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A Numerical Study on Flow Characteristics in a Configuration of Sudden Expansion with Central Restriction and Blowing

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ABSTRACT
In this paper, a numerical simulation of flow through a configuration of sudden expansion with central restriction and blowing has been carried out. The two dimensional steady differential equations for conservation of mass and momentum are solved for blowing (B) from 0% to 10% of inlet mass flow, percentage of central restriction (CR) from 0% to 40%, Reynolds number (Re) ranging from 50 to 200 and aspect ratio (AR) from 1.5 to 6. The effects of each variable on streamline contours have been studied in detail. From the study it is observed that the configuration of sudden expansion with central restriction and blowing with higher percentage of blowing, lower percentage of central restriction and lower aspect ratio may give more benefit in terms of side wall cooling. For better mixing, lower percentage of blowing, higher percentage of central restriction, higher Reynolds number and higher aspect ratio can be considered.

***Keywords* -** Blowing, Central Restriction, Recirculating Bubble, Streamline Contour, Sudden Expansion

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I. INTRODUCTION

The flow through abrupt geometrical expansion has both fundamental scientific interest and numerous practical applications. Among its many applications, particular mention may be made of the function as a combustor, diffuser and mixing chamber etc. This flow field consists of the separated boundary layer, a recirculation zone and a reattachment point at the corner zone. In this paper, study on flow characteristics of fluid passing through a sudden expansion configuration has been carried out by incorporating some central restriction in the inlet zone and a blowing at the top corner on side wall.

From a brief review of literature, it appears that the first work in the field of plain sudden expansion configuration has been carried out by Macagno and Hung [1]. They have considered an expansion ratio of 2:1 for Reynolds number up to 200. They have presented the streamline and vorticity contours as function of the Reynolds number flow. They have observed that the vorticity lines are stretched in the direction of the flow when the Reynolds number becomes higher. Kwon et al. [2] have numerically described an economical prediction procedure for fully developed incompressible flow through a symmetric sudden expansion channel. They have considered Reynolds numbers (based on channel inlet height) ranging from 1 to 320 for fully developed laminar flow undergoing a sudden 2:1 expansion. Tsai et al. [3] have numerically studied dump combustor flows considering with and without swirl at the inlet. They have considered the pipe expansion ratio and the swirl number as 1.5 and 0.3 respectively. They have observed that, for the non swirling case, the flow field is well represented by all the models, though the k-ε predictions show a slightly higher level of radial diffusive transport across the shear layer in the recirculation zone. Chakrabarti et al. [4] have made an extensive study on the performance of sudden expansion from the perspective of a diffuser. They have solved two-dimensional steady differential equations for mass and momentum conservation equations for the range of $20 \le \mathrm{Re} \le 100$, aspect ratio from 1.5 to 4. Neofytou [5] has numerically investigated the flow transition from symmetry to asymmetry through a symmetric sudden expansion configuration. He has used an expansion ratio of 1:2. He has considered that the length of the expanded section is 30 times its height and the length of the inlet section is two times its height. He has observed that the inverse dimensionless wall shear stress that occurs at the flow transition from symmetry to asymmetry is linearly related to the dimensionless shear rate at the wall.

Paschereit and Gutmark [6] have experimentally studied the performance of a gas turbine combustor having sudden expansion configuration with inlet modification. At the upstream of the sudden expansion they have used miniature vortex generators which are small triangular ramps. They have observed that, by the use of miniature vortex generator, low frequency instabilities are reduced by 50% and high-frequency oscillations are suppressed by up to 28 dB. Vanierschot and Bluck [7] have experimentally investigated the influence of swirl on the mean cold flow field of a modified sudden expansion configuration. At the inlet region of the sudden expansion, they have considered a central restriction which creates an annular channel up to the sudden expansion plane. At high Reynolds numbers, they have seen two different types of breakdown. These are axisymmetric (bubble) breakdown and spiral breakdown. Layek et al [8] have carried out numerical simulation to study the effects of suction and blowing on flow separation in a symmetric sudden expansion channel. They have considered uniform blowing or suction at the lower and upper porous step walls. They have used expansion ratio of 1:2 and non-dimensional inlet channel length of 4. During computation, Reynolds number ranging from 100 to 500 is considered by them. Ayache et al. [9] have seen that at low forcing frequencies, the recirculation zone is pulsated with the incoming flow, at a phase lag that depends on spatial location. Tuncer et al. [10] have experimentally investigated the stability and structure of lean premixed methane air flames in a swirl stabilized premixed dump combustor at atmospheric pressure. They have observed two elliptically shaped counter rotating recirculation vortices behind the dump plane and a central recirculation zone just downstream of dump plane.

As per brief review of literature, it is noted that a number of researchers have studied the flow through plain sudden expansion or sudden expansion with some modified configuration. However, it is realized that study on flow characteristic in case of sudden expansion configuration with central restriction and blowing with the help of streamline contours is not addressed. Therefore, in this paper an attempt has been made to study the effect of Reynolds number, percentage of central restriction, aspect ratio and percentage of blowing on streamline contours of fluid passing through a sudden expansion with central restriction and blowing configuration.

II. MATHEMATICAL FORMULATION

2.1 Governing Equations

A schematic diagram of the computational domain for flow through sudden expansion with central restriction and blowing 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: $x^* = x/W_1$, $y^* = y/W_1$, $L_i^* = L_i/W_1$, $L_{ex}^* = L_{ex}/W_1$, $L_R^* = L_R/W_1$, $W^* = W/W_1$, $W_b^* = W_b/W_1$.

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

Pressure: $p^* = p/\rho U^2$

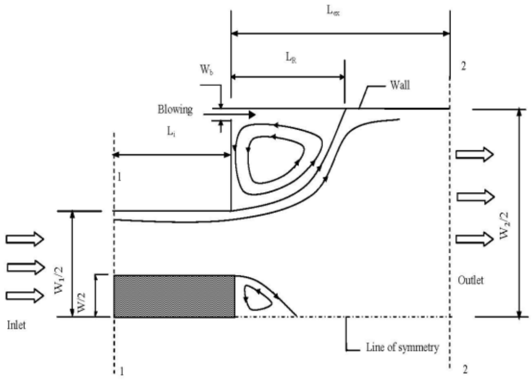

Fig. 1. Schematic diagram of the computational domain sudden expansion with central restriction and blowing

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

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

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

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

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

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., $u^* = 1.5\left[1-\left(2y^*\right)^2\right]$

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 (Patankar, [11]). 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 as fully developed at the inlet and exit and therefore, exit is chosen far away from the throat. The distribution of grid nodes is non-uniform and staggered in both coordinate direction allowing higher grid node concentrations in the region close to the step and walls. The grid sensitivity study has been performed carefully considering aspect ratio of 2 and Re=100 with 20% of central restriction. During this calculation, the non-dimensional inlet and the exit lengths are considered to be 1 and 50 respectively. However the computations are also performed with L^*_{ex} = 100. The results show no significant variation on the important design parameters.

III. RESULTS AND DISCUSSION

In this section, study on flow characteristics of fluid passing through a modified sudden expansion configuration has been carried out by incorporating central restriction in the inlet zone and a blowing at the top corner with a fixed slot size of 0.01 (non dimensional distance) on side wall. The effect of blowing percentage, Reynolds number, percentage of central restriction and aspect ratio on streamline contour has been investigated.

The parameters those affect the flow characteristics are identified as,

(1) Reynolds number, $50 \leq \text{Re} \leq 200$
(2) Aspect ratio, AR = 1.5 to 6
(3) Central restriction, CR = 0% to 40%
(4) Blowing, B = 0% to 10% of inlet mass flow

3.1 The effect of blowing on streamline contour at corner recirculation zone

Fig. 2 illustrates the effect of blowing on streamline contour for sudden expansion with typically 20% central restriction and Reynolds number of 100 for an aspect ratio of 2. Different percentages of blowing are considered as 0% (i.e. without blowing), 2%, 4%, 6%, 8% and 10% respectively. From the figure, it is noted that the length of the corner recirculation zone decreases with increase in percentage of blowing when all other conditions remain same. The probable reason may be that blowing produces additional stream which forces the corner recirculating bubble towards downstream. Actually, corner recirculating bubble does not move rather compresses. Because of this, overall bubble size at corner zone decreases. With the increase in percentage of blowing, our observation regarding the shrinking effect of recirculating bubble at corner zone has also been observed by Layek et al. (2008). From the figures, it is observed that because of blowing, a fluid layer is formed in the side wall. It is also noted that the thickness of this fluid layer on vertical wall increases as blowing percentage increases for a fixed percentage of central restriction and constant value of Reynolds number. There is a possibility of side wall cooling because of this fluid layer. Therefore, for better cooling on the side wall, higher percentage of blowing is preferable.

3.2 The effect of blowing on streamline contour at central recirculation zone

Fig. 3 shows the effect of blowing on streamline contour for sudden expansion with typically 40% central restriction and Reynolds number of 100 for an aspect ratio of 2. Different percentages of blowing are considered as 0% (i.e. without blowing), 2%, 4%, 6%, 8% and 10% respectively. Fig. 3 represents the enlarged view of the central region. It is observed that the size of the recirculating bubble at central zone remains more or less same with increase in percentage of blowing. The probable reason may be that the additional stream of blowing forces the main stream of flow towards central region which may decrease the central recirculating bubble size. But this reduction is negligible at this considered Reynolds number (Re=100) and bubble size remains more or less same.

3.3 The effect of central restriction on streamline contour for 10% blowing

Fig. 4 shows the effect of central restriction for sudden expansion with central restriction and typically 10% blowing of inlet mass flow. Central restrictions are considered as 0%, 10%, 20%, 30%

and 40% for typical Reynolds number of 200 and aspect ratio of 2. From the figure, it is observed that the length of the recirculating bubble at corner region increases with increase in percentage of central restriction. The central recirculating bubble size also increases with increase in percentage of central restriction. The reason is that, the higher diffusion occurs at the central zone as the percentage of central restriction increases. This higher diffusion, at certain percentage of central restriction, affects the corner recirculation zone which increases the size of corner recirculating bubble with increase in percentage of central restriction. It is also observed that the thickness of fluid layer near the throat zone on the vertical wall decreases as percentage of central restriction increases. Therefore, it may be mentioned that, for better cooling on the side wall lower percentage of central restriction is preferable, as thickness of fluid layer (which is the main cause of wall cooling) decreases with increase in percentage of central restriction.

3.4 The effect of Reynolds number on streamline contour for 10% blowing

Fig.5 represents the variation of streamline contours for the configuration of sudden expansion with 40% central restriction and 10% blowing of inlet mass flow. Different Reynolds numbers are considered as 50, 100, 150 and 200 with a constant aspect ratio of 2. The size of recirculating bubble both at corner and central regions has been noted to be increasing with increase in Reynolds number. This can be reasoned as, for higher Reynolds number flow, the kinetic energy contribution towards the working fluid both at corner and central zones will be higher resulting in higher size of recirculating bubbles. From the figure, it is observed that the thickness of fluid layer on the vertical wall remains nearly constant as flow Reynolds number increases. Because of that, variation of Reynolds number may not affect the wall cooling phenomenon for a fixed percentage of blowing.

3.5 The effect of aspect ratio on streamline contour for 10% blowing

The effect of aspect ratio on streamline contour for the configuration of sudden expansion with 40% central restriction and 10% blowing is shown in fig. 6. Different aspect ratios are considered as 1.5, 2, 3, 4, 5 and 6 for a constant Reynolds number of 100. From the figure, it is noted that the corner recirculating bubble size increases and central recirculating bubble size remains nearly constant with increase in aspect ratio. This can be reasoned as, due to higher aspect ratio, there will be an enhanced possibility of kinetic energy diffusion at corner region. But, as the percentage of central restriction and Reynolds number are fixed in the considered case, there is less possibility of increase in the size of recirculating bubble at central zone, instead the possibility of recirculating bubble size may remain same or may decrease to some extent when the aspect ratio increases. For a fixed percentage of blowing and a particular value of aspect ratio, it is seen that the thickness of fluid layer on the vertical wall decreases as aspect ratio increases. Hence, the possibility of wall cooling at higher aspect ratio will be less, when all other considered conditions remain same.

IV. CONCLUSIONS

The effect of blowing, Reynolds number, central restriction and aspect ratio on streamline contour have been investigated for sudden expansion with central restriction and blowing configuration. This leads to the following important observations;

i) Because of blowing, a fluid layer is formed in the side wall. The thickness of this fluid layer increases as blowing percentage increases.
ii) For better cooling on the side wall, higher percentage of blowing, lower percentage of central restriction and lower aspect ratio may be considered.
iii) Variation of Reynolds number may not affect the wall cooling phenomenon for a fixed percentage of blowing.
iv) The length of the corner recirculation zone decreases with increase in percentage of blowing. But the size of the recirculating bubble at central zone remains more or less same with increase in percentage of blowing.
v) The higher performance in terms of mixing possibilities both at corner and central zones may be achieved at lower percentage of blowing higher percentage of central restriction, higher flow Reynolds number and higher aspect ratio.

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
B Blowing
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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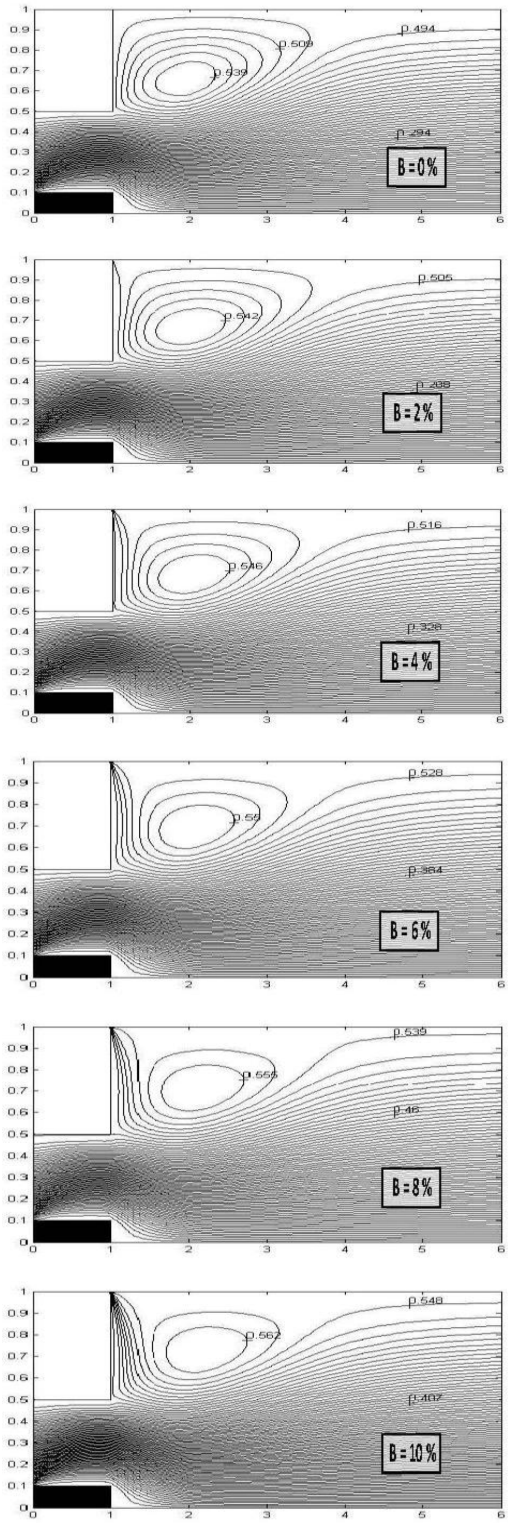

Fig. 2 Effect of blowing on streamline contour for AR=2, Re=100 and CR=20%

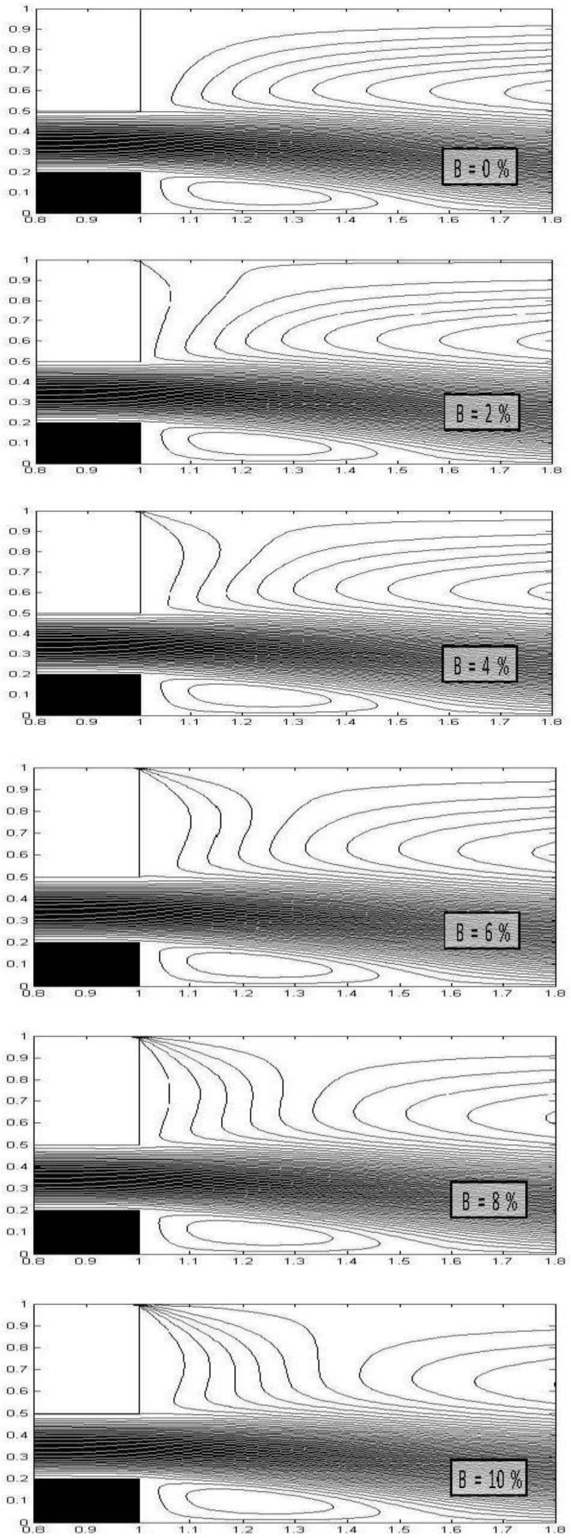

Fig. 3 Effect of blowing on streamline contour for AR=2, Re=100 and CR=40% (enlarged view of central region)

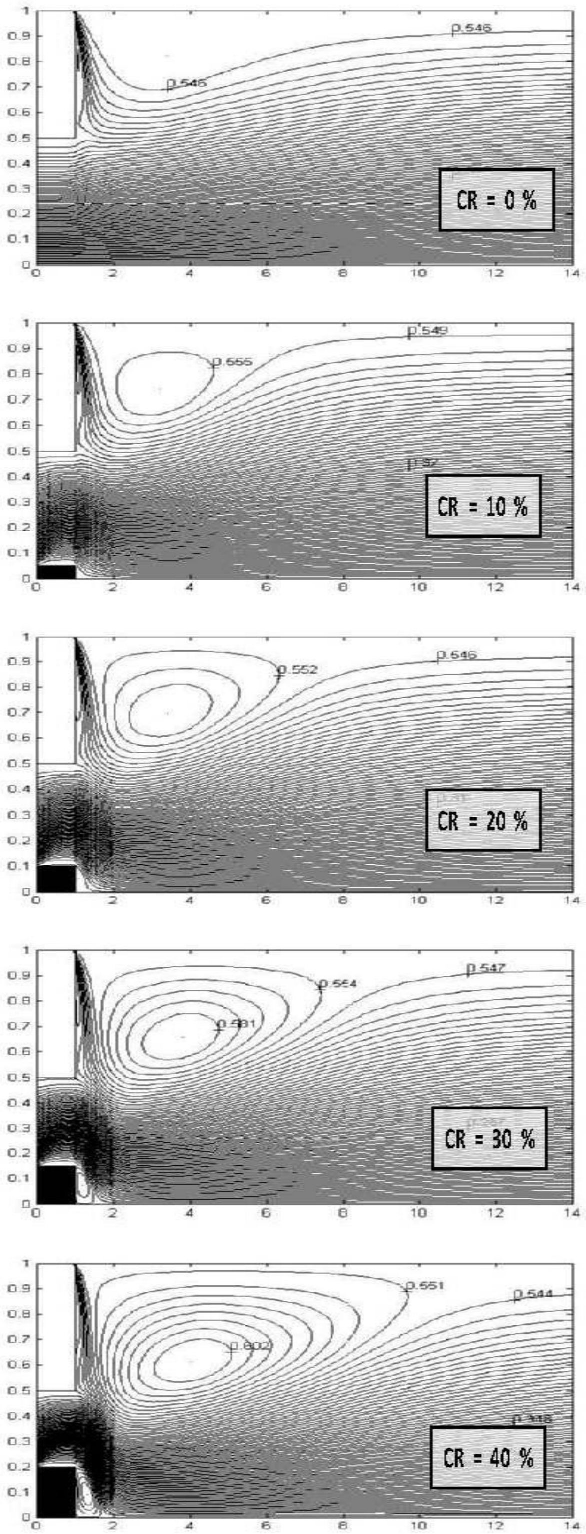

Fig. 4 Effect of central restriction on streamline contour for AR=2, Re=200 and B=10%

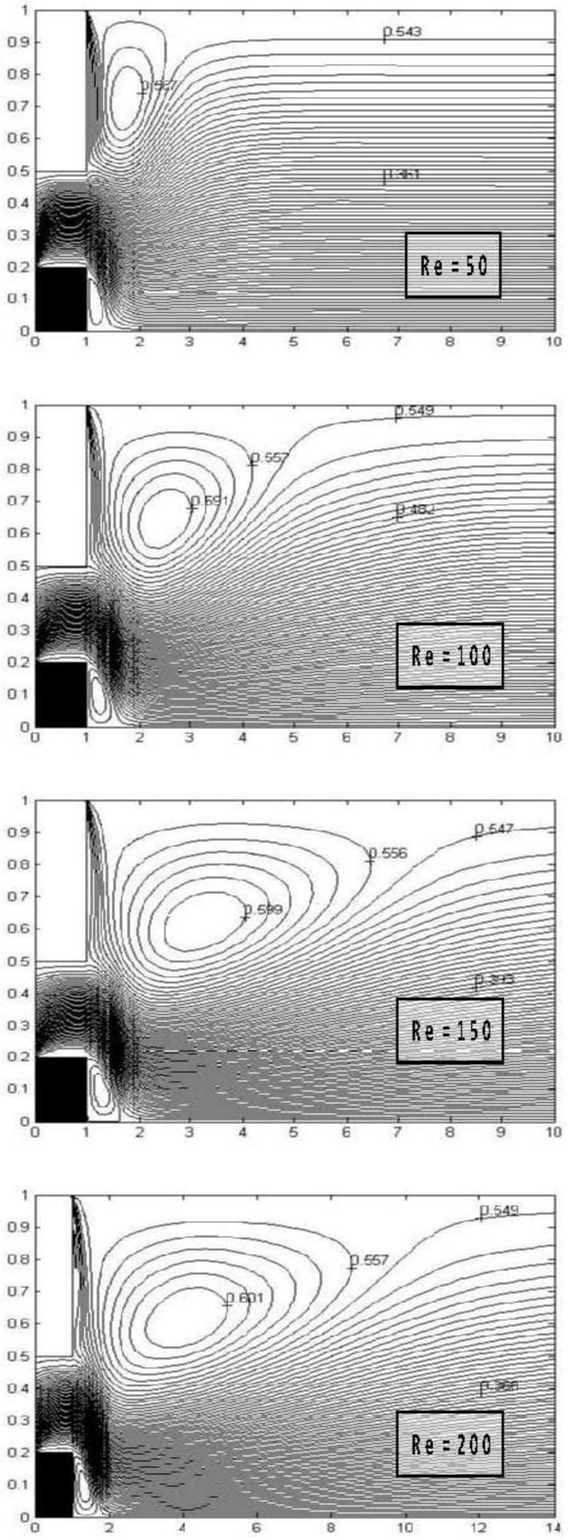

Fig. 5 Effect of Reynolds number on streamline contour for AR=2 and CR=40% with B=10%

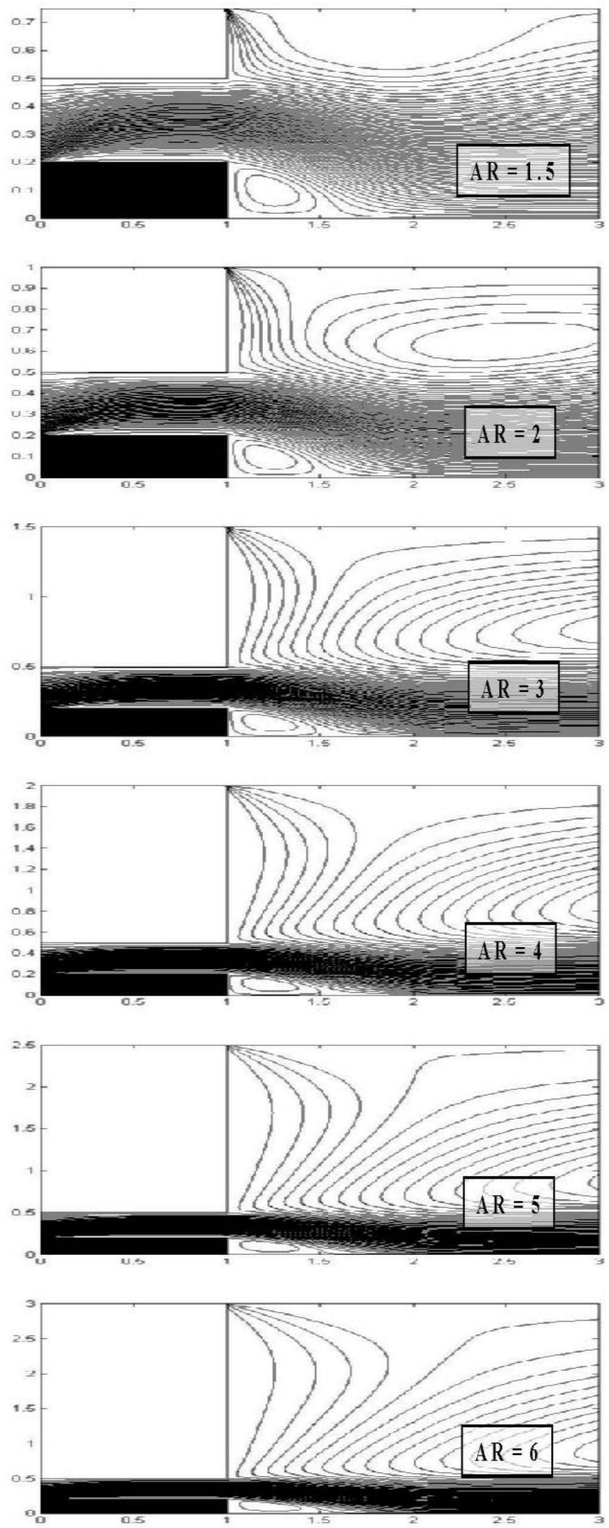

Fig. 6 Effect of aspect ratio on streamline contour for Re=100, CR=40% and B=10%