Flow Characteristic Study in a Configuration of Sudden Expansion with Central Restriction

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Abstract : In this paper, a numerical study on the performance of sudden expansion with central restriction has been carried out. The two dimensional steady differential equations for conservation of mass and momentum are solved for Reynolds number(Re) from 50 to 200 and aspect ratio(AR) from 1.5 to 6 for 0% to 40% central restriction(CR) and fully developed velocity profile at inlet. The effect of each variable on velocity profile has been studied in detail. From the study, it is observed that the region of negative axial velocity at corner zone increases with increase in percentage of central restrictions for a particular value of Reynolds number and aspect ratio. At the main flow region, velocity profiles are flattened downstream to the throat section. This flattenness increases with the increase in percentage of central restrictions. At central region, velocity profiles are also flattened but this is somewhat less compared to the main flow region. Flattenness of main flow region increases with increase in Reynolds number and aspect ratio. It is noted that the magnitude of decreased flattenness in the central region remains more or less same with increase in aspect ratio for fixed value of Reynolds number and central restriction.

***IndexTerms* - central restriction, sudden expansion, velocity profile, aspect ratio.**

I. INTRODUCTION

The performance of the sudden expansion configuration may be improved by modifying its geometry. If a central restriction is placed at the inlet zone (upto throat) of plain sudden expansion, the modified configuration may be thought as annular flow sudden expansion geometry. This annular flow in a sudden expansion may be characterized by two reversed flow regions; the corner recirculation zone and the central recirculation zone. Both recirculation zones result from flow separation due to the abrupt changes of the boundary geometry introduced by the sudden expansion step and the centre body. These recirculation zones may have a significant influence on the mixing as well as combustion process. In this research activity, we have become interested to study the flow characteristics of fluid passing through a sudden expansion configuration with some modification viewed as a mixing chamber. The modification of the said configuration is considered by incorporating some central restriction in the inlet zone.

From literature, it appears that the first work in the field of plain sudden expansion configuration was carried out by Macagno and Hung [1]. They have numerically and experimentally studied the flow visualization in sudden expansion with axisymmetric configurations. They have observed that at Reynolds number of 36, clear cellular eddies are formed behind the sudden expansion and these are symmetric in nature. Durst et al. [2] have experimentally reported flow visualization and laser-anemometry measurements in the flow downstream of a plane symmetric sudden expansion configuration in a duct with an aspect ratio of 9.2:1. They have noted that at the lower Reynolds numbers (Re = 56), the flow is very stable and the separation region behind each step are of equal length. So and Ahmed [3] have numerically investigated the characteristics of dump combustor flows. They have examined the effects of inlet geometry, step height, inlet turbulence and rotation on the flow fields inside the dump combustor. Fu et al. [4] have numerically investigated a transient natural convection in an annular enclosure. They have considered a square enclosure and an annular enclosure, the height and the length of the annular enclosure are equivalent. They have concluded that due to the dominance of heat conduction, the difference of the distributions of the isothermal lines and stream lines in the annular and square enclosures is not remarkable. Sheen et al. [5] have experimentally investigated the flow characteristics in a modified sudden expansion configuration. They have used both flow visualization and laser Doppler anemometry techniques. They have observed four different flow patterns depending upon the value of the Reynolds number. Haidekker et al. [6] have performed a two dimensional numerical simulation of the onset phase of flow through sudden expansion configuration. They have computed wall shear stress action as a function of time and distance from the sudden expansion. Nie and Armaly [7] have presented numerical simulations of three-dimensional laminar forced convection in a plane symmetric sudden expansion in rectangular duct. They have considered expansion ratio of 2 and an upstream aspect ratio of 4. They have used Reynolds number of 50, 100, and 150. Forliti and Strykowski [8] have experimentally studied the control of the isothermal turbulent flow with in a rearward facing step combustor using countercurrent shear. They have seen that counter flow has an effect of augmenting the natural reverse flow, caused by the sudden expansion of the step. Lima et al [9] have numerically studied the flow characteristics of two-dimensional laminar air flow over a backward facing step channel. They have used the Reynolds number (Re_D, Reynolds number based on hydraulic diameter) ranging from 100 to 2500 for an expansion ratio of 1.9423. Tihon et al. [10] have experimentally studied the effect of inlet pulsations on the backward facing flow. They have considered transient flow regime where the Reynolds number based on step height is ranging from 30 to 1800. They have considered rectangular channel geometry with an expansion ratio of 2. Fattah [11] has experimentally and numerically studied fluid flow and heat transfer characteristics in the case of wall injection besides main flow through a circular sudden enlargement. In his configuration, injected flow is achieved through an annular slot of the vertical side wall.

As per brief review of literature, it is noted that a number of researchers have studied the flow through sudden expansion geometry or plain annular configuration geometry separately. However, it is realized that a systematic study on the sudden expansion configurations with central restriction is inadequate. Therefore it has provoked authors to study systematically the effect of Reynolds number and aspect ratio on velocity profile of fluid passing through a sudden expansion with central restriction configuration.

II. MATHEMATICAL FORMULATION

2.1 Governing equations

A schematic diagram of the computational domain for flow through sudden expansion with central restriction is illustrated in Fig.1. The flow under consideration is assumed to be steady, two-dimensional and laminar. The fluid is considered to be Newtonian and incompressible. The following dimensionless variables are defined to obtain the governing conservation equations in the non-dimensional form;

Lengths: $x^* = x/W_1$, $y^* = y/W_1$, $W^* = W/W_1$, $L_i^* = L_i/W_1$, $L_{ex}^* = L_{ex}/W_1$, $L_R^* = L_R/W_1$, $L_f^* = L_f/W_1$

Velocities: $u^* = u/U$, $v^* = v/U$.

Pressure: $p^* = (p + \rho g y)/\rho U^2$.

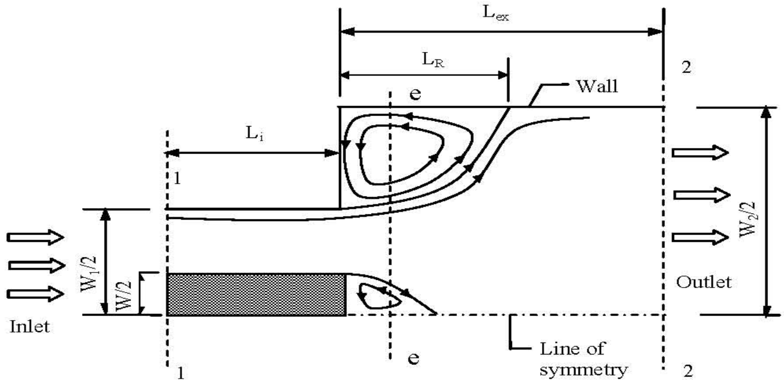

Figure 1. Schematic diagram of the computational domain for sudden expansion with central restriction

With the help of these variables, the mass and momentum conservation equations are written as follows,

$$\frac{\partial u^*}{\partial x^*} + \frac{\partial v^*}{\partial y^*} = 0 \qquad \text{--------} \quad (1)$$

$$u^*\frac{\partial u^*}{\partial x^*} + v^*\frac{\partial u^*}{\partial y^*} = -\frac{\partial p^*}{\partial x^*} + \frac{1}{Re}\left[\frac{\partial}{\partial x^*}\left(\frac{\partial u^*}{\partial x^*}\right) + \frac{\partial}{\partial y^*}\left(\frac{\partial u^*}{\partial y^*}\right)\right] \qquad \text{--------} \quad (2)$$

$$u^*\frac{\partial v^*}{\partial x^*} + v^*\frac{\partial v^*}{\partial y^*} = -\frac{\partial p^*}{\partial x^*} + \frac{1}{Re}\left[\frac{\partial}{\partial x^*}\left(\frac{\partial v^*}{\partial x^*}\right) + \frac{\partial}{\partial y^*}\left(\frac{\partial v^*}{\partial y^*}\right)\right] \qquad \text{--------} \quad (3)$$

Where, the flow Reynolds number, $Re = \rho U W_1/\mu$

2.2 Boundary Conditions

Four different types of boundary conditions are applied to the present problem. They are as follows,

1. At the walls: No slip condition is used, i.e., $u^* = 0$, $v^* = 0$.
2. At the inlet: Axial velocity is specified and the transverse velocity is set to zero, i.e., u^* = specified, $v^* = 0$. Fully developed flow condition is specified at the inlet, i.e., $u^* = 1.5\left[1-(2y^*)^2\right]$.
3. At the exit: Fully developed condition is assumed and hence gradients are set to zero, i.e., $\partial u^*/\partial x^* = 0$, $\partial v^*/\partial x^* = 0$.
4. At the line of symmetry: The normal gradient of the axial velocity and the transverse velocity are set to zero, i.e., $\partial u^*/\partial y^* = 0$, $v^* = 0$.

2.3 Numerical Procedure

The partial differentials equations (1), (2) and (3) are discretised by a control volume based finite difference method. Power law scheme is used to discretise the convective terms [12]. The discretised equations are solved iteratively by SIMPLE algorithm, using line-by-line ADI (Alternating directional implicit) method. The convergence of the iterative scheme is achieved when the normalised residuals for mass and momentum equations summed over the entire calculation domain fall below 10^{-8}.

In the computation, flow is assumed fully developed at the inlet and exit and therefore, exit is chosen far away from the throat.

III. RESULTS AND DISCUSSION

The important results of the present study are reported in this section. The parameters those affect the flow characteristics are identified as,

(1) Reynolds number, $50 \le Re \le 200$
(2) Central restriction, 0% to 40%
(3) Aspect ratio, $1.5 \le AR \le 6$

3.1 Variation of axial velocity profile

It is well known that fluid flow characteristics experience large variation with in separated regions. Thus, it is very essential to understand the mechanism of flow in the recirculation regions. In this section, velocity profile is considered at different axial locations to substantiate flow patterns achieved in the streamline contour for different parametric effect. The velocity profile for the plain sudden expansion (i.e. CR=0%) configuration and sudden expansion with 10%, 20%, 30% and 40% central restriction for each flow Reynolds number of 50 and 200 are shown in fig. 2(a) and fig. 2(b) respectively. For all the cases, aspect ratio is considered as 2. From the figure, it is noted that the velocity profiles are mildly disturbed at all the corner region, main flow region and central region (except CR=0%). From the figure, it is observed that the region of negative axial velocity at corner zone increases with increase in percentage of central restrictions for a particular value of Reynolds number. Since the negative velocity zone reflects the zone of recirculation, therefore, our study depicts the increase in the size of recirculation zone with increase in percentage of central restrictions. This has already been obtained in the earlier flow study through the streamlines. At the main flow region, velocity profiles are flattened downstream to the throat section. This flatteness increases with the increase in percentage of central restrictions. At central region, velocity profiles are also flattened but this is somewhat less compared to the main flow region. It is also observed that the magnitude of flattenness is lower in case of higher percentage of central restriction in the said zone. This less flattenness occurs at central region due to bubble formation at that zone and recirculating bubble size becomes more at higher restriction resulting in the reduction of flattenness. Fig. 3(a), fig. 3(b) and fig. 3(c) show the variation of velocity profile at different axial locations for plain sudden expansion configuration and sudden expansion with 10% and 40% central restriction respectively at an aspect ratio of 2. For each figure, Reynolds number is considered as 50, 100, 150 and 200. From the figure, it is noted that the velocity profiles are mildly disturbed at all the corner and main flow regions. It is observed that a negative axial velocity region is formed at corner zone. The size of the negative axial velocity region increases with the increase in Reynolds number for constant aspect ratio and fixed percentage of central restriction. The same type of flow behaviour is observed during streamline contour variation. This says that recirculating bubble size (i.e. negative axial velocity region) at corner zone increases with increase in Reynolds number. At main flow region, velocity profiles are flattened downstream to the throat section. This flattenness increases with increase in Reynolds number. This is expected because the axial velocity increases with increase in Reynolds number. When central restriction is considered (fig. 3 (b) and fig. 3 (c)), the flattenness at central region becomes less compared to the main flow region like earlier observation. From the figures, it is observed that the magnitude of flattenness in the central region decreases with increase in Reynolds number. The effects of aspect ratio of 1.5, 2, 3, 4, 5 and 6 on axial velocity profile are shown in fig. 4(a), fig. 4(b) and fig. 4(c) for the configurations of plain dump combustor and sudden expansion with 10% and 40% central restrictions respectively. For all the cases, a constant Reynolds number is considered as 100. For a particular value of Reynolds number and fixed percentage of central restriction, it is noted that negative axial velocity region at corner zone increases with increase in aspect ratio for all considered typical cases. At main flow region, velocity profiles are flattened and this flattenness increases with increase in aspect ratio when all other conditions remain same. From fig. 4(b) and fig. 4(c), it is observed that the magnitude of decreased flattenness in the central region remains more or less same with increase in aspect ratio for fixed value of Reynolds number and central restriction. This shows that the recirculating bubble size (i.e. negative axial velocity region) at central zone remains nearly constant with increase in aspect ratio. For constant aspect ratio and fixed value of flow Reynolds number, it is seen that the magnitude of decreased flattenness in the central region increases with increase in percentage of central restriction. The reason is explained earlier. Fig. 5(a) and fig. 5(b) illustrate the effect of aspect ratio on velocity profile at different axial locations for two limiting cases of Reynolds number of 50 and 200 respectively at 40% central restriction. For each case, aspect ratio variation is considered as 1.5, 2, 3, 4, 5 and 6. From fig. 5(a) and fig. 5(b), it is noted that the negative axial velocity region at corner zone increases with increase in Reynolds number for a fixed percentage of central restriction and constant aspect ratio. At main flow region, flattened velocity profile increases with increase in Reynolds number when all other parameters remain constant. In the central region, the magnitude of decreased flattenness increases with increase in Reynolds number. Similar type of axial velocity profile is also observed at any considered value of aspect ratio. From this observation, it can be concluded that the effect of Reynolds number on velocity profile shows same type of flow behaviour when aspect ratio changes.

IV. CONCLUSION

In the present study, a performance simulation of a sudden expansion with central restriction with fully developed velocity profile at inlet has been carried out. The effects of Reynolds number, percentage of central restriction and aspect ratio on velocity profile have been investigated and these lead to the following important observations;

i) The velocity profiles are mildly disturbed at all the corner region, main flow region and central region (except CR=0%). The region of negative axial velocity at corner zone increases with increase in percentage of central restrictions for a particular value of Reynolds number. This flattenness increases with the increase in percentage of central restrictions. At central region, flattenness is lower in case of higher percentage of central restriction.

ii) The negative axial velocity region at corner zone increases with increase in Reynolds number for a fixed percentage of central restriction and constant aspect ratio. At main flow region, flattened velocity profile increases with increase in Reynolds number. In the central region, the magnitude of decreased flattenness increases with increase in Reynolds number.

iii) At main flow region, the flattenness increases with increase in aspect ratio. The magnitude of decreased flattenness in the central region remains more or less same with increase in aspect ratio for fixed value of Reynolds number and central restriction.

NOMENCLATURE

L_i Inlet length (i.e., length between inlet and throat sections), m
L_{ex} Exit length (i.e., length between throat and exit sections), m
L_R Reattachment length, m
P or p Static pressure, [N/m^2]
Re Reynolds Number

u Velocity in x-direction, ms^{-1}
v Velocity in y-direction, ms^{-1}
U Average velocity, ms^{-1}
W width of central restriction, m
W_1 Width of inlet duct, m
W_2 Width of exit duct, m
AR Aspect ratio = W_2/W_1
CR Percentage of central restriction = W/W_1
x, y Cartesian co-ordinates
ρ Density, kg m^{-3}
µ Dynamic viscosity, kg $m^{-1}s^{-1}$

Subscripts

* Dimensionless terms
1-1 Inlet
2-2 Exit

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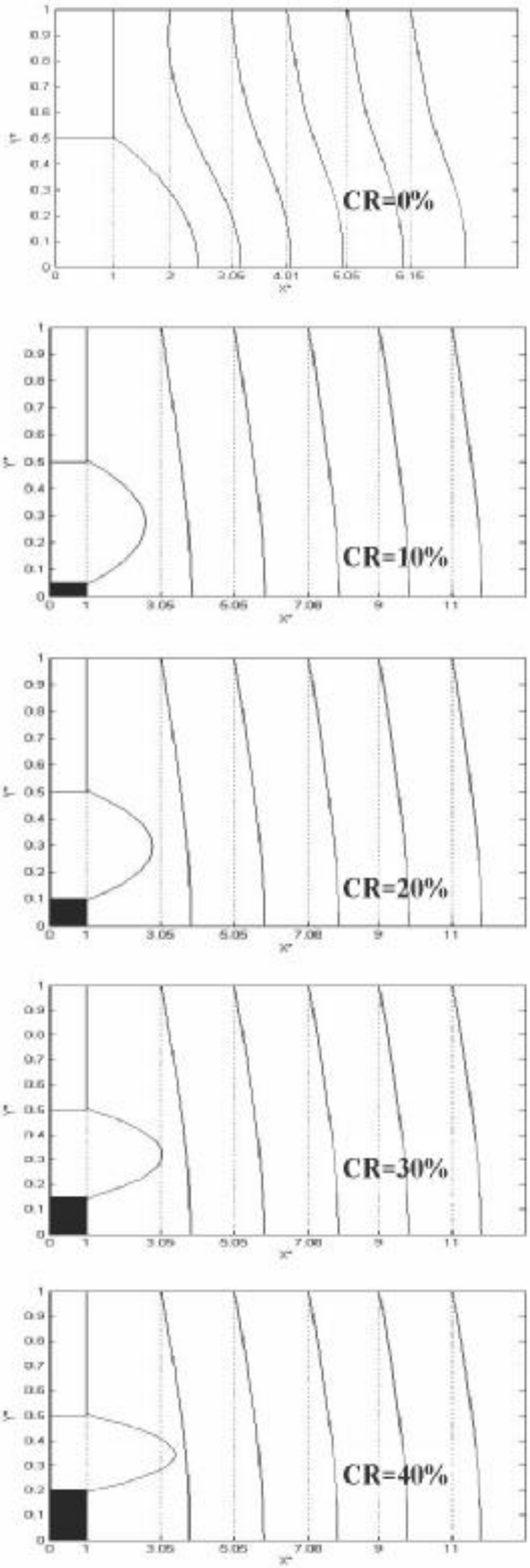

Fig. 2(a) Effect of central restriction on axial velocity profile for AR=2 and Re=50

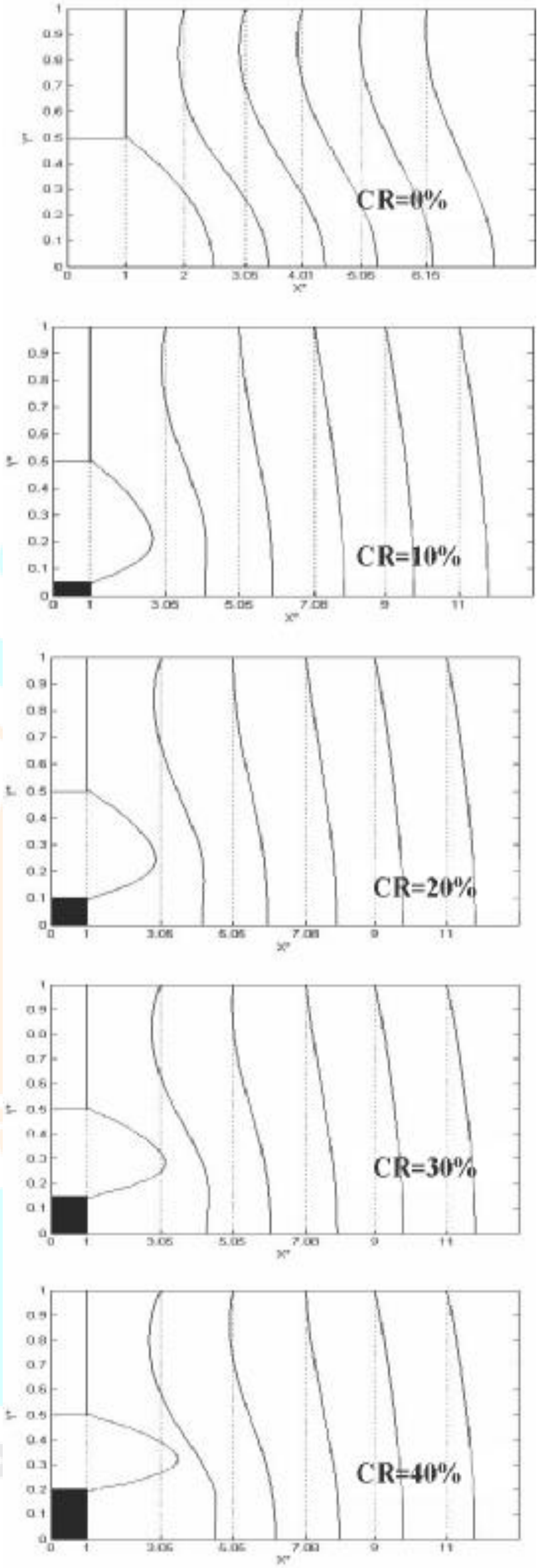

Fig. 2(b) Effect of central restriction on axial velocity profile for AR=2 and Re=200

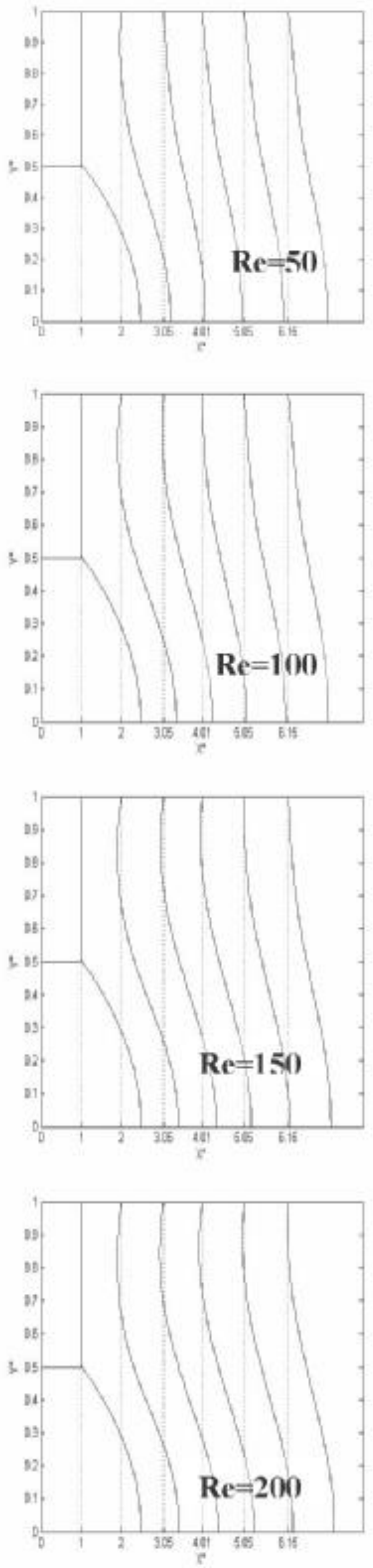

Fig. 3(a) Effect of Reynolds number on axial velocity profile for AR=2 and CR=0%

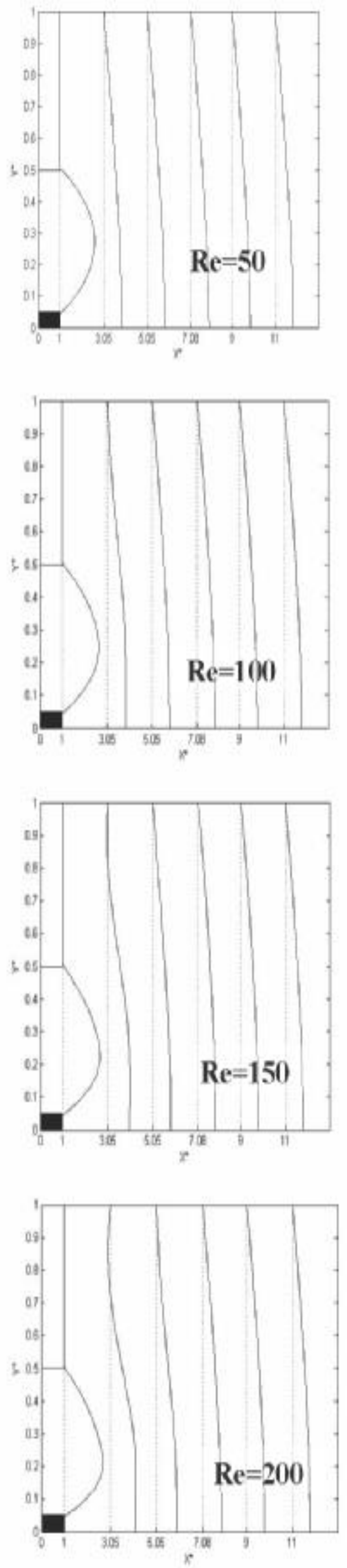

Fig. 3(b) Effect of Reynolds number on axial velocity profile for AR=2 and CR=10%

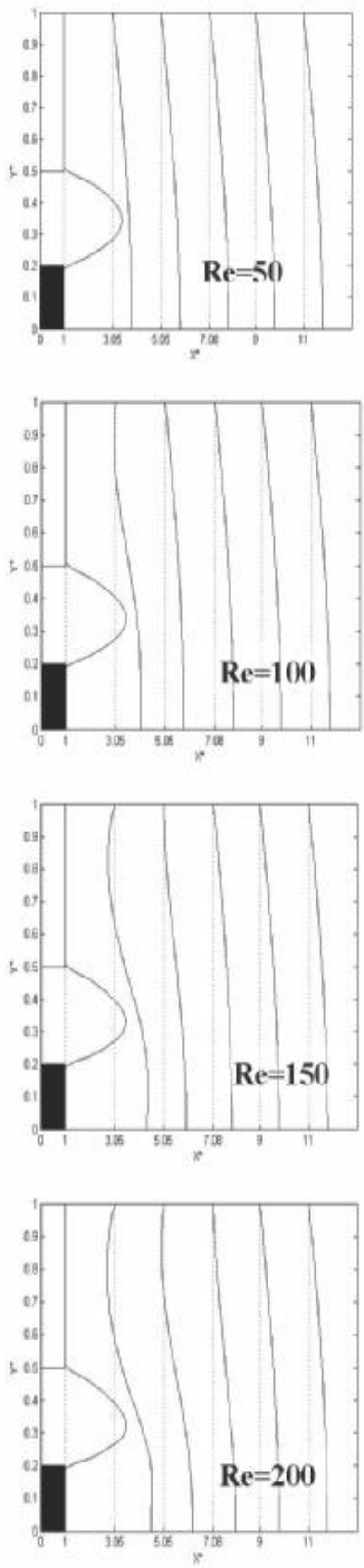

Fig. 3(c) Effect of Reynolds number on axial velocity profile for AR=2 and CR=40%

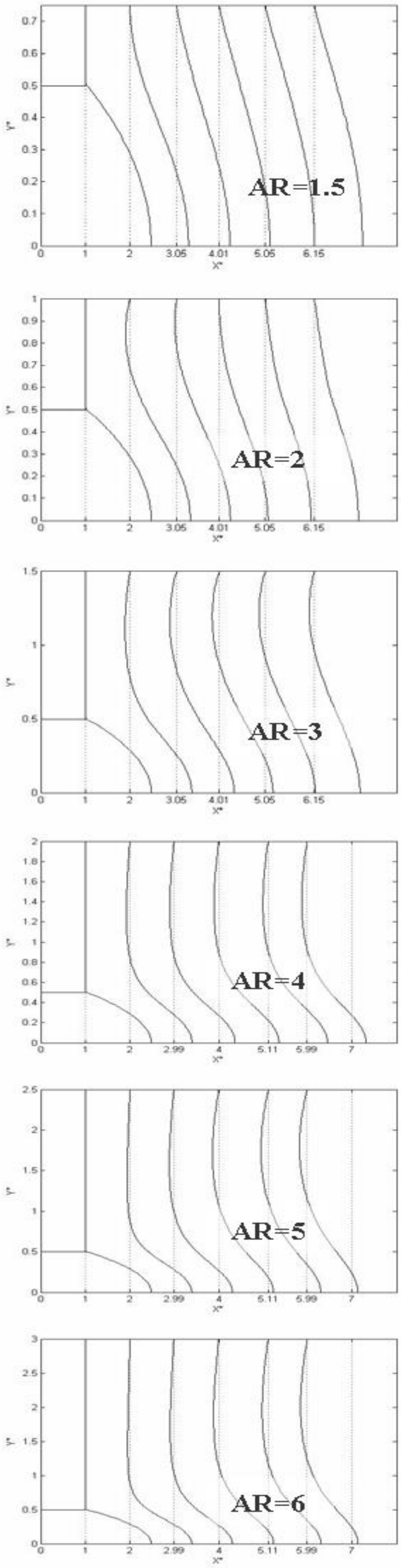

Fig. 4(a) Effect of aspect ratio on axial velocity profile for Re=100 and CR=0%

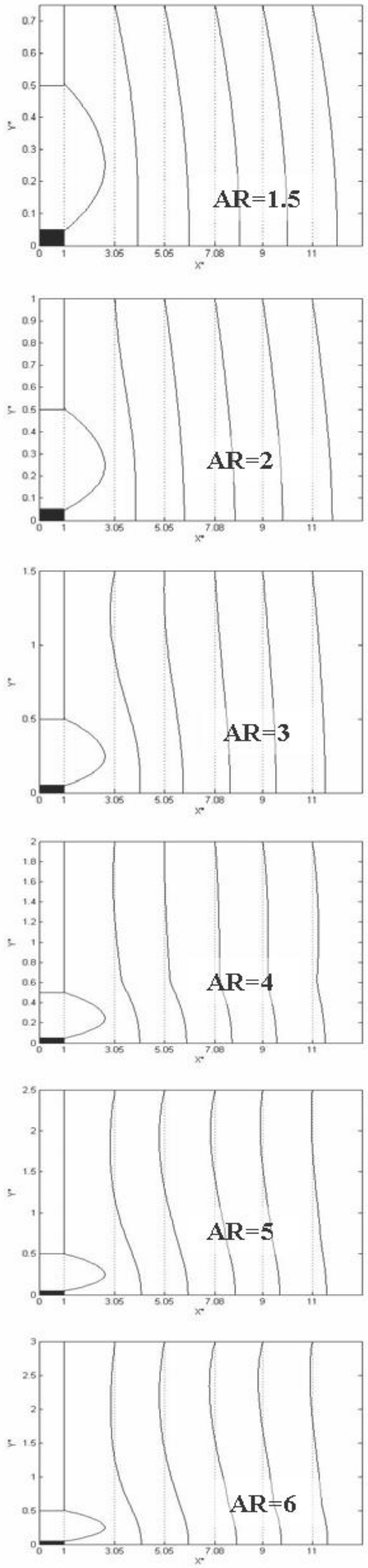

Fig. 4(b) Effect of aspect ratio on axial velocity profile for Re=100 and CR=10%

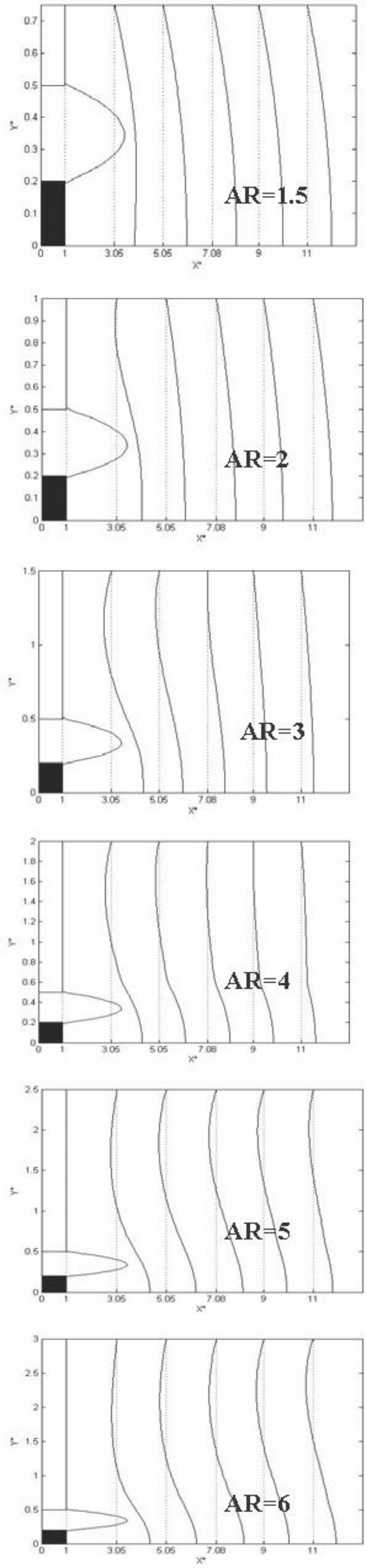

Fig. 4(c) Effect of aspect ratio on axial velocity profile for Re=100 and CR=40%

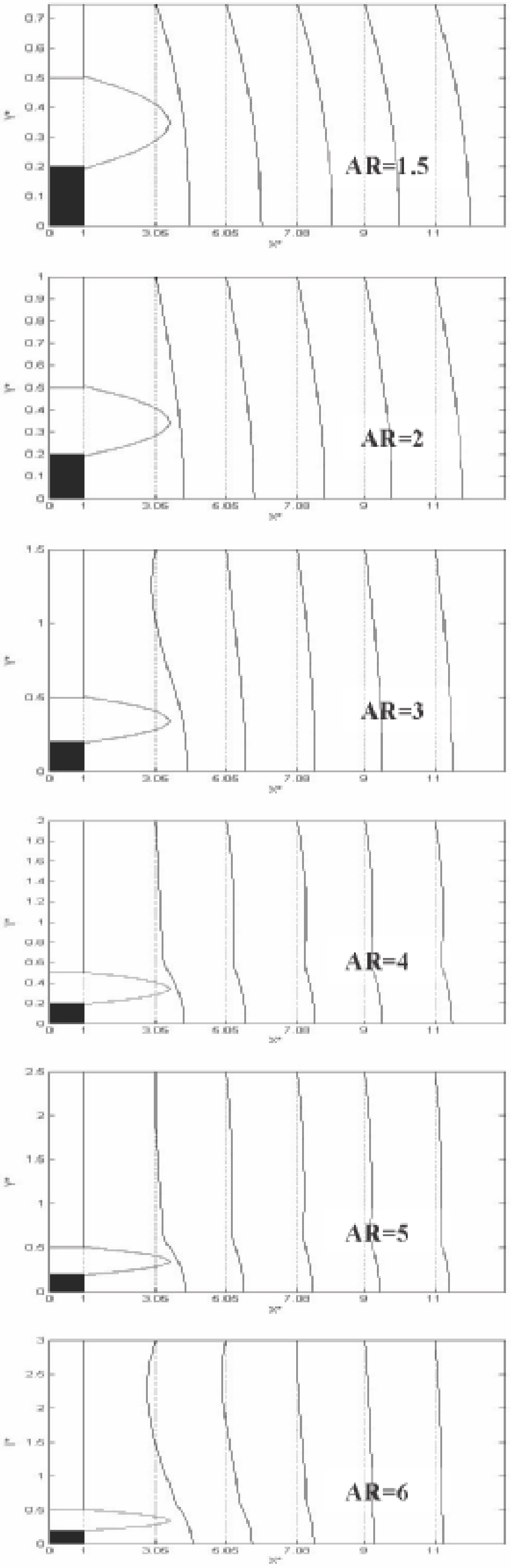

Fig. 5(a) Effect of aspect ratio on axial velocity profile for CR=40% and Re=50

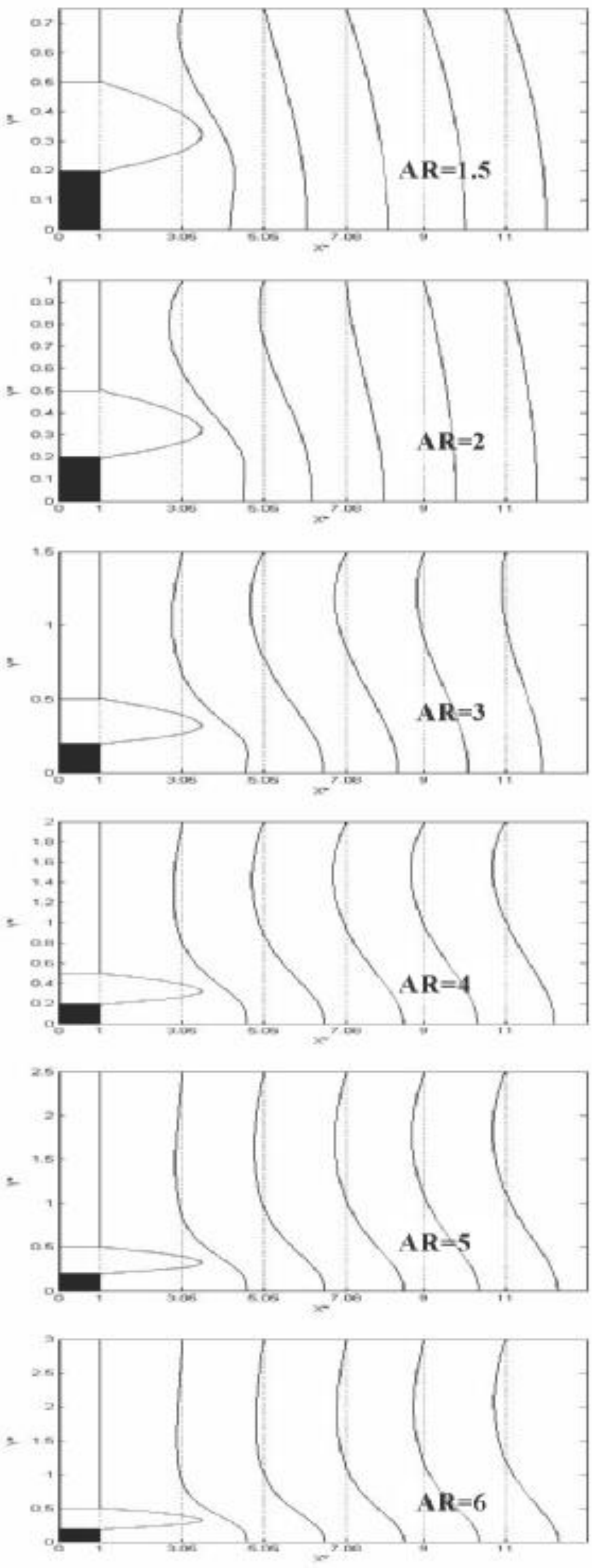

Fig. 5(b) Effect of aspect ratio on axial velocity profile for CR=40% and Re=200