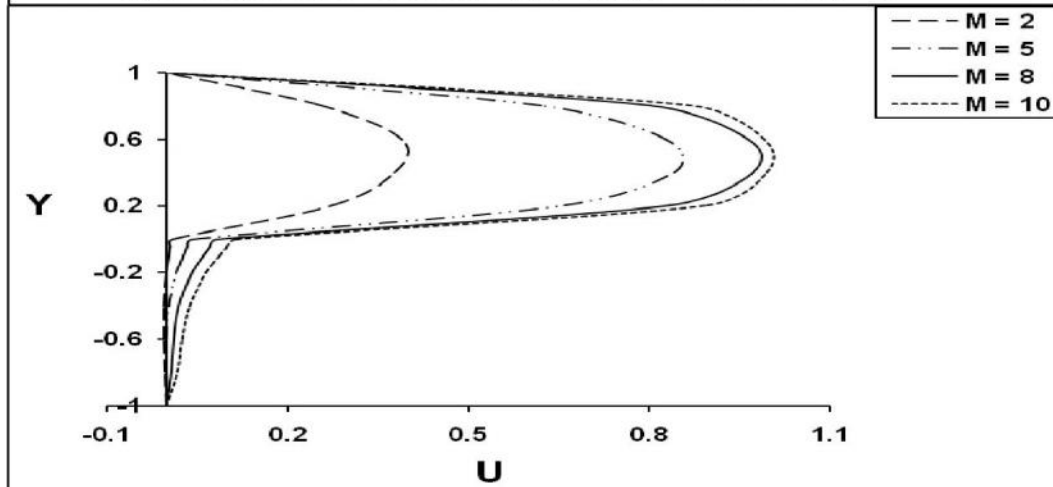


Fig. 6 Primary velocity profiles for different $M, \lambda=0.5, K=2, \alpha=0.333, \beta=1, \sigma=2, h=0.1, Re=-1, P=2$

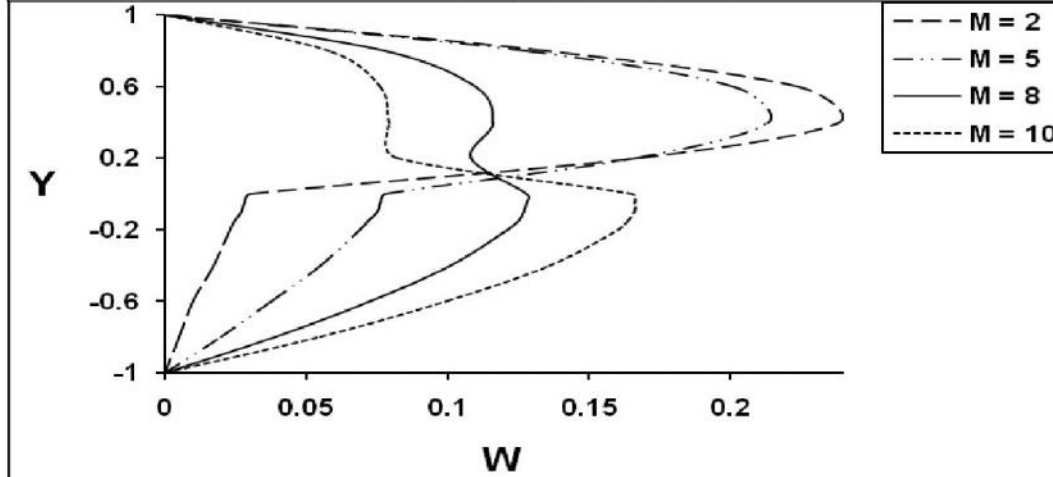


Fig. 7 Secondary velocity profiles for different $M, \lambda=0.5, K=2, \alpha=0.333, \beta=1, \sigma=2, h=0.1, Re=-1, P=2$

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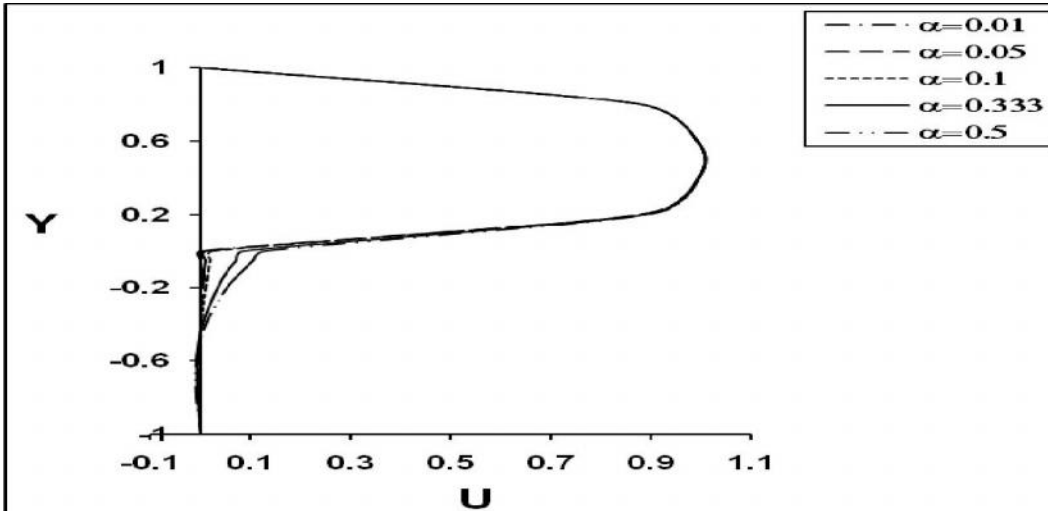


Fig. 8 Primary velocity profiles for different $\alpha, \lambda=0.5, K=2, \beta=1, \sigma=0.2, h=0.1, M=10, Re=-1, P=2$

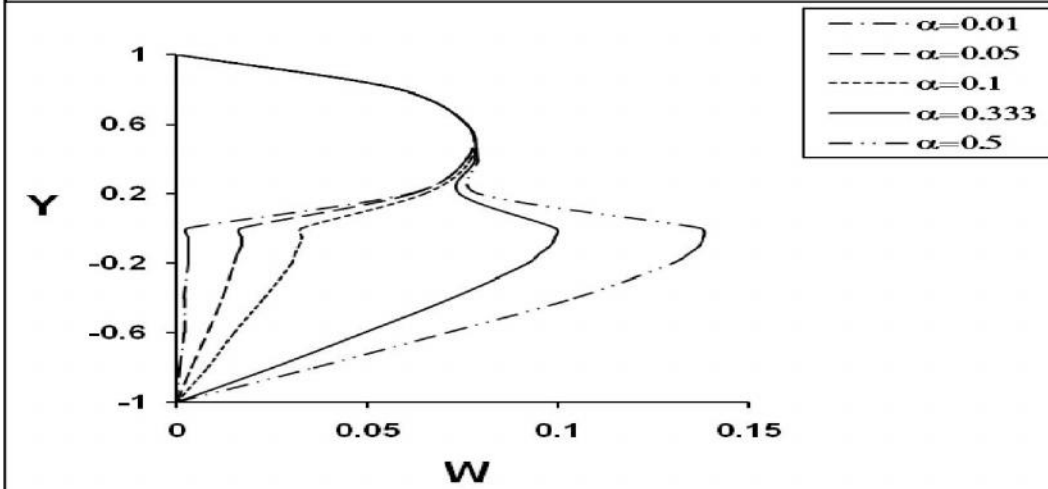


Fig. 9 Secondary velocity profiles for different $\alpha, \lambda=0.5, K=2, \beta=1, \sigma=0.2, h=0.1, M=10, Re=-1, P=2$

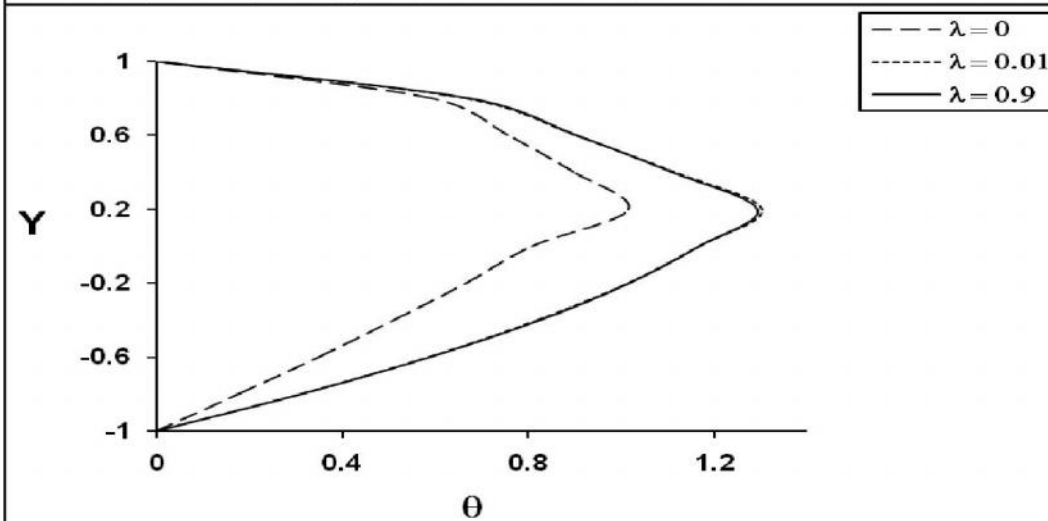


Fig. 10 Temperature profiles for different $\lambda, K=2, \alpha=0.333, \beta=1, \sigma=0.2, h=0.1, M=10, Re=-1, P=2$

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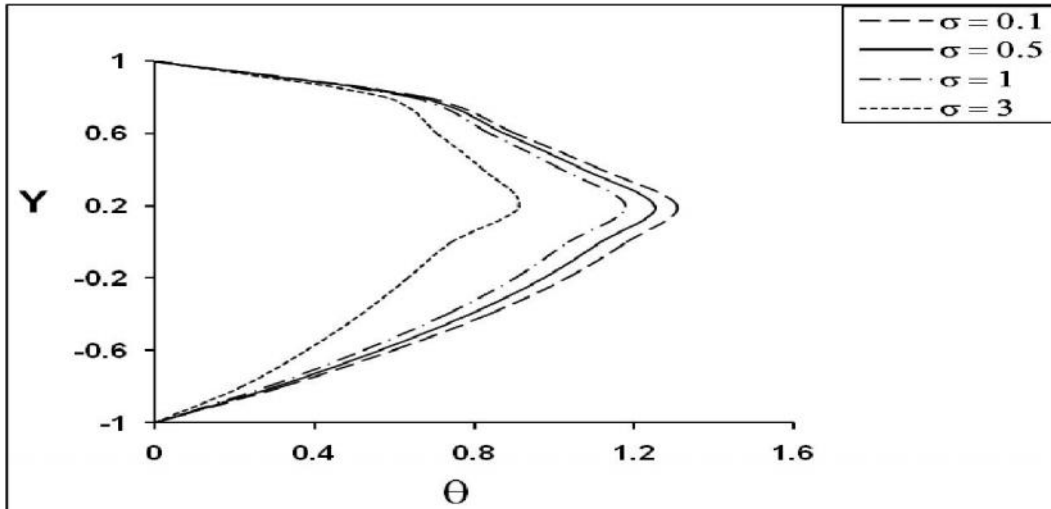


Fig. 11 Temperature profiles for different $\sigma, \lambda=0.5, K=2, \alpha=0.333, \beta=1, h=0.1, M=10, Re=-1, P=2$

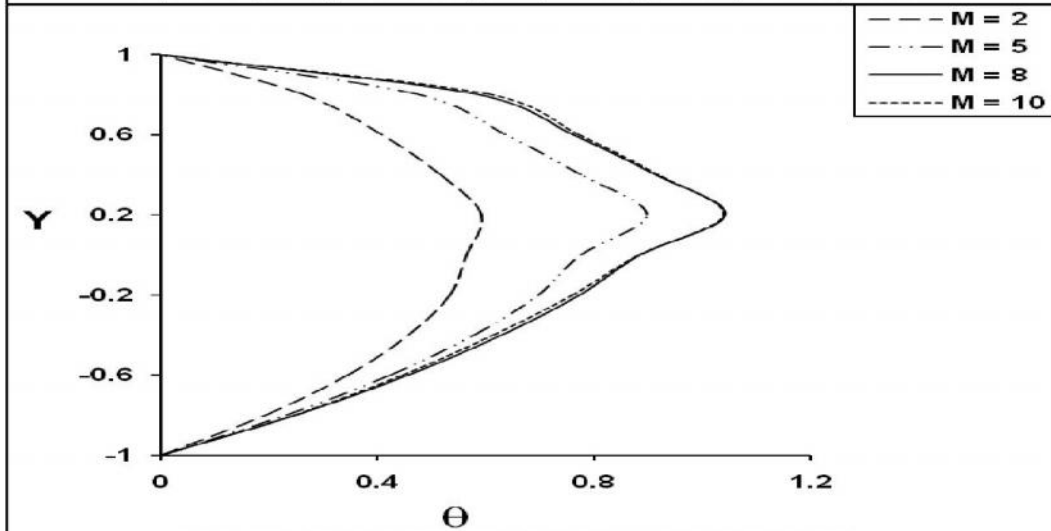


Fig. 12 Temperature profiles for different $M, \lambda=0.5, K=2, \alpha=0.333, \beta=1, \sigma=2, h=0.1, Re=-1, P=2$

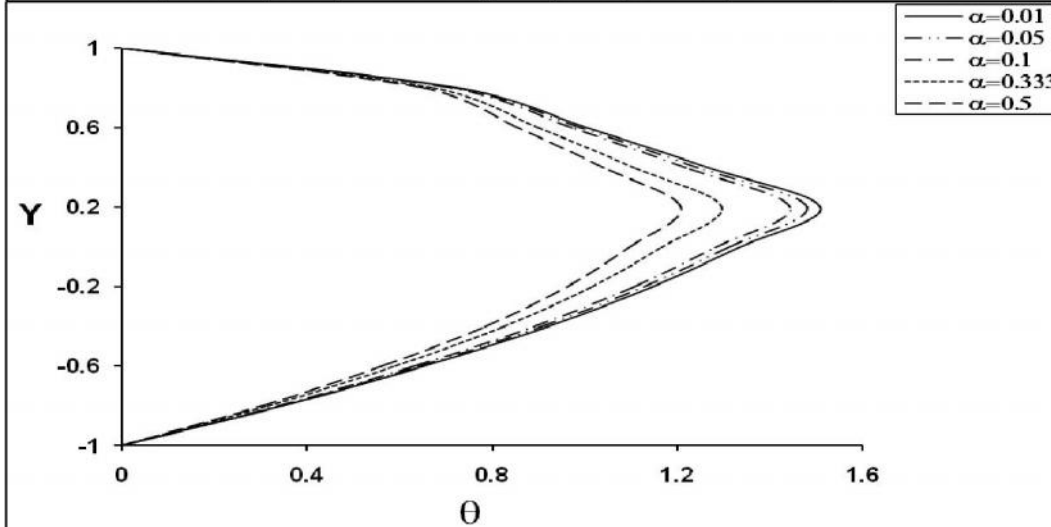


Fig. 13 Temperature profiles for different $\alpha, \lambda=0.5, K=2, \beta=1, \sigma=0.2, h=0.1, M=10, Re=-1, P=2$