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Research Article

A NUMERICAL STUDY ON THE PRESSURE VARIATION IN A SUDDEN EXPANSION AND A 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, viewed as a diffuser, has been carried out. The two dimensional steady differential equations for conservation of mass and momentum are solved for Reynolds number(Re) from 10 to 100 and CR from 0% to 30% for an aspect ratio (AR) of 2 and fully developed velocity profile at inlet. From the study, it is revealed that for sudden expansion, maximum wall pressure decreases with the increase in Re. Sudden expansion with central restriction also behaves in same way. Location of the maximum wall pressure increases with increase in Re for both sudden expansion and sudden expansion with central restriction. The value of maximum average static pressure increases with increase in Re for both sudden expansion and sudden expansion with central restriction. Location of the maximum average static pressure from the throat, which may be considered as the effective length of the diffuser, increases with Re for both the cases. In case of sudden expansion with central restriction, maximum average static pressure increases with the increase in CR but its location from throat remains more or less same, at a particular value of Re. In comparison to a simple sudden expansion, the magnitude of maximum average static pressure is more and the location of maximum average static pressure from the throat is less for sudden expansion with central restriction.
Therefore, choice of the configuration of sudden expansion with central restriction, as a diffuser, is more attractive in comparison to the configuration of a simple sudden expansion.

Keywords: *central restriction, wall pressure, static pressure*

1. Introduction

In many flow situations, fluid is decelerated to ensure in increase in the static pressure and the mixing capabilities in the decelerated zone. Among its many applications, particular mention must be made of the function of the diffuser, or mixing chamber and combustor etc. At the outset, the sudden expansion configuration uses to come in mind as the required device. In this research activity, we have become interested to see the effect of incorporation of central restriction in the inlet portion in sudden expansion configuration.

From literature, it appears that the first work in the field of sudden expansion was carried out by Macagno and Hung [1] who studied flow visualization in sudden expansions in axisymmetric flows for a Reynolds number range of 36 to 4500, by means of computational simulation, for an aspect ratio of 2 and of Reynolds number up to 200. They concluded that, for laminar flow, the main role of the eddy was that of shaping the flow with a rather small energy exchange. Durst and Pereira [2] carried out numerical prediction of laminar, steady, two-dimensional, backward facing step channel flow with an area ratio 1:1.94 for three different Reynolds numbers of 10, 389 and 648. Schadow and Gutmark [3] experimentally studied combustion instabilities in a variety of dump combustors and bluff-body flameholder geometries, including two-dimensional and axisymmetric dump combustors, side dump, cylindrical, and rectangular flame stabilizers. Schreck and Schafer [4] studied numerically bifurcation phenomena in channels with a sudden expansion. They considered the bifurcation diagram for three different channel geometry taking aspect ratio 2, 5, and ". Chakrabarti et al. [5] carried out an extensive study on the performance of sudden expansion from the perspective of a diffuser. They used Reynolds number ranging from 20 to 100, aspect ratio from 1.5 to 4, for uniform velocity profile and fully developed velocity profile at inlet, and for different inlet lengths. They studied the effect of each variable on the diffuser efficiency and the stagnation pressure drop gradient in detail. They observed that the maximum diffuser efficiency occur at an aspect ratio of around two.

Some researchers studied the problem numerically and experimentally by considering vortex controlled phenomenon. Among them, Sullerey et. al. [6] carried out investigations to evaluate experimentally the effect of various vortex controlled diffusers geometry, suction rates and diffuser inlet velocity profile on the diffuser exit flow distribution and pressure recovery. In their work, they considered two types of two-dimensional diffusers, vortex controlled and hybrid diffusers. Chakrabarti et. al. [7] carried out the performance simulation of a vortex controlled diffuser in low Reynolds number regime. They solved the two dimensional steady differential equations for conservation of mass and momentum for the Reynolds number ranging from 20 to 100, aspect ratio for 2 and 4, and bleed fraction for 2 per cent, 5 per cent and 10 per cent. They observed that the static pressure rise increases with increase in bleed for a given aspect ratio and Reynolds number.

As per brief review of literature, it is noted that the flow through sudden expansion geometry or annular configuration geometry has been studied numerically and experimentally by a number of investigators separately. However, it is realized that a systematic study on the variations in average static pressure and average stagnation pressure in sudden expansion with central restriction is inadequate. Hence, in the present work an attempt is made to study the effect of sudden expansion configuration and sudden expansion with central restriction configuration on average static pressure and average stagnation pressure.

2. Mathematical Formulation

2.1 Governing equations

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

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

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

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

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

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

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

where, the flow Reynolds number, $\mathrm{Re} = \rho U W_1/\mu$.

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 [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 fully developed at the inlet and exit and therefore, exit is chosen far away from the throat. For all the calculations, the non-dimensional inlet and the exit lengths are considered to be 1 and 50 respectively. 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. During the study of the grid independence test, the discritization of the inlet section was held at 41×37 grid i.e, 11 nodes along the x direction and 13 nodes along the y-direction. After grid independence test, finally the numerical mesh comprised of 221×121 grid nodes for the exit section in x and y directions has been considered in the present work.

3. 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 d” Re d” 100
(2) Central restriction from 0% to 40%
(3) Aspect ratio, AR = 2

3.1 Variation of static pressure along the solid boundary

The variation of wall pressure along the solid boundary is shown in Fig. 2. The variation of the wall pressure along the solid boundary for Reynolds number of 50, 70 and 100 and the aspect ratio of 2 for plain sudden expansion and sudden expansion with typically 20% central restriction has been shown in Fig. 2(a) and Fig. 2(b) respectively. It is seen that for all the Reynolds numbers, the flow behaves in a similar manner characterised by a sharp drop in the wall pressure, as it approaches the step where the flow expansion occurs for sudden expansion and sudden expansion with central restriction. This similarity is expected, as the flow is fully developed at the inlet. After this sharp drop in wall pressure, the wall begins to experience a rise in static pressure due to diffusion of fluid kinetic energy in the expanded section and thereafter the static pressure drop occur due to friction for all the cases. It is seen that the maximum wall pressure decreases with the increase in Re and the location of maximum wall pressure increases with increase in Re for the case of sudden expansion and sudden expansion with 20% central restriction for an AR of 2. Fig. 2(c) shows the variation of wall pressure along the solid boundary for sudden expansion with different percentage of central restrictions for typical Reynolds number of 100 and aspect ratio of 2. From the figure, it is observed that the maximum wall pressure increases with the increase in percentage of central restriction and the location of maximum wall pressure from throat remains nearly same position for 10%, 20% and 30% of central restriction but for plain sudden expansion configuration the distance is somewhat more.

3.2 Average static pressure rise along the axial distance

The variation of average static pressure along the axial distance is shown in Fig. 3. The variation of the average static pressure for Reynolds number of 50, 70 and 100 and the aspect ratio of 2 for plain sudden expansion and sudden expansion with typically 20% central restriction has been shown in Fig. 3(a) and Fig. 3(b) respectively. From the figures, it is observed that for both the cases of plain sudden expansion and sudden expansion with 20% central restriction, the general characteristics of the curves is that in the inlet section the steep fall of average static pressure takes place at the throat for each Reynolds number. The average static pressure rise in the just at the post throat region is small. With the increase in the distance in the downstream zone from the throat, there is more positive pressure and also increased kinetic energy diffusion resulting in significant pressure recovery at that zone. In case of plain sudden expansion, as the Reynolds number increases, the maximum average static pressure magnitude increases due to higher diffusion and the length of the maximum average static pressure rise from the throat also increases with flow Reynolds number. In case of sudden expansion with central restriction, the interesting feature is that at a particular value of Reynolds number, the maximum average static pressure rise is more compared to the case of plain sudden expansion. It may be attributed that the larger zone of diffusion with the increase in central restriction may cause the enhancement of static pressure rise. Fig. 3(c) shows the variation of average static pressure along the axial distance for sudden expansion with different percentage of central restrictions for typical Reynolds number of 100 and aspect ratio of 2. It is seen that the maximum average static pressure increases with increase in percentage of central restriction for a particular value of Reynolds number and aspect ratio. This can be reasoned as, with increase in percentage of central restriction, the static pressure rise increases steeply due to more diffusion for the central restriction.

4. Conclusions

In the present study, performance analysis of sudden expansion and sudden expansion with central restriction in low Reynolds number regime with fully developed velocity profile at inlet has been carried out. The effects of Reynolds number and central restriction on wall pressure and average static pressure have been investigated and this leads to the following important observations;

(i) As far as wall pressure is concerned, the maximum wall pressure decreases with the increase in Re and the location of maximum wall pressure increases with increase in Re at a particular value of aspect ratio. The maximum wall pressure increases with the increase in percentage of central restriction and the location of maximum wall pressure from throat remains nearly same position except plain sudden expansion configuration.

(ii) The average static pressure rise typically depends on flow Reynolds number, central restriction. At a particular value of Reynolds number, the maximum average static pressure rise is always more in case of sudden expansion with central restriction compared to the case of plain sudden expansion.

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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]
Pav Average static pressure, [N/m^2]
Ps Stagnation pressure, [N/m^2]
Psav Average stagnation 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
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
e Pertaining to section e-e

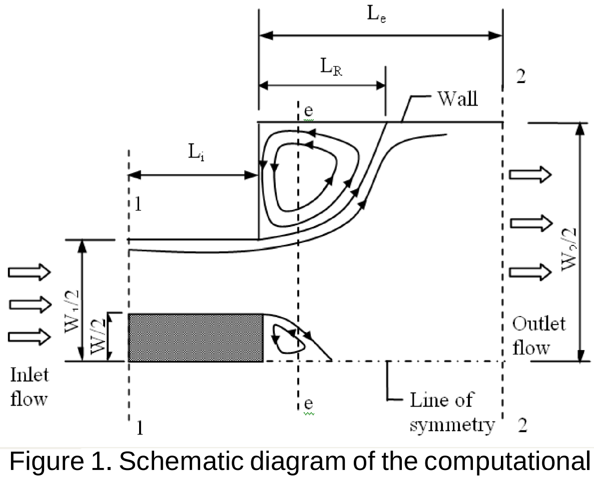

Figure 1. Schematic diagram of the computational domain (a) plain sudden expansion
(b) sudden expansion with central restriction

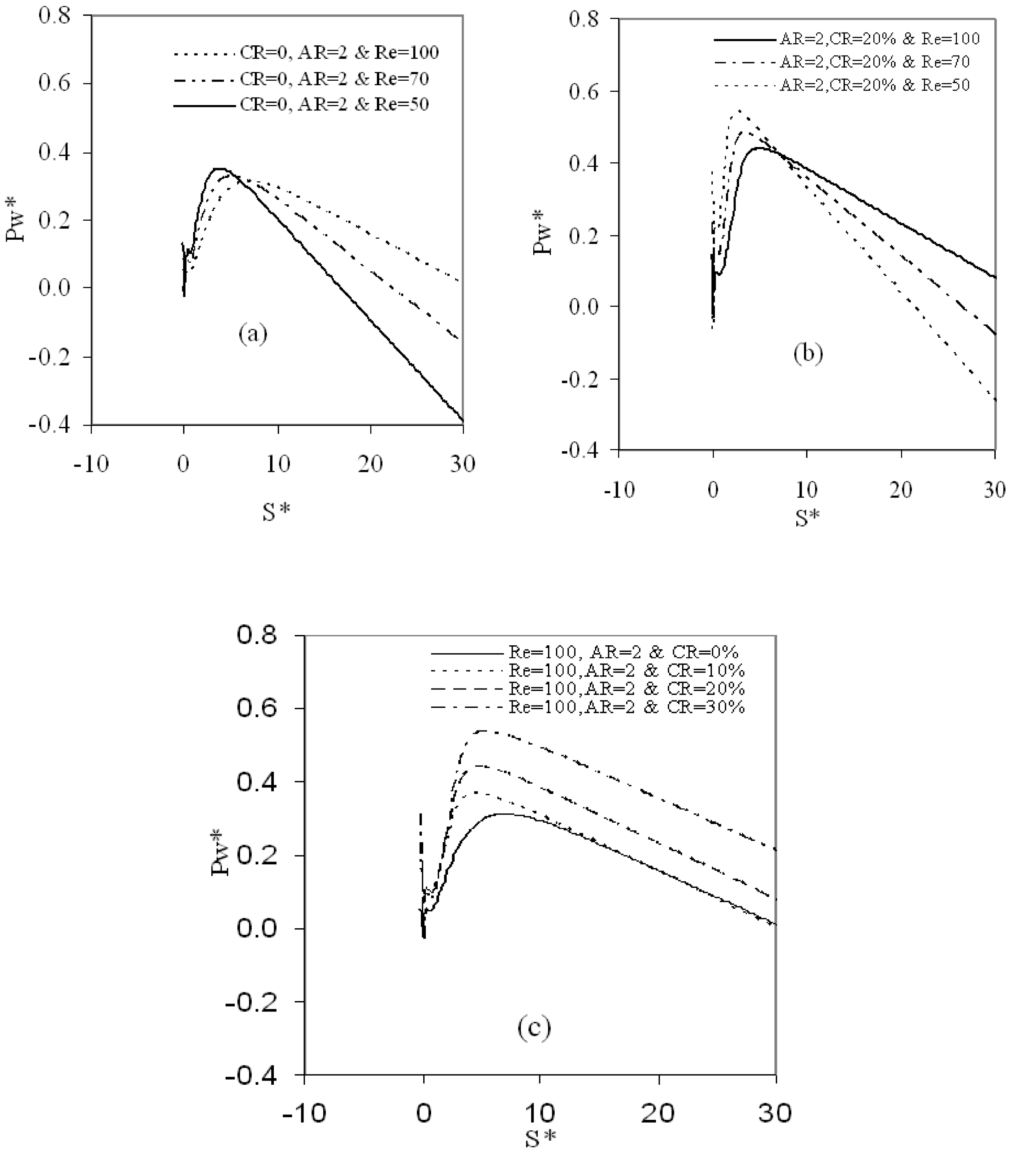

Figure 2. Variation of wall pressure with distance along the wall. (a) Plain sudden expansion (b) Sudden expansion with typically 20% central restriction (c) central restrictions from 0 to 30%

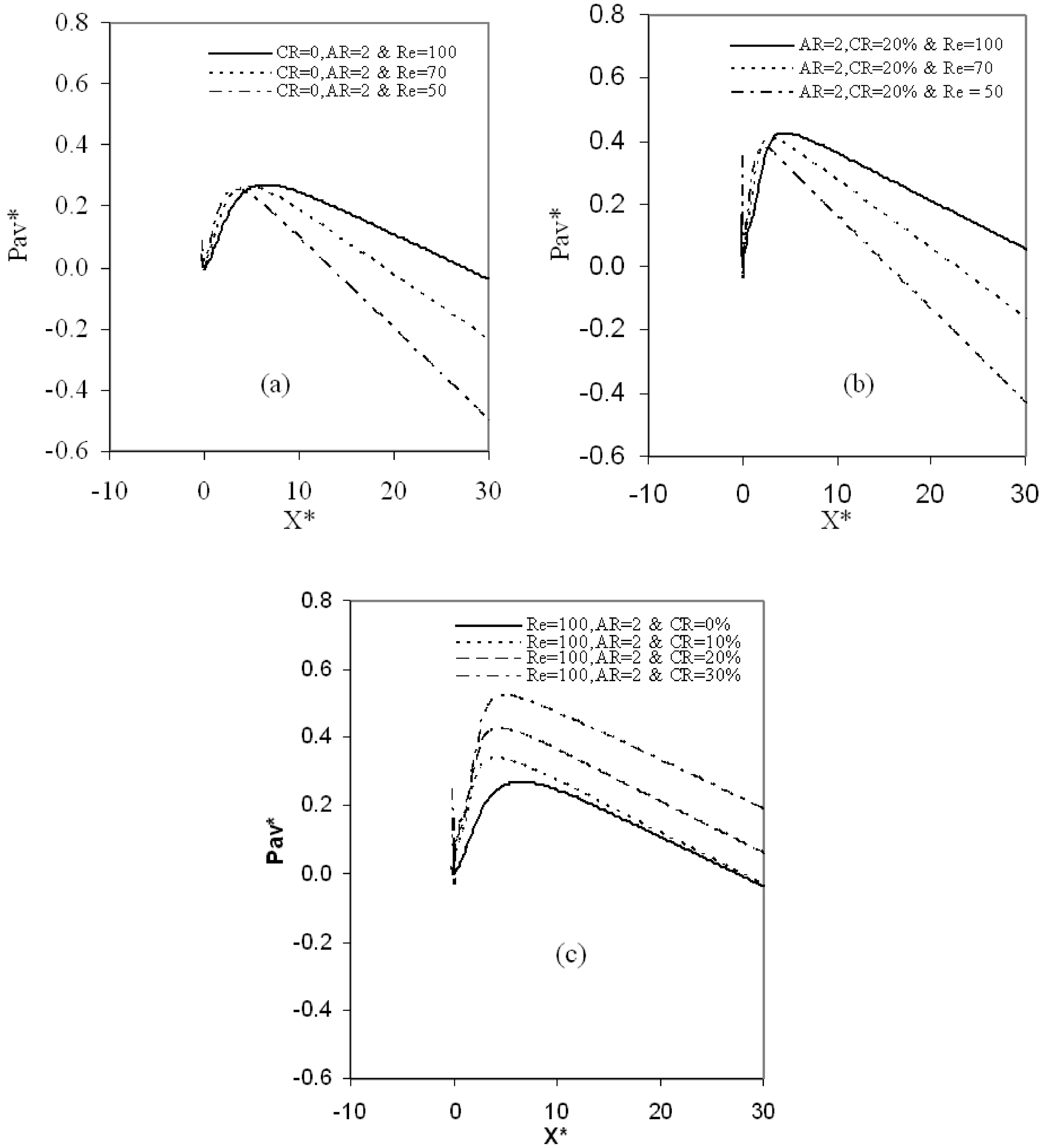

Figure 3. Variation of average static pressure with axial distance (a) Plain sudden expansion (b) Sudden expansion with typically 20% central restriction (c) central restrictions from 0 to 30%