

# A 2-D Flow Simulation for Sudden Expansion with Central Restriction and Suction

Tridibesh.Das<sup>1</sup>, Somnath Chakrabarti<sup>2</sup>

Assistant Professor, Department of Mechanical Engineering, Kalyani Government Engineering College, Kalyani,  
Nadia, West Bengal, India<sup>1</sup>

Professor, Department of Mechanical Engineering, Indian Institute of Engineering Science and Technology, Shibpur,  
Howrah, West Bengal, India<sup>2</sup>

**ABSTRACT:** In this paper, a numerical study on flow characteristics in the configuration of sudden expansion with central restriction at inlet zone and suction at top on vertical wall has been carried out. The two dimensional steady differential equations for conservation of mass and momentum are solved for Reynolds number (Re) ranging from 50 to 200, percentage of central restriction (CR) from 10% to 40%, suction 2% to 10% of inlet mass flow and a fixed aspect ratio (AR) of 2. The effect of each variable on streamline contour has been studied in detail. The results have been compared with the configurations of plain sudden expansion and sudden expansion with central restriction only. From the streamline contour variation, it is noted that size of recirculating bubble at corner zone decreases with increase in suction percentage but central recirculation zone remains more or less same with the variation of suction. The size of corner and central region increases with increase in Reynolds number and percentage of central restriction for all the considered configurations. The size of corner recirculating bubble is noted to be decreasing in case of suction configuration with respect to without suction configuration.

**KEYWORDS:** sudden expansion, central restriction, Reynolds number, suction.

## I. INTRODUCTION

Flow with recirculation through axisymmetric sudden expansion is of considerable interest to researchers because of its fundamental as well as practical importance. The geometry can be found in numerous applicable equipments, such as heat exchangers, combustion chambers, mixing vessels, reactors, as well as many other fluids processing, handling, and transport equipment. In this paper, study on flow characteristics of fluid passing through a sudden expansion configuration has been carried out by incorporating central restriction in the inlet zone and suction 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 carried out flow visualization studies in sudden expansions in axisymmetric flows for a Reynolds number range of 36 to 4500. Tsai et al. [2] 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. The inlet velocity is used as 19.2 m/s, corresponding to a Reynolds number of  $1.25 \times 10^5$  based on the inlet pipe diameter. They have used an eddy viscosity type k- $\epsilon$  model and Reynolds stress transport model variants. Galvin and Fitzpatrick [3] have experimentally observed strong acoustic interactions in a premixed dump combustor having configuration of plane sudden expansion. They have considered Reynolds number in the range of  $1.5 \times 10^4$  to  $2 \times 10^4$  and two different expansion ratios of 18:1 and 12:1.

Sheen et al. [4] have experimentally investigated the flow characteristics in a modified sudden expansion configuration with central restriction in the inlet zone. They have used both flow visualization and laser Doppler anemometry techniques. Layek et al [5] 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. Das and Chakrabarti [6] have

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carried out a numerical study on the performance of a sudden expansion configuration with central restriction at its inlet zone. They have used Reynolds number in the range of 50–200 and aspect ratio from 1.5 to 6 for 40% central restriction. Tuncer et al. [7] have experimentally investigated the stability and structure of lean premixed methane air flames in a swirl stabilized premixed dump combustor at atmospheric pressure. At the inlet of the dump plane, they have considered a 45° angled eight blades swirl vane which is installed on a 20 mm diameter centre body.

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 configurations with central restriction and suction 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 and percentage of suction variation on streamline contours of fluid passing through a sudden expansion with central restriction and suction configuration.

## II. MATHEMATICAL FORMULATION

### Governing Equations

A schematic diagram of the computational domain for flow through plain sudden expansion, sudden expansion with central restriction only and sudden expansion with central restriction and suction is illustrated in Fig.1. (a), (b) and (c) respectively. 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:  $x^* = x/W_1$ ,  $y^* = y/W_1$ ,  $L_i^* = L_i/W_1$ ,  $L_{ex}^* = L_{ex}/W_1$ ,  $L_R^* = L_R/W_1$ ,  $W^* = W/W_1$ ,  $W_s^* = W_s/W_1$ .

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

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

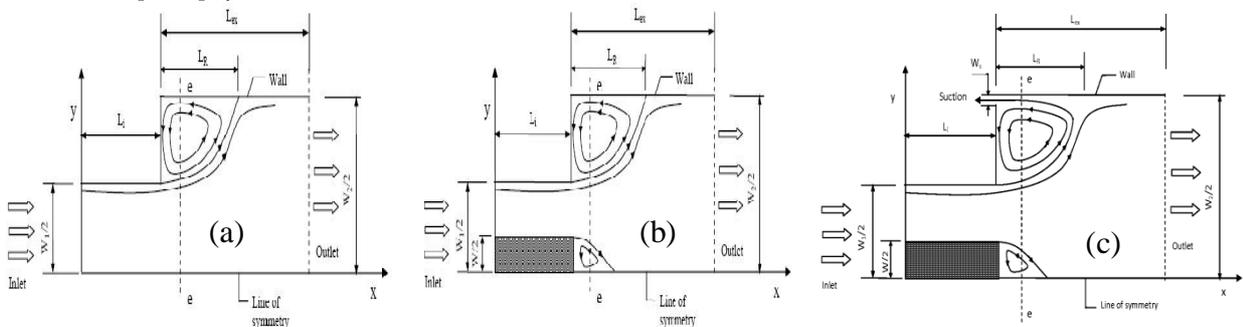


Fig. 1. Schematic diagram of the computational domain (a) plain sudden expansion (b) sudden expansion with central restriction only (c) sudden expansion with central restriction and suction

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

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

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

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

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

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## 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.,  $u^* = \text{specified}$ ,  $v^* = 0$ . Fully developed flow condition is specified at the inlet, i.e.,  $u^* = 1.5 [1 - (2y^*)^2]$ .
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.,  $\partial u^* / \partial y^* = 0$ ,  $v^* = 0$ .

## Numerical procedure

The partial differential 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 [8]. 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 the grid independence test. 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. Several test cases are run by using different grid size to quantify grid independence study in terms of magnitude and location of  $\Psi_{max}$ . This study has been discussed in detail by Das and Chakrabarti [9]. Finally in our work we have considered the meshes comprising of  $41 \times 37$  grid nodes in the inlet section and  $221 \times 121$  grid nodes in the exit section in the x- and y-directions, respectively.

## 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,  $50 \leq Re \leq 200$
- (2) Aspect ratio,  $AR = 2$
- (3) Central restriction from 10% to 40%
- (4) Suction,  $S = 2\%$  to 10% of inlet mass flow

### Variation of Streamline Contours

The recirculating bubble, immediately downstream of the sudden expansion is encountered in many practical systems like chemical process industry, mixing chamber or combustor. This recirculation zone improves the mixing of the reactants, provides higher heat release inside chamber, and improves performance of the system. Therefore, the detailed numerical study on the recirculation zone is included in this work. Fig. 2(a) illustrates the effect of suction on streamline contour for the configuration of sudden expansion with typically 40% central restriction and Reynolds numbers of 100 for an aspect ratio of 2. Different percentages of suction are considered as 0% (i.e. without suction), 2%, 4%, 6%, 8% and 10%. From the figure, it is noted that the size of the corner recirculation zone decreases with increase in percentage of suction when all other conditions remain constant. This happens because; the suction effect shrinks the recirculating bubble at corner zone which corroborates the observation of Layek et al. [5]. Fig. 2(b) represents the enlarged view of the central region, keeping all conditions same as in fig. 2(a). It is observed that the size of the recirculating bubble at central zone remains more or less constant with increase in percentage of suction.

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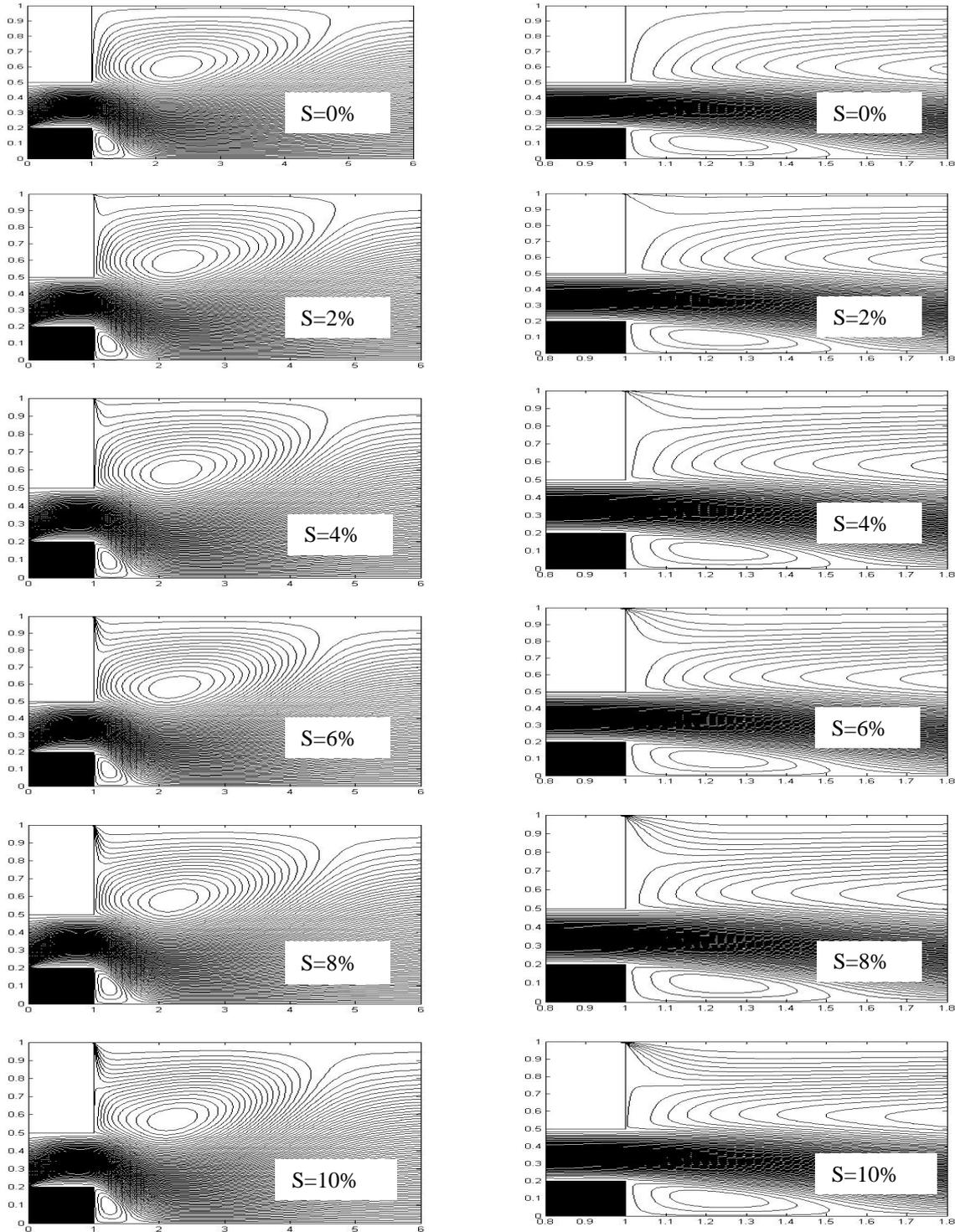


Fig. 2(a) Effect of suction on streamline contour for AR=2, Re=100 and CR=40%

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

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Fig. 3(a) and 3(b) show the effect of central restriction for sudden expansion with 0 (plain sudden expansion) 10, 20 and 40 percent central restrictions without and with 10% suction of inlet mass flow respectively. For both the cases, a typical Reynolds number of 200 with a constant aspect ratio of 2 are considered. From the figure, it is observed that the size 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. This can be reasoned as, with increase in percentage of central restriction, diffusion increases at the central zone, resulting in higher size of recirculating bubbles at this zone. This increased diffusion also influences at corner zone and because of that, corner recirculating bubble size increases. For fixed percentage of central restriction, it is noted that the size of the corner recirculation region decreases but the central recirculation zone remains nearly constant for the case of sudden expansion with central restriction and suction configuration compared to the case of sudden expansion with central restriction only or plain sudden expansion

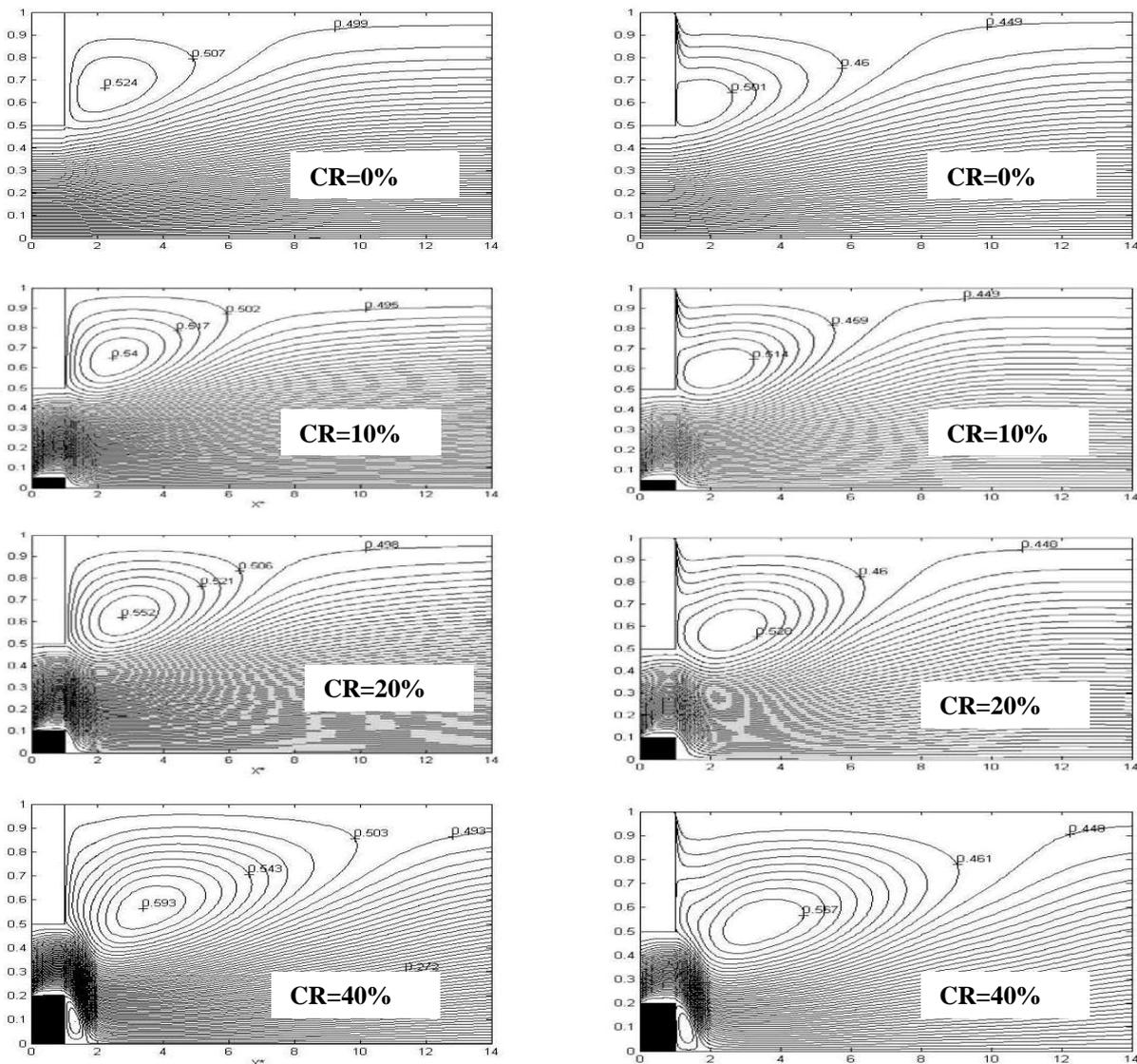


Fig. 3(a). Effect of central restriction on streamline contour for AR=2 and Re=200

Fig. 3(b). Effect of central restriction on streamline contour for AR=2, Re=200 and S=10%

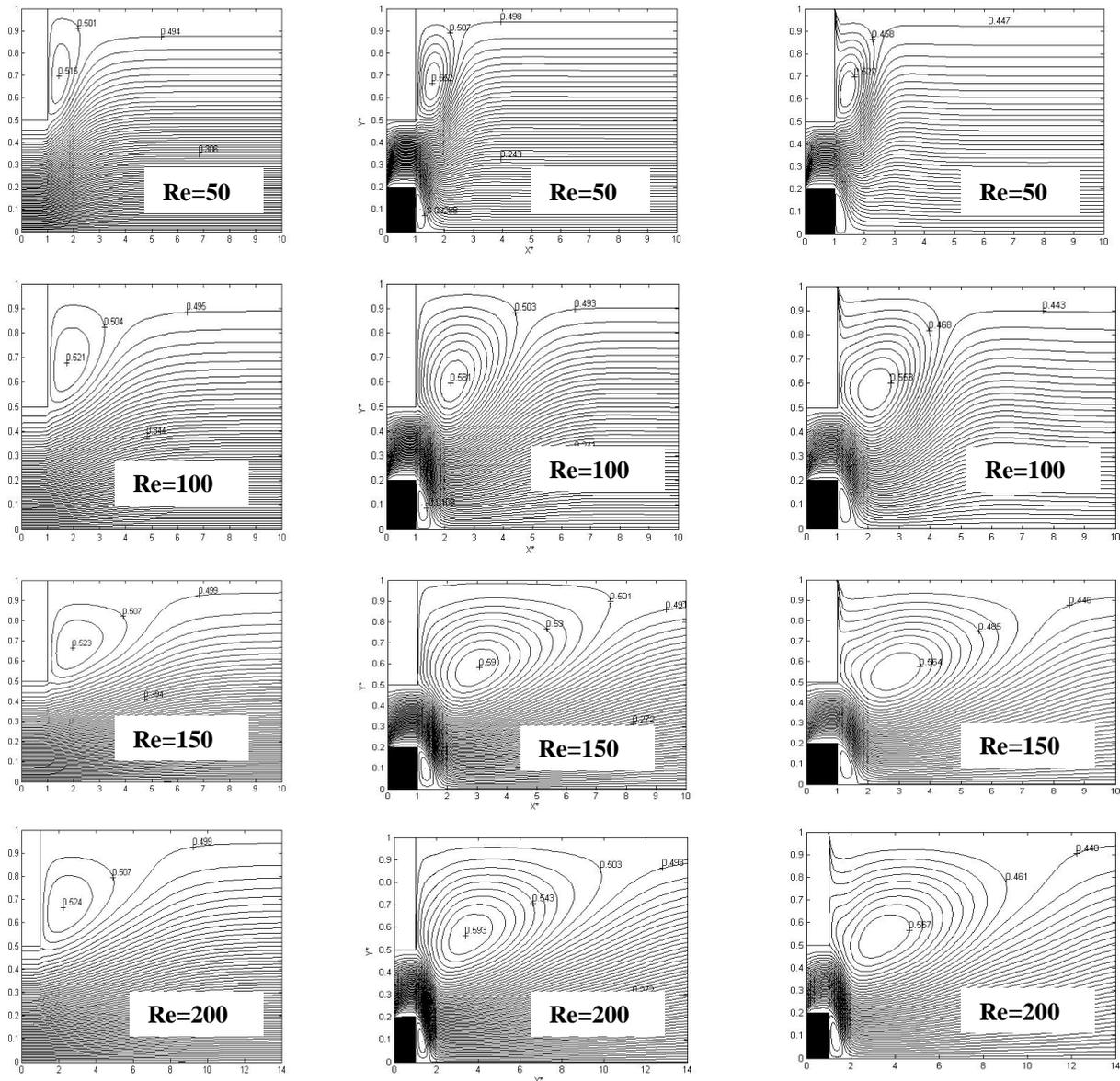


Fig. 4(a). Effect of Reynolds number on streamline contour for AR=2 and CR=0%

Fig. 4(b). Effect of Reynolds number on streamline contour for AR=2 and CR=40%

Fig. 4(c). Effect of Reynolds number on streamline contour for AR=2 and CR=40% with S=10%

Fig. 4(a), 4(b) and 4(c) represent the variation of streamline contours for the configuration of plain sudden expansion, sudden expansion with 40% central restriction and sudden expansion with 40% central restriction along with 10% suction respectively. In each case, Reynolds numbers of 50, 100, 150 and 200 with a constant aspect ratio of 2 is considered. The size of recirculating bubble both at corner and central regions has been noted to be increasing with increase in Reynolds number for all the considered cases. 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. So, mixing will be better at higher flow Reynolds number. At a fixed value of flow Reynolds number, it is observed that the size of the corner recirculating bubble is more for both the sudden expansion

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with central restriction only and sudden expansion with central restriction suction configuration compared to the plain sudden expansion configuration. When sudden expansion with central restriction with and without suction configurations are compared, corner recirculating bubble size decreases for the case of sudden expansion with central restriction and suction configuration. Like earlier observation, size of central recirculating bubble remains more or less same for both the configurations of sudden expansion with central restriction only and sudden expansion with central restriction and suction.

## IV. CONCLUSIONS

The effect of Reynolds number, percentage of central restriction and percentage of suction on streamline contours have been investigated for both sudden expansion with central restriction only and sudden expansion with central restriction and suction configuration. This leads to the following important observations;

1. The size of the corner recirculation zone decreases with increase in percentage of suction when all other conditions remain constant, but the recirculating bubble at central zone remains nearly constant during variation of suction percentage.
2. The recirculating bubble size at corner and central region increases with increase in percentage of central restriction for all considered configurations. When suction is considered, at a fixed percentage of central restriction, the size of the corner recirculating bubble decreases compared to the case of without suction configuration, but the central recirculating bubble size remains nearly constant.
3. The size of recirculating bubble at corner and central region increases with increase in Reynolds number for both the configuration of with and without suction. At a fixed value of flow Reynolds number, the size of the corner recirculating bubble decreases in case of sudden expansion with central restriction and suction of fixed magnitude compared to the case of without suction.

### 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
$p$	Static pressure, [N/m <sup>2</sup> ]
$Re$	Reynolds Number
$u$	Velocity in x-direction, ms <sup>-1</sup>
$v$	Velocity in y-direction, ms <sup>-1</sup>
$U$	Average velocity, ms <sup>-1</sup>
$W$	Width of central restriction, m
$W_s$	Width of suction slot, 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
$\rho$	Density, kg m <sup>-3</sup>
$\mu$	Dynamic viscosity, kg m <sup>-1</sup> s <sup>-1</sup>

### Subscripts

*	Dimensionless terms
1-1	Inlet
2-2	Exit

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