Numerical Simulation of Flow in a Configuration of Combined Sudden Expansion and Contraction with Rectangular Tab

Bishnu Pada Biswas[1], Somnath Chakrabarti[2]

Abstract— In this paper, the computational investigations have been performed to study the flow characteristics of an incompressible fluid flowing through a configuration of combined sudden expansion and contraction with rectangular tab at throat. The two-dimensional steady differential equations for conservation of mass and momentum have been solved for the Reynolds number (Re) ranging from 50 to 300, the tab restriction (TR) ranging from 0% to 40%, the tab length (L_t^*) ranging from 0 to 1, the expansion length (L_{exp}^*) of 9, aspect ratio (AR) of 2 and fully developed velocity profile at inlet. The effect of each variable on average static pressure distribution, average stagnation pressure drop and streamline contour has been studied in detail and compared with the configurations of plain sudden expansion and contraction (i.e. without tab), and sudden expansion and contraction with fence for few cases. From the study, it is revealed that the maximum magnitude of average static pressure rise for sudden expansion and contraction with rectangular tab configuration is more compared to the considered two configurations of plain sudden expansion and contraction, and sudden expansion and contraction with fence. The average stagnation pressure drop across a section and the size of the corner recirculating bubble are always more for rectangular tab configuration compared to other two considered configurations.

Index Terms— Sudden expansion and contraction, expansion length, tab restriction, tab length, static pressure, stagnation pressure, streamline contour.

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1 Introduction

The symmetric expansion and contraction, in particular, is a primitive geometry occurring in numerous engineering and industrial applications for various equipments e.g. burners, spray driers, heat exchangers, diffuser, dump combustors, extrusion processes, mixing chamber, plastic modelling processes, chemical plants, processing of pharmaceutical matter, handling transport equipment and many other manufacturing processes. In such flow situations, fluid is decelerated to ensure in increase in the static pressure and to get the recirculating bubbles for the mixing of two or several fluid as a mixing chamber in the decelerated zone. In this research activity, we have become interested to study the flow characteristics of fluid passing through a sudden expansion and contraction geometry with some modification. The modification of the said configuration is considered by incorporating some rectangular tab restrictions with different height and length, and placed in the inlet zone.

Since long, plain sudden expansion configurations, some modified sudden expansion configurations, some plain sudden expansion and contraction configurations, and some modified sudden expansion and contraction configurations have been noted to be of interest of number of researchers. Some of them have considered the configuration as diffuser and some have considered as combustor or mixing chamber. From review of literature, it has been noted that Abdelall et al. [1] have experimentally investigated the pressure drops separately caused by abrupt flow area expansion as well as contraction in small circular channels using air and water at room temperature and near-atmospheric pressure as the working fluids. Brewster [2] has computed numerical solution of pressure drops and centreline velocity for the steady laminar fully-developed flow of non-Newtonian fluids in circular ducts. Chakrabarti et al. [3] have numerically investigated the performance simulation of a vertex controlled diffuser (VCD) in low Reynolds number regime. Chakrabarti et al. [4] have presented the results of numerical simulation on the performance of a sudden expansion with fence viewed as a diffuser. Chalfi and Ghiaasiaan [5] have experimentally investigated the single phase and two-phase flow pressure drop caused by flow area expansion as well as contraction separately of two capillaries using air and water. Hermany et al. [6] have analysed the effect of inertia on the flow of viscoplastic liquids through an axisymmetric expansion followed by a contraction. Mendes et al. [7] have experimentally and numerically studied the internal flow of viscoplastic liquids through ducts consisting of an abrupt axisymmetric expansion followed by an abrupt contraction. Naccache and Barbosa [8] have analysed numerically the creeping flow of a viscoplastic fluid flow through a planar channel with an expansion followed by a contraction. Nassar et al. [9] have numerically investigated the elastic behavior of viscoplastic liquids. Sau [10] has numerically studied the vortex dynamics and mass entrainment in a rectangular channel with a combination of suddenly expanded and contracted part. Sunarso et al. [11] have performed numerical simulation to investigate the effect of wall slip on the flow of Newtonian and non-Newtonian fluids in micro and micro contraction channels.

As per brief review of literature, it is noted that a number of researchers have studied separately the fluid flow characteristics through plain sudden expansion configurations; some modified sudden expansion

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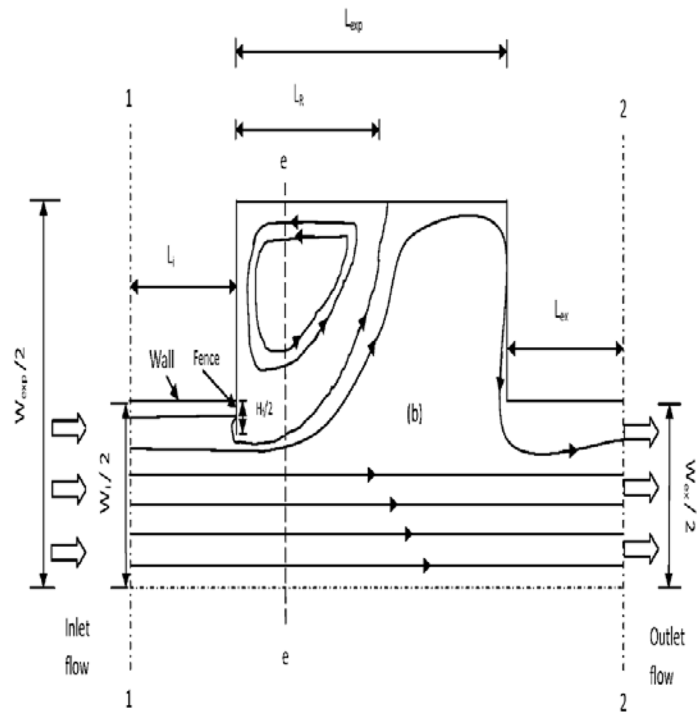
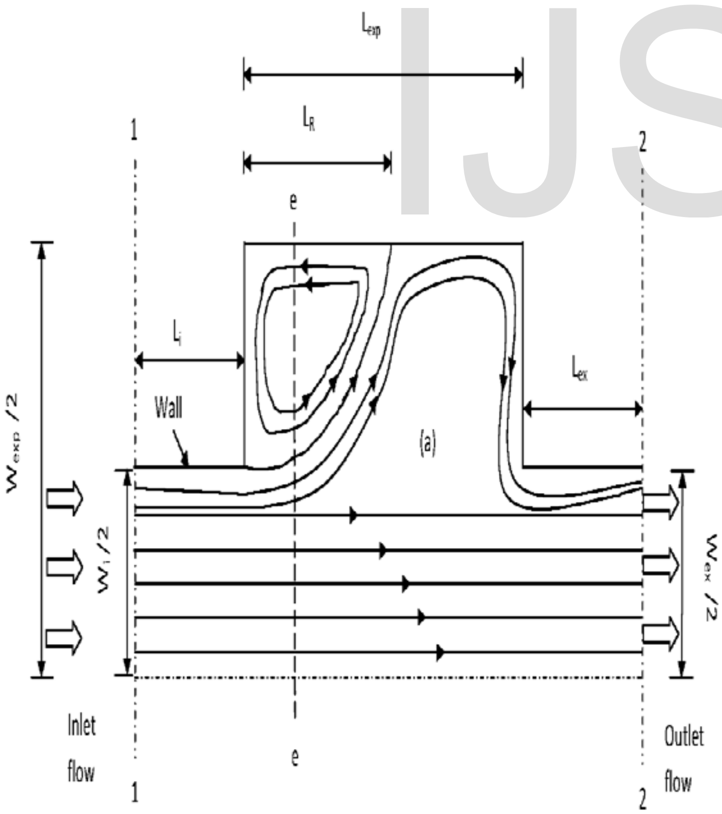
configurations, some plain sudden expansion and contraction configurations, and very rarely modified sudden expansion and contraction configurations. However, the authors have noted that a systematic study on the fluid flow analysis in respect of pressure characteristics and streamlines contour through the rectangular configuration of combined sudden expansion and contraction with rectangular tab geometry is inadequate. Therefore, in this paper, an attempt has been made to perform a numerical experimentation on effect of Reynolds number, tab restriction and tab length on average static pressure, average stagnation pressure and streamline contour of fluid passing through expansion and contraction with rectangular tab configuration.

2 MATHEMATICAL FORMULATION

2.1 Governing Equations

A Schematic diagram of the computational domain of flow through a plain sudden expansion and contraction, sudden expansion and contraction with fence and sudden expansion and contraction with rectangular tab configuration is illustrated in Fig. 1. (a), (b) and (c) respectively.





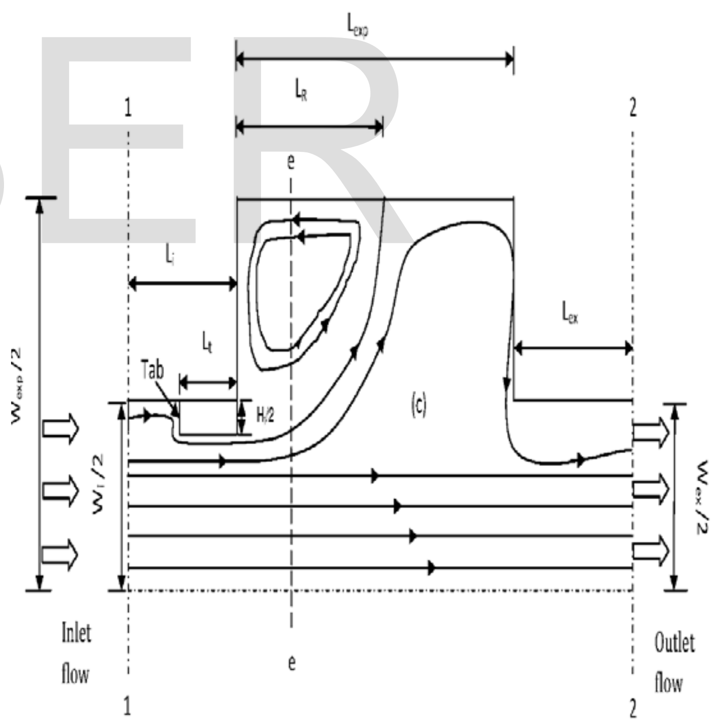


Fig. 1. Schematic diagram of the computational domain of flow through (a) plain sudden expansion and contraction (b) sudden expansion and contraction with fence (c) sudden expansion and contraction with rectangular tab

The flow under consideration is assumed to be steady, two dimensional, laminar and axisymmetric and 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;

$$\text{Lengths}: x^* = x/W_i,\ y^* = y/W_i,\ L_i^* = L_i/W_i,$$
$$L_{exp}^* = L_{exp}/W_i,\ L_{ex}^* = L_{ex}/W_i,\ L_R^* = L_R/W_i,$$
$$H_f^* = H_f/W_i,\ H_t^* = H_t/W_i,\ L_t^* = L_t/W_i$$
$$\text{Velocity}: u^* = u/U,\ v^* = v/U$$
$$\text{Pressure}: p^* = p/\rho U^2$$

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

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

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

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

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

2.2 Boundary Conditions

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

1. At the walls: No slip condition will be used, i.e., $u^* = 0,\ v^* = 0$.
2. At the inlet: Axial velocity will be specified and the transverse velocity will be set to zero, i.e., $u^* = specified,\ v^* = 0$.
   Fully developed flow condition will be specified at the inlet,
   i.e., $u^* = 1.5\left[1 - \left(2y^*\right)^2\right]$.
3. At the exit: Fully developed condition will be assumed and hence gradients will be 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 will be set to zero, i.e., $\partial u^*/\partial y^* = 0,\ v^* = 0$

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2.3 Numerical Procedure

The partial differential equations of mass and momentum conservation equations (1)-(3) have been discretized by a control volume based finite difference method. Power law scheme is used to discretise the convective terms from Patankar (1980). 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 present computation, the flow is assumed to be fully developed at the inlet and exit. For all the calculations, inlet length (L_i^*), expansion length (L_{exp}^*) and exit length (L_{ex}^*) are considered to be 1, 9 and 9 respectively during computation. 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 independence test has been carried out with different grid densities for AR=2 and Re=100. The result of the grid independence test is quantified and the outcome of such an exercise, in terms of the magnitude and location of Ψ_{max} has been performed. Finally, the numerical mesh comprised of 19x17 grid nodes in the inlet section, 147x43 grid nodes in the expansion section and 147x37 in the exit section in x and y directions respectively have been considered in the numerical computations during study.

3 RESULTS AND DISCUSSIONS

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

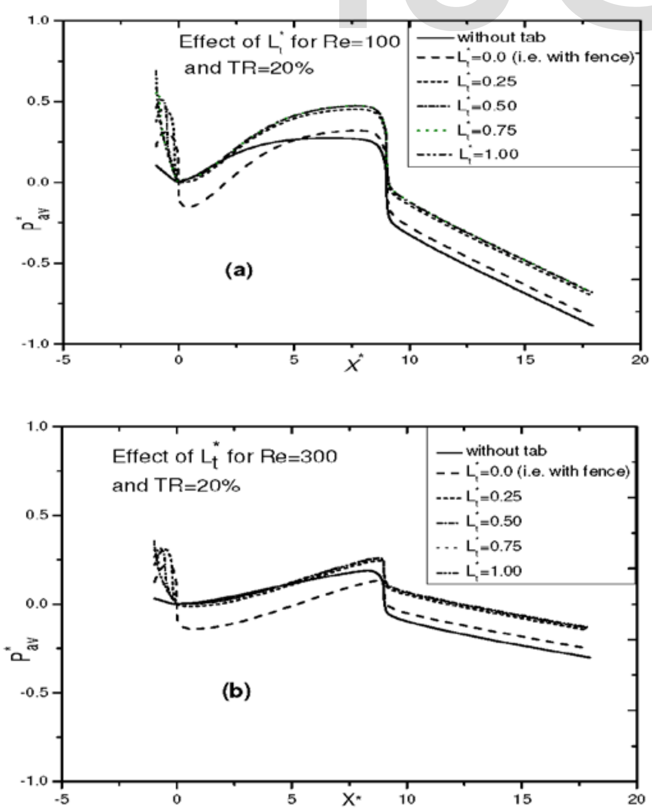
(i) Reynolds number, $50 \leq Re \leq 300$
(ii) Aspect ratio, $A^* = 2$
(iii) Tab restriction (TR)=0% to 40%, Tab length (L_t^*) = 0 to 1
(iv) Length(non-dimensional): Inlet = 1, Expansion length = 9, Exit = 9
(v) Inlet velocity distribution: Fully developed

3.1 Average Static Pressure Distribution along the axial Length

In view of engineering and industrial applications, the static pressure is considered to be an important parameter in assessing the performance of various equipments or components e.g., diffuser, combustor, mixing chamber etc. Therefore, in this section, an attempt has been made to study the effect of Reynolds numbers and percentage of tab restriction on the average static pressure in different regions of sudden expansion and contraction with tab configuration. In the present work, the average static pressure at any cross-section is determined by the following expression:

$$P_{av} = \frac{\int p\,dA}{\int dA} \qquad (4)$$

Fig. 2 represents the variation of average static pressure along the axial distance of the equipments. The most remarkable feature of this study is that it clearly shows the advantages of sudden expansion and contraction with tab restriction over the plain sudden expansion and contraction configuration as far as the maximum magnitude of the static pressure rise is concerned. The general behaviour of the curves is that in the inlet section, the steep fall of average static pressure takes place at the throat. This is an expected behaviour because, across the throat region, there is a sudden increase in area i.e. the denominator in the above expression increases sharply and compensates the steep fall of average static pressure at the throat. Then at the post throat region, at a given section there are zones of positive pressure and negative pressure. So the numerator is greatly affected by the presence of the negative pressure zone. For this reason, the average static pressure rise during this post-throat zone is small. As one move further downstream towards the end of expansion length, the zone of positive pressure increases at the expense of the negative pressure zone. Thereafter, in combination with the higher kinetic energy diffusion within the main stream this produces a significant pressure recovery. After that, the spatial rate of pressure rise gradually decreases as the average static pressure moves towards its maximum value. This is because the rate of increase in the average static pressure is decayed by the higher fluid friction involved in larger length of the wall of the expansion section. After reaching the maximum value, the average static pressure gradually droops due to dominating frictional effect for the rest of the expansion region. At the end of expansion length, the pressure is abruptly decreased up to the starting of contraction wall due to obstruction and fluid friction. From the beginning of contraction section or exit section, the average static pressure gradually droops due to higher fluid friction involved in larger contraction length.



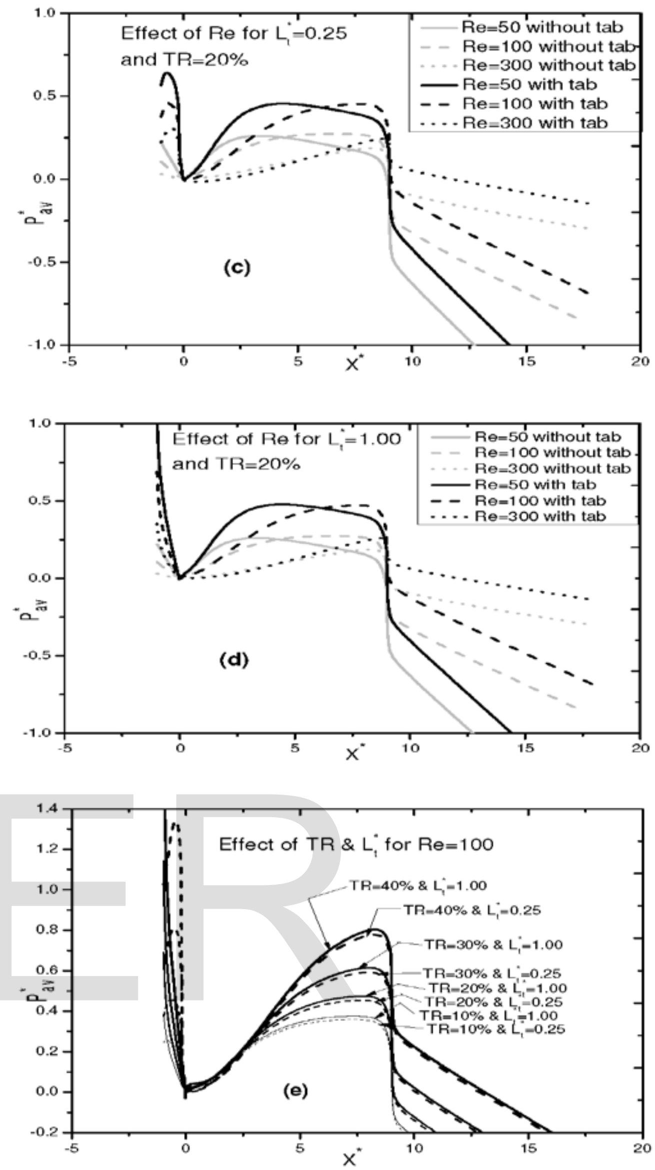


Fig. 2. Average static pressure distribution with axial length

In fig. 2(a) and 2(b), the average static pressure variations along the axial distance are plotted for plain sudden expansion and contraction (i.e. without tab), and sudden expansion and contraction with tab length ranging from 0 to 1 and tab restriction of 20% for typical Reynolds numbers of 100 and 300 respectively. From the said figures, it is observed that the maximum magnitude of average static pressure increases as the length of tab increases up to 0.50 and no further increase with increase of length of tab. This can be reasoned as, with increase in length of tab, the static pressure rise increases steeply due to more kinetic energy diffusion for the tab restriction up to some extent. Further increase in length of the tab, though the kinetic energy diffusion increases, simultaneously the length of the corner recirculation zone increases which gives more negative pressure zone, resulting in loss of static pressure at a particular section. It is also observed that the maximum

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magnitude of average static pressure is more for sudden expansion and contraction with rectangular tab configuration than sudden expansion and contraction with fence. This can be reasoned as, there is more kinetic energy diffusion in case of rectangular tab. Fig. 2(c) and 2(d) represent the variation of average static pressure with distance for plain sudden expansion and contraction, and sudden expansion and contraction with tab for Reynolds numbers of 50, 100 and 300 and typically tab length of 0.25 and 1.00. From the figure, it is observed that the maximum magnitude of average static pressure increases with increase in Reynolds number of 50 and 100 for typical length of tab. This can be reasoned as, with increase in Reynolds number, the kinetic energy diffusion increases. For the Reynolds number of 300, the maximum magnitude of average static pressure decreases for typical length of tab. The reason is explained earlier. Fig. 2(e) shows the distribution of average static pressure with axial distance considering three limiting cases of tab restriction of 10%, 30% and 40% for sudden expansion and contraction with tab with different length of tabs and typical Reynolds number of 100. From the figure it is observed that the maximum average static pressure rise increases with increase in both height and length of the tab. This can be reasoned as, with increase in tab restriction, the kinetic energy diffusion increases. Moreover, the important feature is that the maximum magnitude of average static pressure rise for sudden expansion and contraction with rectangular tab configuration is more compared to the plain sudden expansion and contraction configuration and sudden expansion and contraction with fence configuration.

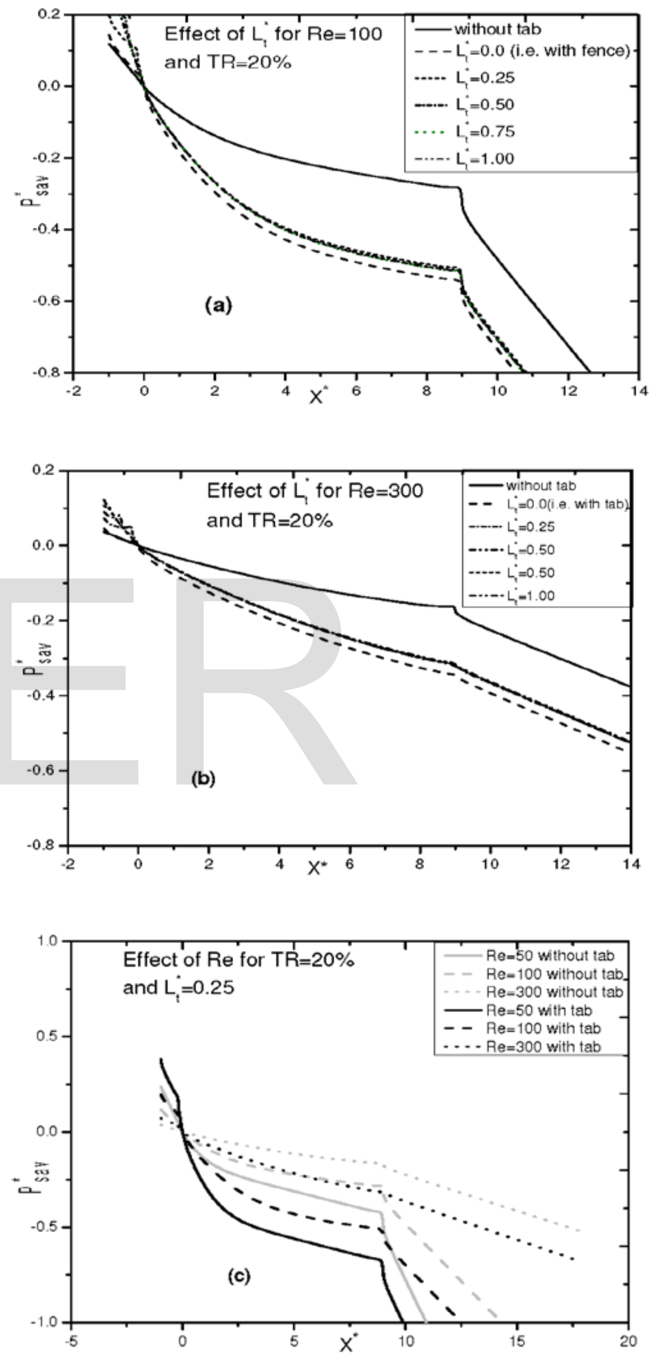
3.2 Average Stagnation Pressure Distribution along the Axial Length

The average stagnation pressure at any section is an important parameter to determine the performance of various industrial equipments or components e.g., diffuser, combustor, mixing chamber etc which are significant with the cycle calculations, as a whole, depends to a large extent on the stagnation pressure drops across such components. But, this parameter is non-important in case of biomedical area. However, stagnation pressure is constant in a stream flowing without heat or work transfer only if friction is absent i.e. the stagnation pressure drop can be used as a measure of fluid friction. The average stagnation pressure at any section can be computed by the following expression:

$$\overline{P_s} = \frac{\int_{A_e} \left(p_e + \frac{1}{2}\rho \overline{V_e}^{\,2} \right) u_e \, dA_e}{\int_{A_e} u_e \, dA_e} \qquad (5)$$

Where the subscript 'e' refers to the plane of measurement. The direction of the velocity vector, particularly for a recirculating type flow situation, has been taken into account during the calculation of average stagnation pressure at any given section.

The average stagnation pressure along the length is calculated by using the above equation in dimensionless form. The effect of flow Reynolds numbers and tab restriction on average stagnation pressure is described in Fig.3. The general behaviour of all curves is drooping characteristics.



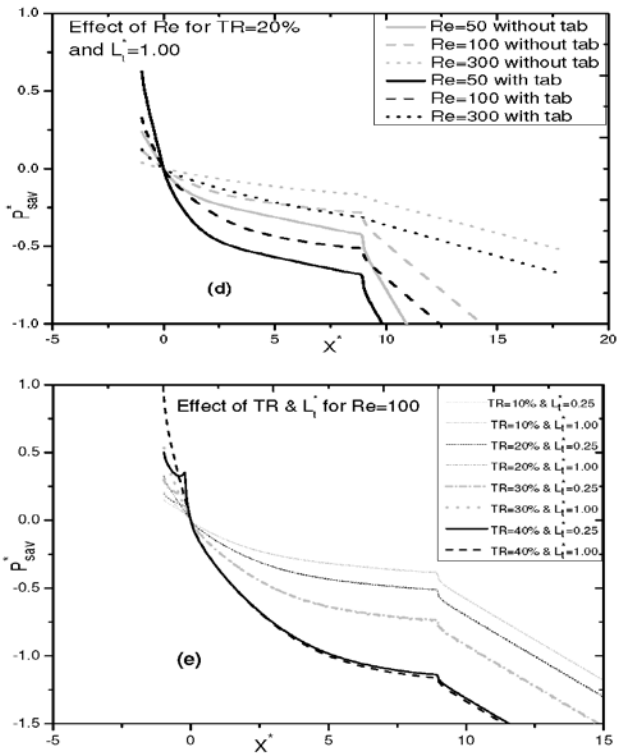


Fig. 3. Average stagnation pressure distribution with axial length

In fig. 3(a) and 3(b), the average stagnation pressure variations along the axial distance are plotted for plain sudden expansion and contraction (i.e. without tab), and sudden expansion and contraction with length of tabs 0.0, 0.25, 0.50, 0.75 and 1.00 at tab restriction of 20% for typical Reynolds numbers of 100 and 300 respectively. From the figure, it is observed that as the length of the tab increases (i.e. tab restriction increases) with a fixed Reynolds number, the average stagnation pressure drop at any section increases in post throat zone. This is happening because, with increase in tab restriction, the viscous dissipative effect dominates the effect of kinetic energy diffusion which decreases static pressure, and this leads to increase in average stagnation pressure drop at any section. Fig. 3(c) and 3(d) represent the variation of average stagnation pressure with axial distance for plain sudden expansion and contraction, and sudden expansion and contraction for Reynolds numbers of 50, 100 and 300 with typically length of tab 0.25 and 1.00 respectively. From the figure, it is again seen that average stagnation pressure drop at any section decreases with increase in Reynolds number. This can be reasoned as, for higher Reynolds number the kinetic energy contribution towards the working fluid at a section will be higher leading to the possibility of higher average stagnation pressure at that section. Fig. 3(e) shows the variation of average stagnation pressure with axial distance considering three limiting cases of height of the tab 0.10, 0.30 and 0.40 for sudden expansion and contraction with tab with different length of tabs and typical Reynolds number of 100. From the figure it is observed that the average stagnation pressure drop increases with increase in both height and length of the tab. This is happening because, with increase in tab restriction, the viscous dissipative effect dominates the effect of kinetic energy diffusion which decreases static pressure, and this leads to increase in average stagnation pressure drop at any section. From the figures, it is also observed that at a particular value of Reynolds number, average stagnation pressure drop at any section is always more when a fixed rectangular tab restriction is considered compared to the plain sudden expansion and contraction configuration. But the average stagnation pressure drop across a section for rectangular tab configuration is less compared to the fence configuration.

3.3 Variation of Streamline Contours

The recirculating bubble occurs immediately downstream of the sudden expansion is encountered in many practical systems the 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. The mixing intensity of the combustion process is increased with increasing of recirculation zone. The proper mixing inside combustion chamber results stable combustion, fuel economy, lower NO_x emission etc. Therefore, the detail study on the recirculation zone is included in this section. The streamline contours for sudden expansion and contraction with typical length of the tab 0.25 and 1.00 for Reynolds numbers of 50, 100, 200 and 300 at aspect ratio of 2 are shown in fig.4(a) and 4(b) respectively. At these considered tab restriction, it is observed that the size of recirculating bubble at corner region increases with increase in Reynolds number. This can be reasoned as, for higher Reynolds number flow, the kinetic energy contribution towards the working fluid at corner restriction zone becomes higher resulting in higher size of recirculating bubbles at this zone. This reveals that at a fixed value of Reynolds number, kinetic energy diffusion increases when tab restriction is considered.

Fig. 5(a) & 5(b) show the variation of streamline contours for sudden expansion and contraction with the length of the tab 0.0, 0.25, 0.50, 0.75 and 1.00 for typical Reynolds number of 100 and 300. From the figure, it is observed that at a fixed value of Reynolds number the length of the recirculating bubble at corner region increases with increase in length of the tab restriction. This can be reasoned as, with increase in percentage of tab restriction diffusion increases at the corner zone, resulting in higher size of recirculating bubbles at this zone. From the said figures it is also noted that at expansion length of 9 for higher Reynolds numbers, the bubble becomes compacted due to shortage of space. From the figure it is interesting to note that the size of the corner recirculating bubble is more in case of sudden expansion and contraction with tab configuration compared to plain sudden expansion and contraction configuration and sudden expansion and contraction with fence configuration for a particular value of Reynolds number.

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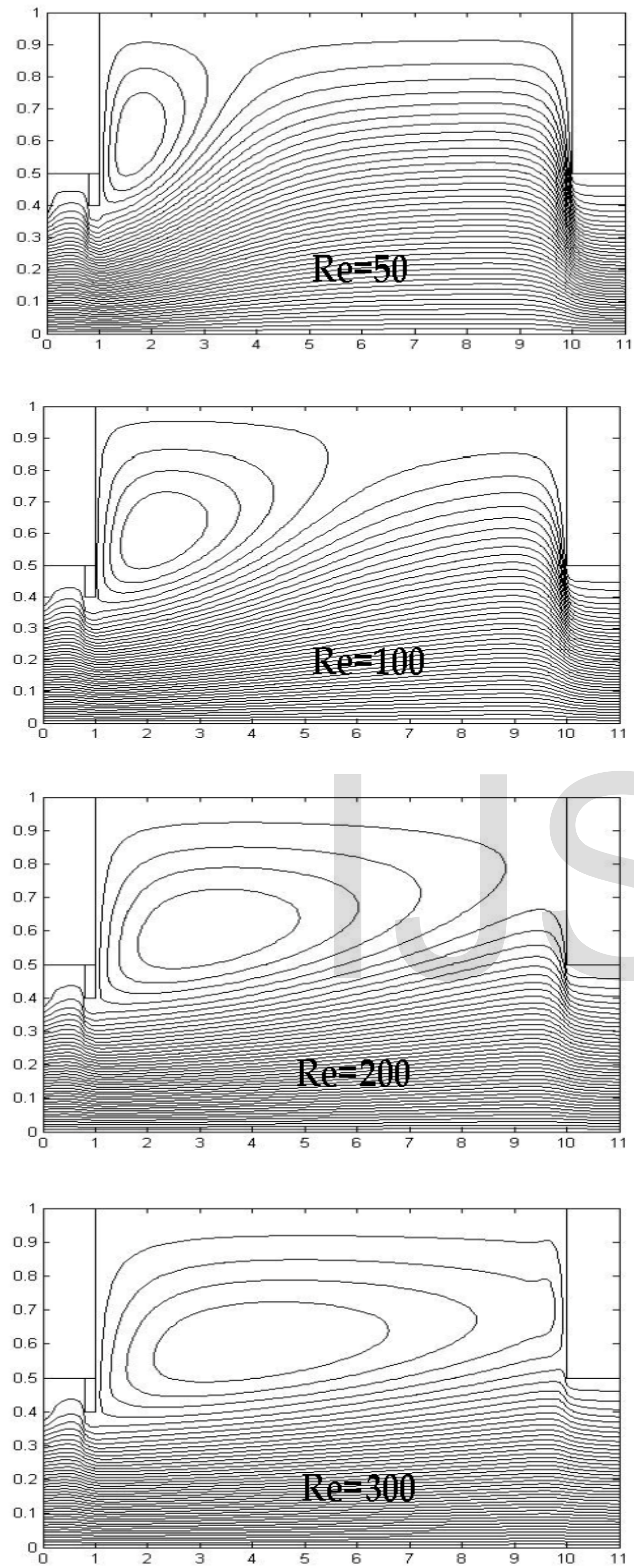

Fig. 4(a) Variation of streamline contour for TR=20% and L_t^* = 0.25

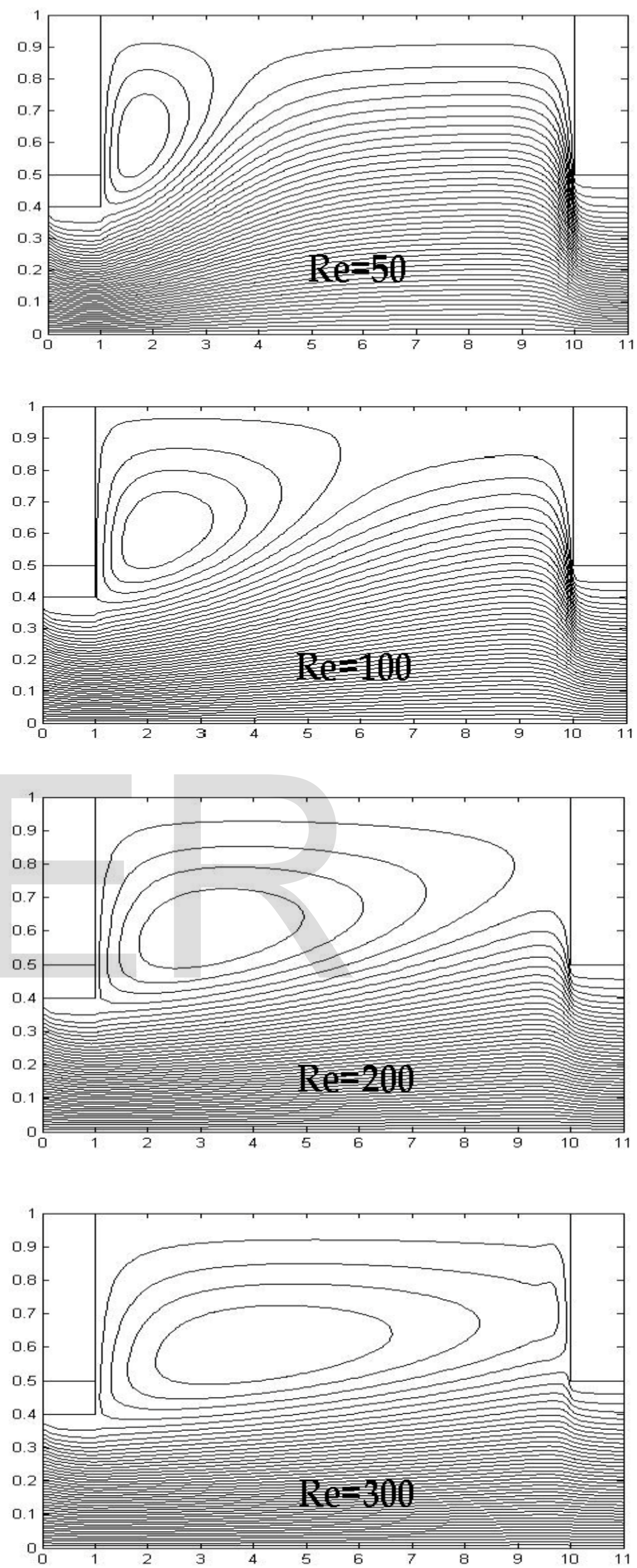

Fig. 4(b) Variation of Streamline contour for TR=20% and L_t^* = 1.00

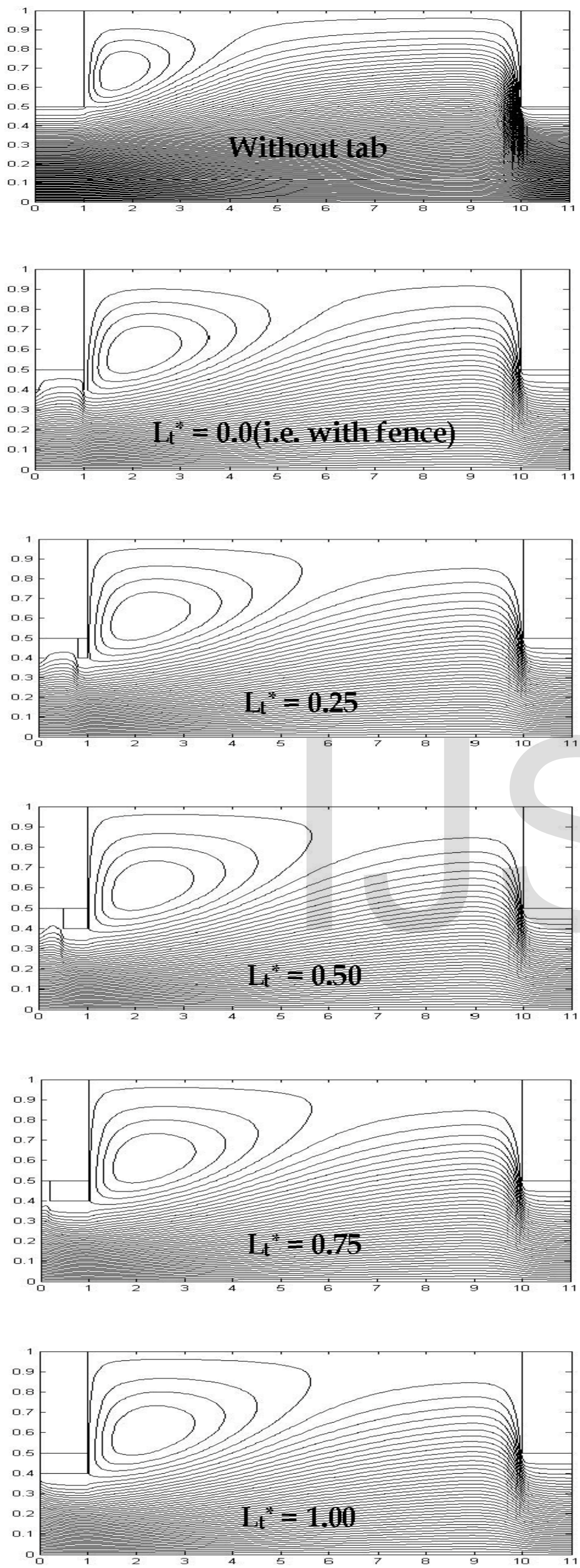

Fig. 5(a) Variation of Streamline contour for Re=100 and TR=20%

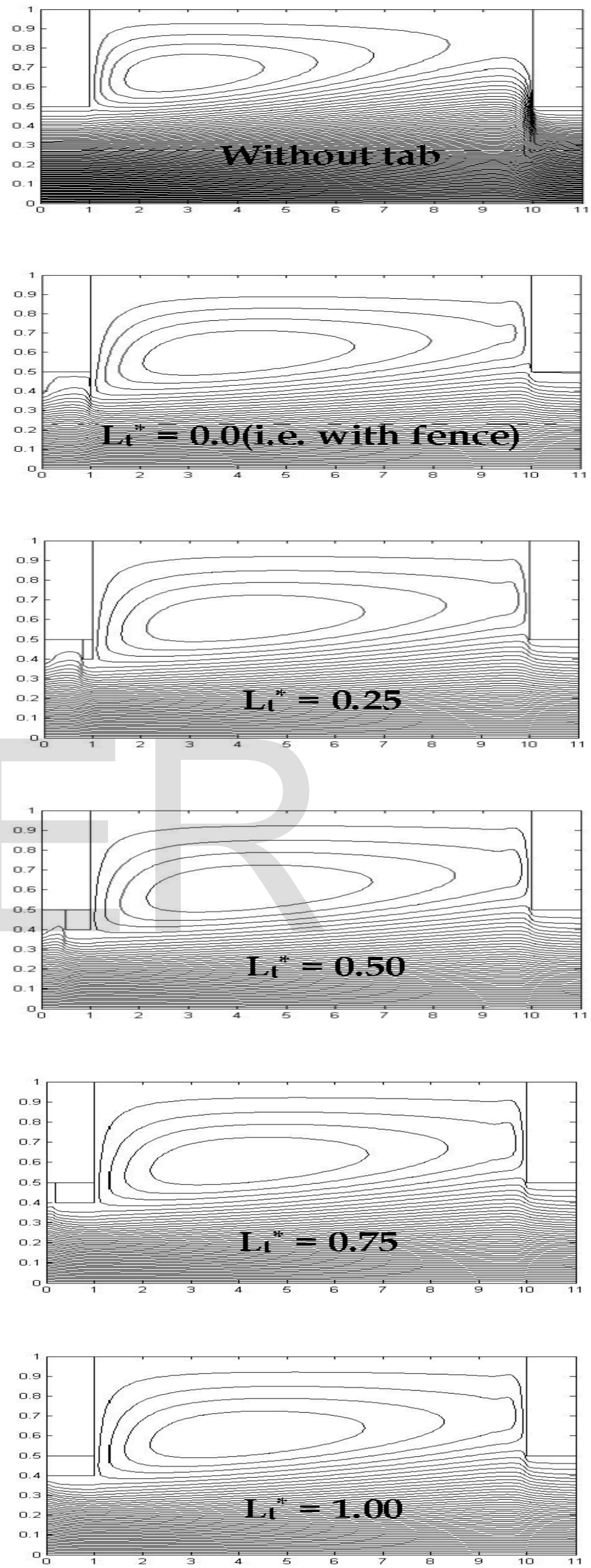

Fig. 5(b) Variation of Streamline contour for Re=300 and TR=20%

4 CONCLUSIONS

In this work, a flow characteristics study in a configuration of combined sudden expansion and contraction with rectangular tab in low Reynolds number regime with fully developed velocity profile at inlet has been carried out. The effect of Reynolds number, tab restriction and tab length on average static pressure, average stagnation pressure and streamline contour have been studied in detail and the following important features have been revealed by us as:

1. The average static pressure rise typically depends on flow Reynolds number and tab sizes. The maximum magnitude of average static pressure increases with increase in Reynolds number for typical length of tab of 0.25. The maximum average static pressure rise increases with increase in both tab restriction and tab length. Higher the Reynolds number lower is the rate of increase in the average static pressure. The maximum average static pressure rise occurs earlier for lower value of Reynolds number. Moreover, the important feature is that the maximum magnitude of average static pressure rise is more for sudden expansion and contraction with rectangular tab configuration as compared to the configurations of plain sudden expansion and contraction, and sudden expansion and contraction with fence.
2. As the size of the rectangular tab restriction increases with a fixed Reynolds number, the average stagnation pressure drop at any section increases in post throat zone. But this average stagnation pressure drop at any section decreases with increase in Reynolds number. When other parameters remain constant the average stagnation pressure drop across a section is more for rectangular tab configuration compared to the plain sudden expansion and contraction configuration. But, the average stagnation pressure drop across a section for rectangular tab configuration is less compared to the fence configuration.
3. From the streamlines, it is revealed that the size of the corner recirculating bubble size increases with increase in Reynolds number for all considered configurations. At a fixed value of Reynolds number, the length of the recirculating bubble at corner region increases with increase in tab restriction and tab length. The size of the corner recirculating bubble for sudden expansion and contraction with rectangular tab configuration is more compared to plain sudden expansion and contraction configuration and sudden expansion and contraction with fence configuration. At higher magnitude of Reynolds number, the size of recirculation bubble becomes compacted due to shortage of space.

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