A NUMERICAL STUDY ON DEVELOPED LAMINAR MIXED CONVECTION WITH VERTICAL CHANNEL IN DOWNFLOW

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Abstract:

In this paper, a numerical study on developed laminar mixed convection in vertical channel is considered. The flow problem is described by means of partial differential equations and the solutions are obtained by an implicit finite difference technique coupled with a marching procedure. The velocity, the temperature and the pressure profiles are obtained and their behaviour is discussed computationally for different values of governing parameters like buoyancy parameter Gr/Re, the wall temperature difference ratio r_T and Prandtl number Pr. The analysis of the obtained results showed that the flow is significantly influenced by these governing parameters.

Keywords: Buoyancy Parameter, Vertical Channel, Mixed Convection.

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1 INTRODUCTION:

Understanding the flow development is essential in the analysis of the flow of heat as well as the development of temperature and other heat transfer parameters. The research related to flow and heat transfer through parallel plate channels has been well cited by Inagaki and Komori [12]. The literature pertinent to mixed convection in vertical channels between vertical parallel plates is reviewed hereunder and is divided according to the flow status (i.e., fully developed or developing).

For laminar flow, in the fully developed region, i.e., in the region far from the channel entrance, the fluid velocity does not undergo appreciable changes in the stream-wise direction. Under these conditions, mixed convection between vertical parallel plates has been of interest in research for many years. Early work includes studies by Cebeci et al. [6] and by Aung and Worku [2]. The work by these investigators has shown that mixed convection between parallel plates exhibits both similarities and contrasts with flow in a vertical tube.

Using dimensionless parameters, Aung and Worku [2] solved the problem of mixed convection between parallel plates and obtained closed form analytical solution. Recently, Boulama and Galanis [5] presented exact solutions for fully developed, steady state laminar mixed convection between parallel plates with heat and mass transfer under the thermal boundary conditions of (uniform wall temperature) UWT and (uniform heat flux) UHF. The results revealed that buoyancy effects significantly improve heat and momentum transfer rates near heated walls of the channel. They [5] also analyzed the conditions for flow reversal.

To analyze the behaviour of the flow with opposing buoyancy forces, Hamadah and Wirtz [9] studied the laminar mixed convection under three different thermal boundary conditions. Yao [18] studied mixed convection in a channel with symmetric uniform temperature and symmetric uniform flux heating. He presented no quantitative information; he conjectured that fully developed flow might consist of periodic reversed flow. Quantitative information on the temperature and velocity fields has been provided in a numerical study reported by Aung and Worku [1]. These authors noted that buoyancy effects dramatically increase the hydrodynamic development distance. With asymmetric heating, the bulk temperature is a function of Gr/Re and r_T, and decreases as r_T is reduced. Buoyancy effects are noticeable through a large segment of the channel, but not near the channel entrance or far downstream from it.

Wirtz and Mckinley [16] conducted laboratory experiments on downward mixed convection between parallel plates where one plate heated the fluid (i.e., buoyancy-opposed flow situation). Ingham et al. [13] presented a numerical investigation for the steady laminar combined convection flows in vertical parallel plate ducts with asymmetric constant wall temperature boundary conditions. Reversed flow has been recorded in the vicinity of the cold wall for some combinations of the ratio (Gr/Re) and the difference in the temperature between the walls. Zouhair Ait Hammou [20], studied laminar mixed convection of humid air in a vertical channel with evaporation or condensation at the wall. The results showed that the effect of buoyancy forces on the latent Nusselt number is small. However the axial velocity, the friction factor, the sensible Nusselt number and the Sherwood number are significantly influenced by buoyancy forces.

Chamkha [7] studied the laminar hydromagnetic mixed convection flow in a vertical channel with symmetric and asymmetric wall heating conditions. Yan et al. [17] were studied simultaneous heat and mass transfer in laminar mixed convection flow between vertical parallel plates with asymmetric heating. Yih Nen Jeng et al. [19] were studied on the Reynolds- number independence of mixed convection in a vertical channel subjected to asymmetric wall temperatures with and without flow reversal. Evans and Greif [8] were studied buoyant instabilities in downward flow in asymmetrically heated vertical channel.

Barletta [3] studied laminar and fully developed mixed convection in a vertical rectangular duct with one or more isothermal walls. The analysis refers to thermal boundary conditions such that atleast one of the four duct wall is kept isothermal. Huang et al. [11] were studied experimentally the mixed convection flow and heat transfer in a vertical convergent channel. The effect of thermal and mass buoyancy forces on fully developed laminar forced convection in a vertical channel has been studied analytically by Salah El-din [15]. Markus Nickolay and Holger Martin [14] were studied improved approximation for the Nusselt number for hydrodynamically developed laminar flow between parallel plates.

The in-depth literature cited above has revealed that, in spite of the huge amount of knowledge accumulated over the last few decades into the subject of laminar mixed convection in vertical channels, the mixed convection in such geometry is still not fully understood, especially the hydrodynamics of it. For instance, the term "aiding flow" is generally used in the literature as synonym for "up-flow in a heated vertical channel or down-flow for a cooled vertical channel" and vice versa for the term "opposing flow". The general findings in the literature are that buoyancy effects enhance the pressure drop in buoyancy-aided flow (upward flow in a vertical heated channel), i.e., there is a monotonic pressure decrease of pressure in the axial direction of upward flow in a vertical heated channel. However, Han [10] proved that in aiding flow situations the pressure build up in the axial direction of the vertical channel. In these two articles it was shown that above certain values of the buoyancy parameter (Gr/Re), the vertical channel can act as a diffuser. However, flow reversal was shown for higher buoyancy effect, which was also pointed out by Han [10] who showed that for more buoyancy effects, the aiding flow is converted to opposed flow. Based on these findings, Han [10] introduced a more precise definition for the terms aiding and opposing flows such that the term aiding flow is used when the external pressure forces and the buoyancy forces works together in the same direction and vice versa for opposing flow.

2. NOMENCLATURE:

b	Distance between the parallel plates
C_p	Specific heat of the fluid
g	Gravitational body force per unit mass (acceleration)
Gr	Grashoff number, $g\beta\,(T_1 - T_0)\, b^3 / \upsilon^2$
k	Thermal conductivity of fluid
p	Local pressure at any cross section of the vertical channel
p_0	Hydrostatic pressure
P	Dimensionless pressure inside the channel at any cross section, $(p - p_0) / \rho\, u_0^2$

Pr	Prandtl Number, $\mu C_p / k$
Re	Reynolds number, $(b u_0)/\upsilon$
r_T	Wall temperature difference ratio, $\frac{T_2 - T_0}{T_1 - T_0}$
T	Dimensional temperature at any point in the channel
T_0	Ambient of fluid inlet temperature
T_w	Isothermal temperatures of circular heated wall
T_1, T_2	Isothermal temperatures of plate 1 and plate 2 of parallel plates
u	Axial velocity component
$\bar{u}$	Average axial velocity
u_0	Uniform entrance axial velocity
U	Dimensionless axial velocity at any point, u / u_0
v	Transverse velocity component
V	Dimensionless transverse velocity, v / u_0
x	Axial coordinate (measured from the channel entrance)
X	Dimensionless axial coordinate in Cartesian, $x / (b\ Re)$
y	Transverse coordinate of the vertical channel between parallel plates
Y	Dimensionless transverse coordinate, y / b
θ	Dimensionless temperature
ρ	Density of the fluid
ρ_0	Density of the fluid at the channel entrance
μ	Dynamic viscosity of the fluid
υ	Kinematic viscosity of the fluid, μ/ρ
β	Volumetric coefficient of thermal expansion

3. FORMULATION OF THE PROBLEM:

We consider the laminar steady flow in a vertical channel. Both channel walls are assumed to be isothermal, one with temperature T_1 and the other with temperature T_2. The system under consideration as well as the choice of the coordinate axes is illustrated in Figure 1. The distance between the plates is 'b' i.e., the channel width. The Cartesian coordinate system is chosen such that the x-axis is in the vertical direction that is parallel to the flow direction and the gravitational force 'g' always acting downwards independent of flow direction. The y-axis is orthogonal to the channel walls, and the origin of the axes is such that the positions of the channel walls are y = 0 and y = b. The classic boundary approximation is invoked to model the buoyancy effect.

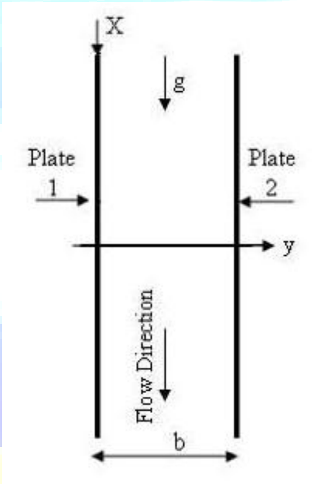

Figure 1: Schematic view of the system and coordinate axes corresponding to down-flow

The governing equations for the steady viscous flow with the following assumptions are made:

(i) The flow is steady, viscous, incompressible and developed.

(ii) The flow is assumed to be two-dimensional steady, and the fluid properties are constant except for the variation of density in the buoyancy term of the momentum equation.

(iii) Energy dissipation is neglected.

After applying the above assumptions the boundary layer equations appropriate for this problem are

Continuity Equation

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{1}$$

X momentum Equation

$$U\frac{\partial U}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{dP}{dX}-\frac{Gr}{\mathrm{Re}}\theta+\frac{\partial^2 U}{\partial Y^2} \tag{2}$$

Energy Equation

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{1}{\mathrm{Pr}}\frac{\partial^2 \theta}{\partial Y^2} \tag{3}$$

The form of continuity equation can be written in integral form as

$$\int_0^1 U\,dY=1 \tag{4}$$

The boundary conditions are

Entrance conditions

At X = 0, 0≤ Y≤ 1 : U = 1, V = 0, θ = 0, P = 0 (5a)

No slip conditions

At X > 0, Y = 0 : U = 0, V = 0

At X > 0, Y = 1 : U = 0, V = 0 (5b)

Thermal boundary conditions

At X > 0, Y = 0 : θ = 1

At X > 0, Y = 1 : $\theta = r_T$ (5c)

In the above, dimensionless parameter have been defined as :

$U = u / u_0$, $V = vb / \upsilon$, $X = x / (b\,\mathrm{Re})$, $Y = y / b$

$P = (p - p_0)/\rho u_0^{\,2}$, $Pr = \mu C_p / k$, $Re = (b\, u_0)/\upsilon$ (6)

$Gr = g\beta\,(T_1 - T_0)\, b^3 / \upsilon^2$, $\theta = (T - T_0)/(T_1 - T_0)$

The systems of non-linear equations (1) to (3) are solved by a numerical method based on finite difference approximations. An implicit finite difference technique is employed whereby the differential equations are transformed into a set of simultaneous linear algebraic equations.

4 NUMERICAL SOLUTION:

The solution of the governing equations for developing flow is discussed in this section. Considering the finite difference grid net work of figure. 2, equations (2) and (3) are replaced by the following difference equations which were also used in [4].

$$U(i,j)\frac{U(i+1,j)-U(i,j)}{\Delta X}+V(i,j)\frac{U(i+1,j+1)-U(i+1,j-1)}{2\Delta Y}$$

$$=\frac{U(i+1,j+1)-2U(i+1,j)+U(i+1,j-1)}{(\Delta Y)^2}-\frac{P(i+1)-P(i)}{\Delta X}-\frac{Gr}{\mathrm{Re}}\theta(i+1,j) \quad (7)$$

$$U(i,j)\frac{\theta(i+1,j)-\theta(i,j)}{\Delta X}+V(i,j)\frac{\theta(i+1,j+1)-\theta(i+1,j-1)}{2\Delta Y}$$

$$=\frac{1}{\mathrm{Pr}}\frac{\theta(i+1,j+1)-2\theta(i+1,j)+\theta(i+1,j-1)}{(\Delta Y)^2} \quad (8)$$

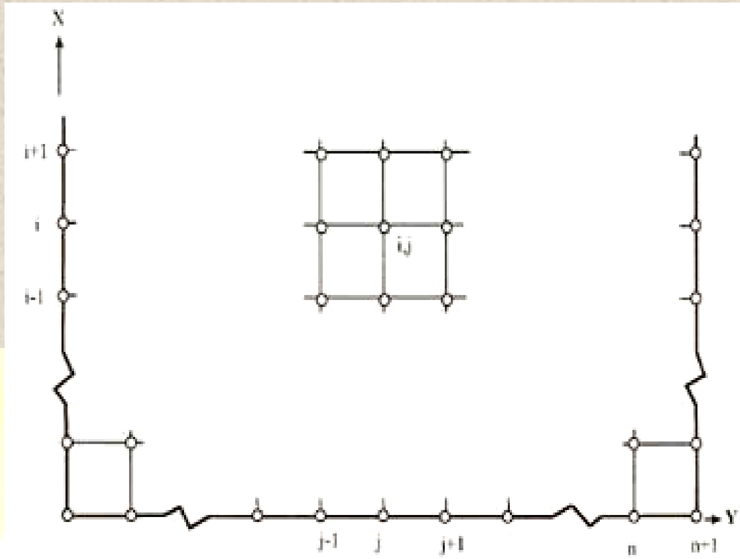

Figure 2: Mesh Network for Difference Representations

Numerical representation of the Integral Continuity Equation

The integral continuity equation can be represented by the employing a trapezoidal rule of numerical integration and is as follows:

$$\left[\sum_{j=1}^{n} U(i+1,j) + 0.5\left(U(i+1,0) + U(i+1,n+1)\right)\right]\Delta Y = 1$$

However, from the no slip boundary conditions

U(i+1, 0) = U(i+1, n+1) = 0

Therefore, the integral equation reduces to:

$$\left[\sum_{j=1}^{n} U(i+1,j)\right]\Delta Y = 1 \qquad (9)$$

A set of finite-difference equations written about each mesh point in a column for the equation (7) as shown:

$$\beta_1 U(i+1,1) + \gamma_1 U(i+1,2) + \xi P(i+1) - \frac{Gr}{\mathrm{Re}}\theta(i+1,1) = \phi_1$$

$$\alpha_2 U(+1,1)+\beta_2 U(+1,2)+\gamma_2 U(+1,3)+\xi P(+1)-\frac{Gr}{\mathrm{Re}}\theta(+1,2)=\phi_2$$

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$$\alpha_n U(+1,n-1)+\beta_n U(+1,n)+\xi P(+1)-\frac{Gr}{\mathrm{Re}}\theta(+1,n)=\phi_n$$

where

$$\alpha_k=\frac{1}{(\Delta Y)^2}+\frac{V(i,j)}{2\Delta Y},\qquad \beta_k=-\left[\frac{2}{(\Delta Y)^2}+\frac{U(i,j)}{\Delta X}\right]$$

$$\gamma_k=\frac{1}{(\Delta Y)^2}-\frac{V(i,j)}{2\Delta Y},\qquad \xi=\frac{-1}{\Delta X},\qquad \phi_k=-\left[\frac{P(i)+U^2(i,j)}{\Delta X}\right]$$

for k = 1,2… n

A set of finite-difference equations written about each mesh point in a column for the equation (8) as shown:

$$\bar{\beta}_1\theta(i+1,1)+\bar{\gamma}_1\theta(i+1,2)+--------------=\bar{\phi}_1-\bar{\alpha}_1,$$

$$\bar{\alpha}_2\theta(i+1,1)+\bar{\beta}_2\theta(i+1,2)+\bar{\gamma}_2\theta(i+1,3)+------------=\bar{\phi}_2$$

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$$\bar{\alpha}_n\theta(i+1,n-1)+\bar{\beta}_n\theta(i+1,n)=\bar{\phi}_n-r_T\bar{\gamma}_n$$

where

$$\bar{\alpha}_k=\frac{1}{\mathrm{Pr}(\Delta Y)^2}+\frac{V(i,j)}{2\Delta Y},\quad \bar{\beta}_k=-\left[\frac{2}{\mathrm{Pr}(\Delta Y)^2}+\frac{U(i,j)}{\Delta X}\right]$$

$$\bar{\gamma}_k=\frac{1}{\mathrm{Pr}(\Delta Y)^2}-\frac{V(i,j)}{2\Delta Y},\qquad \bar{\phi}_k=-\frac{U(i,j)\theta(i,j)}{\Delta X}$$

for k = 1,2… n

Equation (1) can be written as

$$V(+1,j)=V(+1,j-1)-\frac{\Delta Y}{2\Delta x}\left(U(+1,j)+U(+1,j-1)-U(j)-U(j-1)\right)\quad j=1,2,.....n \tag{10}$$

The numerical solution of the equations is obtained by first selecting the parameters that are involved such as Gr/Re, Pr and r_T. Then by means of a marching procedure the variables U, V, θ and P for each row beginning at row (i+1) = 2 are obtained using the values at the previous row 'i'. Thus, by applying equations (7), (8) and (9) to the points 1, 2, ..., n on row i, 2n+1 algebraic equations with the 2n+1 unknowns U(i+1,1), U(i+1,2), …….., U(i+1,n), P(i+1), θ(i+1,1), θ(i+1,2), ... ,θ(i+1, n) are obtained. This system of equations is then solved by Gauss – Jordan elimination method. Equations (10) are then used to calculate V(i+1,1), V(i+1,2), ..., V(i+1,n).

5 RESULTS AND DISCUSSION:

The numerical solution of the equations is obtained by first selecting the parameters that are involved such as Gr/Re, Pr and r_T. For fixed Pr = 0.7 and different values of Gr/Re and r_T, the velocity profiles are shown in figures 3(a) to 4(c) and the temperature profiles are shown in figures 5(a) to 6(c).

The developing axial velocity profiles from the channel entrance up to the fully developed region are shown in figures 4(a) and 4(c) for buoyancy-aided flow with the buoyancy parameter Gr/Re = -100. Figure 4(c) depicts the development of the velocity profiles along the channel with r_T =1 (i.e., for symmetrically heated channel, the two walls are isothermally heated at the same elevated temperature). Figure 3(a), fluid decelerates near the two walls of the channel (due to the formation of the two boundary layers on the walls) and accelerates in the core region as a result of the continuity principle. However, further downstream, heating one of the walls, cases represented by Figure 3(a) , or heating of the two walls symmetrically, the case represented by figure 3(c), shifts the location of the velocity profile peaks towards the heated wall. This represents a clear distortion of the velocity profiles due to the buoyancy effects, which deviate the velocity profiles from its parabolic shape. However, the peaks for symmetric heating cases, represented in figure 3(c) are shifted again towards the middle of the gap reflecting that the flow is approaching full development.

The velocity profile will suffer a permanent distortion and will never restore its fully developed parabolic velocity profile due to the flow reversal occurrence. In such situations, the flow reversal takes place at the cold wall to compensate for the high flow velocities generated near the heated walls as result of the high buoyancy forces resulted from the high heating rates at the heated wall and thus satisfying the continuity principle. On the other hand, for a symmetrically heated channel, figure 4(c), flow reversal will never take place at either wall and the highly distorted velocity profile will develop and eventually achieve its fully developed parabolic velocity profile.

It is clear that the flow reversal will take place for asymmetrically heated channels with high values of the buoyancy parameter Gr/Re. Values of the buoyancy parameter Gr/Re that represents heating rates that are enough to create severe flow reversal at the cooler wall in asymmetrically heated channels usually results in a flow instability and consequentially numerical instability

Temperature profiles developments are shown in figures 5 to 6. Figure 6(a) for symmetric heating with r_T =0 and Gr/Re =-100 and in figure 6(c) for symmetric heating with r_T =1 and Gr/Re =-100. These two figures show how the temperature profiles are developing approaching their invariant analytical fully developed profiles. For the asymmetric heating conditions the temperature from the entrance till approach its linear profile at the fully developed region where the fluid flows in laminated layers and all the heat transferred from the heated wall goes to the cold wall through the fluid laminated layers by pure conduction. Higher temperature near the heated wall result in buoyancy aiding effect for upward flow while the cooling effects of the cold wall results in opposite buoyancy effects and for large asymmetrical heating conditions flow reversal might take place at the cold wall. Figure 6(c) shows the development of the temperature profiles that have its maximum at the two symmetrically heated walls and the minimum at the core of the channel.

This type of developing temperature profiles is consistent with the pertinent developing velocity profiles that have two peaks near the two heated walls and minimum velocities near the core of the channel where that heat did not penetrate yet. These profiles show clearly how is heat takes time (distance) until it penetrates the fluid layers reaching to the core at large enough distances from the channel entrance till it reaches fully developed region where all the fluid layers will attain the same temperature of a dimensionless value of 1.

Figures 7(a) to 7(c) depict the development of the pressure (P), to the entrance reason of vertical channels. It is observed that for buoyancy opposed flow is to create and develop more negative pressure in the flow direction which is evidently for the cases of $Gr/Re \leq 0$. It is worth mentioning here that large values of the opposing buoyancy parameters lead to flow reversal and consequentially it leads faster to flow instability.

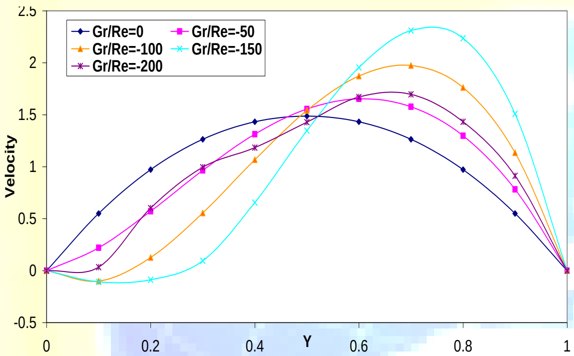

Fig. 3(a): Velocity profile for fixed r_T=0 and X=0.04

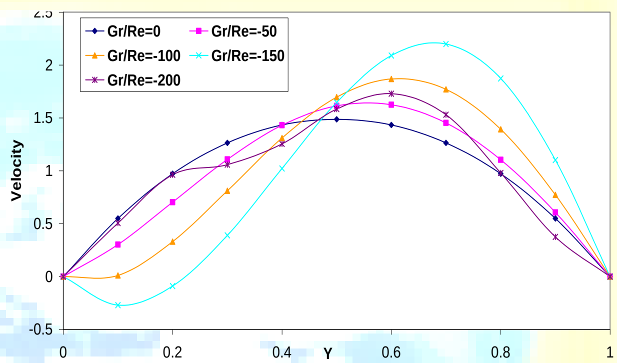

Fig. 3(b): Velocity profile for fixed r_T=0.5 and X=0.04

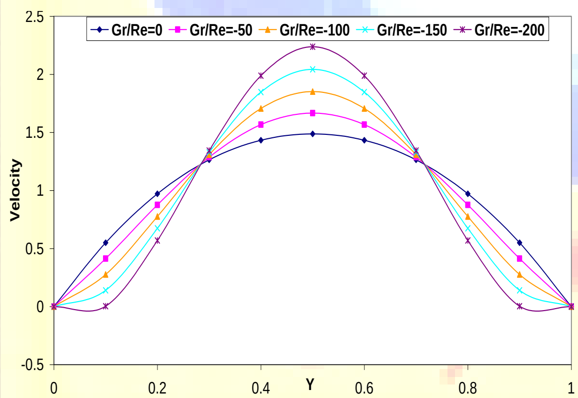

Fig. 3(c): Velocity profile for fixed r_T=1.0 and X=0.04

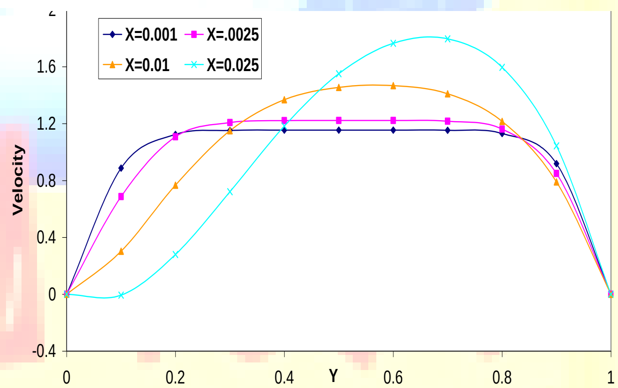

Fig. 4(a): Velocity profile for fixed r_T=0 and Gr/Re= - 100

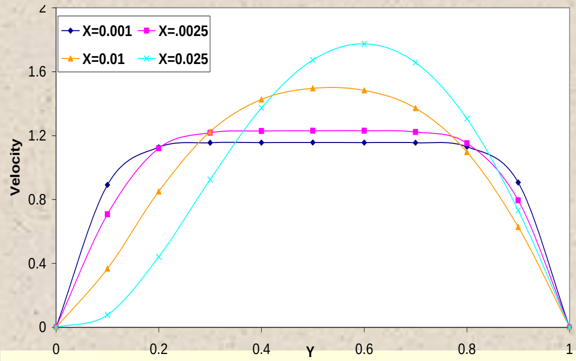

Fig. 4(b): Velocity profile for fixed r_T=0.5 and Gr/Re= - 100

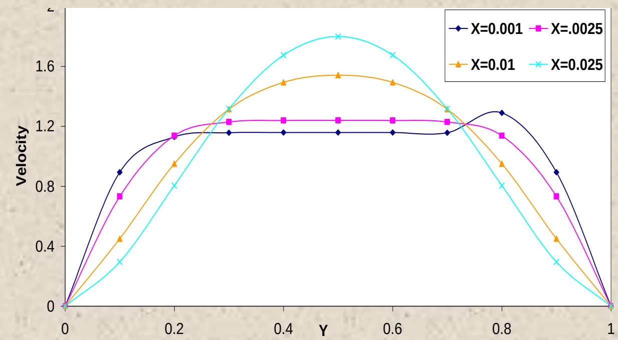

Fig. 4(c): Velocity profile for fixed r_T=1.0 and Gr/Re= - 100

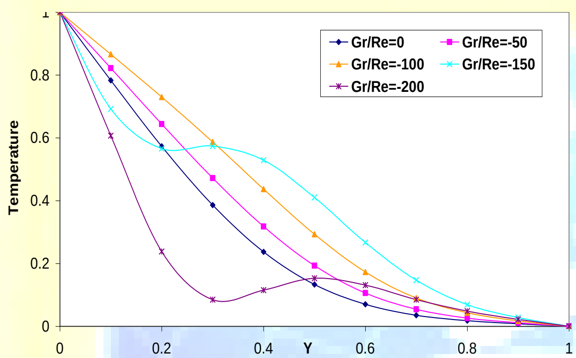

Fig. 5(a): Temperature profile for fixed r_T=0 and X=0.04

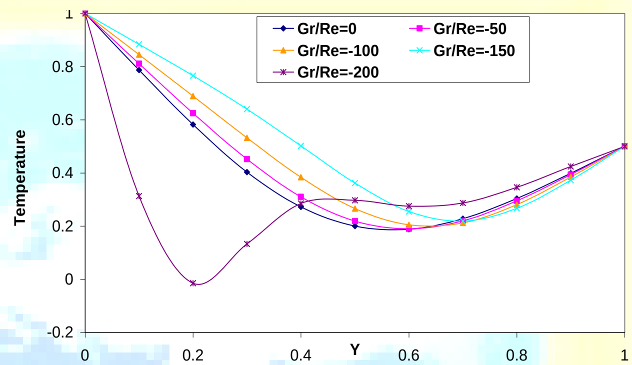

Fig. 5(b): Temperature profile for fixed r_T=0.5 and X=0.04

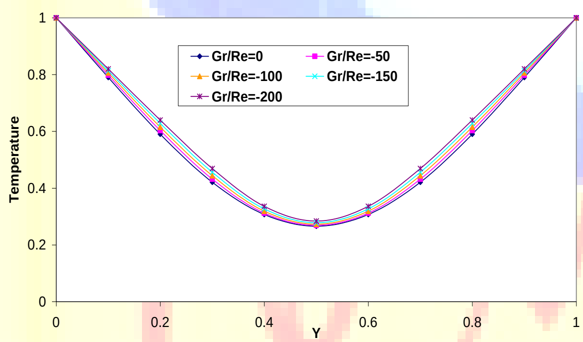

Fig. 5(c):Temperature profile for fixed r_T=1.0 and X=0.04

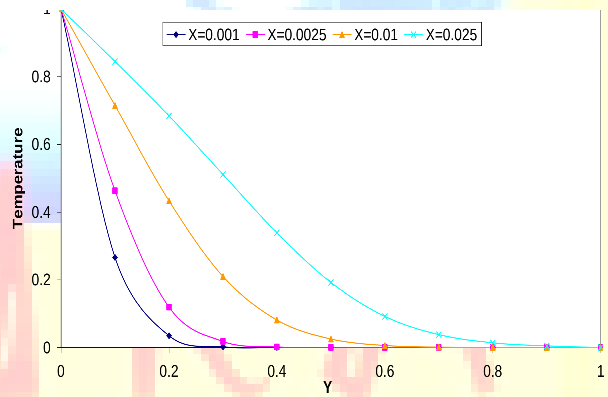

Fig. 6(a):Temperature profile for fixed r_T=0 and Gr/Re=-100

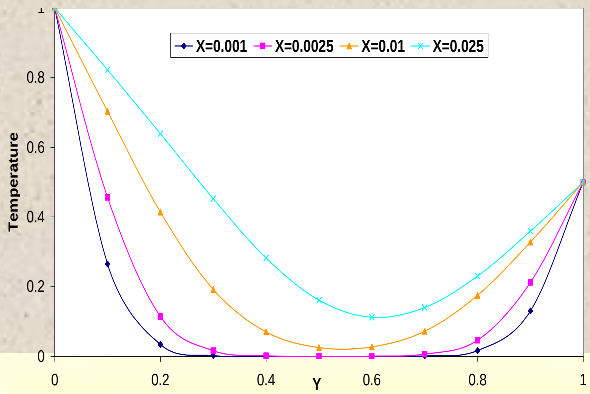

Fig. 6(b):Temperature profile for fixed r_T=0.5 and Gr/Re=-100

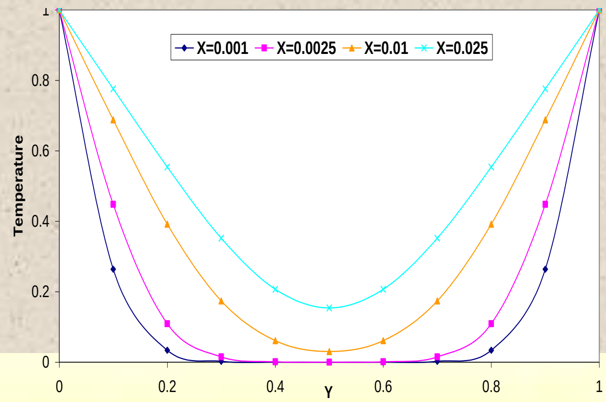

Fig. 6(c): Temperature profile for fixed r_T=1.0 and Gr/Re=-100

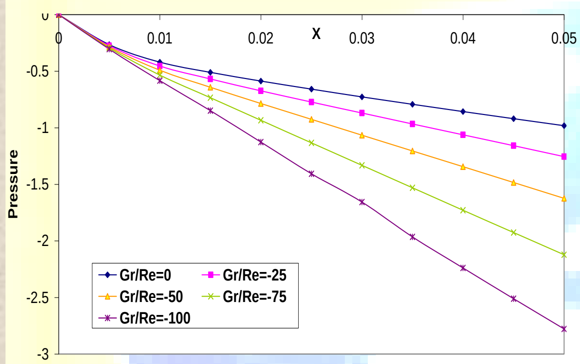

Fig. 7(a): Pressure profiel for fixed r_T = 0

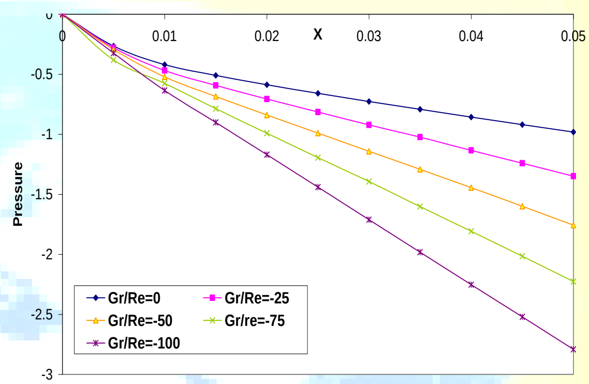

Fig. 7(b): Pressure profile for fixed r_T=0.5

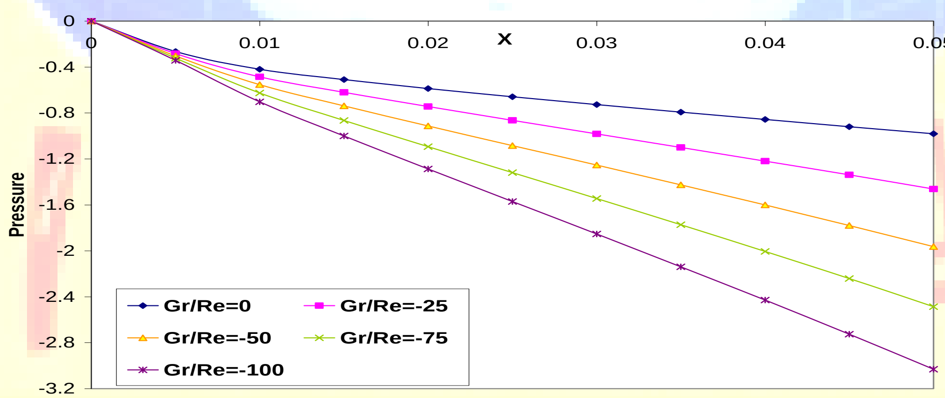

Fig. 7(c): Pressure profile for fixed r_T=1.0

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