A Numerical Study on Stagnation Pressure Drop Characteristics of Fluid Passing Through Two Modified Sudden Expansion Configurations

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Abstract : In this paper, a numerical study on stagnation pressure drop characteristics in configurations of sudden expansion with central restriction only (Model-1) and sudden expansion with central restriction and fence (Model-2) has been carried out. The two dimensional steady differential equations for conservation of mass and momentum are solved for Reynolds number ranging from 50 to 200, percentage of central restriction (CR) from 10% to 40% and for an aspect ratio (AR) from 1.5 to 6 for both the sudden expansion configurations. The effect of each variable on average stagnation pressure drop at the location of maximum average static pressure rise has been studied in detail. From the result it is noted that average stagnation pressure drop at the location of maximum average static pressure rise is less at lower aspect ratio, lower percentage of central restriction and higher flow Reynolds number. When two models are compared this pressure drop is always less for Model-2 when all other conditions remain same.

***IndexTerms* - Stagnation Pressure, Sudden Expansion, Central Restriction, Sudden expansion with fence.**

I. INTRODUCTION

In sudden expansion configuration, the fluid is required to flow through a passage of sudden increasing cross-sectional area; this results in a recovery of static pressure. Because, significant amount of energy is transferred from the main flow irreversibly to the recirculating eddies. However, since the flow is subjected to adverse pressure gradient, the flow separates from the walls resulting in substantial loss of stagnation pressure. As stagnation pressure is a matter of utmost significance in assessing the performance of various components and the cycle of a gas turbine based power plant, such losses in stagnation pressure in the said configuration may drop the overall plant efficiency. In this research activity, we have become interested to study the pressure characteristics in terms of average stagnation pressure drop considering two modified sudden expansion configurations. This modification is considered by incorporating some central restriction in the inlet zone of sudden expansion (Model-1) and a fence at the post throat zone of sudden expansion along with the inlet central restriction (Model-2).

Since long, sudden expansion configurations and some modified sudden expansion configurations have been noted to be of interest of number of researchers. From literature, it appears that the numerical study on modified sudden expansion configuration was carried out by Shyy [1]. He has investigated the flow characteristics of 2-D axisymmetric steady flow through an annular dump diffuser. He has considered Reynolds number of 10^5, based on the inlet height. He has used Reynolds-averaged equations for conservation of mass and momentum. Finite volume approximation along with SIMPLE solution procedure and staggered grid system are considered during numerical calculation. Sullerey et al. [2] have experimentally studied the effect of inlet flow distortion on the performance of vortex controlled diffusers. For this diffuser, they have considered sudden expansion geometry with a suction slot at the top and bottom portion of the vertical wall and fence (downstream of the sudden expansion) with a fence subtended angle in the range of 0 to 30 deg. They have studied the performance in terms of diffuser effectiveness and outlet velocity profiles. The diffuser effectiveness increases up to a particular bleed off is noted by them. They have observed that the nature of the exit velocity profile can be controlled by differential bleed. Foumeny et al. [3] have numerically investigated the bifurcation of incompressible flow through plane symmetric channel expansions. In their configuration, they have considered one, two and three parallel channels at the inlet of the symmetric sudden expansion geometry with an expansion ratio of 3. Sheen et al. [4] have experimentally investigated the flow characteristics in a concentric annular flow over an axisymmetric sudden expansion with inlet modification. They have used a centrebody at the inlet region to the sudden expansion configuration and inlet region becomes concentric annulus shape. Chakrabarti et al. [5] have numerically carried out the performance simulation of a vortex controlled diffuser in low Reynolds number regime. They have considered a sudden expansion configuration with suction slot on different position of vertical and horizontal walls. They have used 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. Abu-Nada et al. [6] have carried out numerical investigation of heat transfer and fluid flow over a backward facing step configuration under the effect of suction and blowing. In their configuration, part of the channel's bottom wall, adjacent to the step, is considered permeable and constant uniform velocity is allowed to bleed through it. They have used Reynolds number in the range of 200 to 800 and bleed coefficient ranging from -0.005 to 0.005 for an expansion ratio of 2. Chakrabarti et al. [7] have carried out numerical simulation on the performance of a modified sudden expansion configuration, viewed as a diffuser. In modification, they have considered a fence downstream of the throat of sudden expansion with a fixed fence subtended angle of 10°. They have considered Reynolds number ranging from 20 to 100, and distance of fence from throat from 0.2 to 2 for the aspect ratio of 2. Banerjee et al. [8] have numerically studied the performance of a modified sudden expansion diffuser in terms of static pressure rise. In their configuration, they have considered two fences at the downstream of the sudden expansion for fixed fence subtended angle of 10º. Tuncer et al. [9] have experimentally investigated the stability and structure of lean premixed methane air flames in a swirl stabilized premixed dump combustor at atmospheric pressure.

As per brief review of literature, it is noted that a number of researchers have studied the flow through sudden expansion geometry or sudden expansion with some modification. However, it is realized that study on pressure characteristics in case of sudden expansion configurations with central restriction and combined with fence is not addressed. Therefore it has motivated author to study systematically the effect of Reynolds number, percentage of central restriction and aspect ratio on average stagnation pressure drop at the location where static pressure rise becomes maximum of fluid passing through the configurations of sudden expansion with central restriction (Model-1) and sudden expansion with central restriction and fence (Model-2).

II. MATHEMATICAL FORMULATION

2.1 Governing Equations

Schematic diagram of the computational domain for flow through sudden expansion with central restriction (Model-1) and sudden expansion with central restriction and fence (Model-2) is illustrated in Fig.1. During study flow is assumed as 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: $p^* = p/\rho U^2$

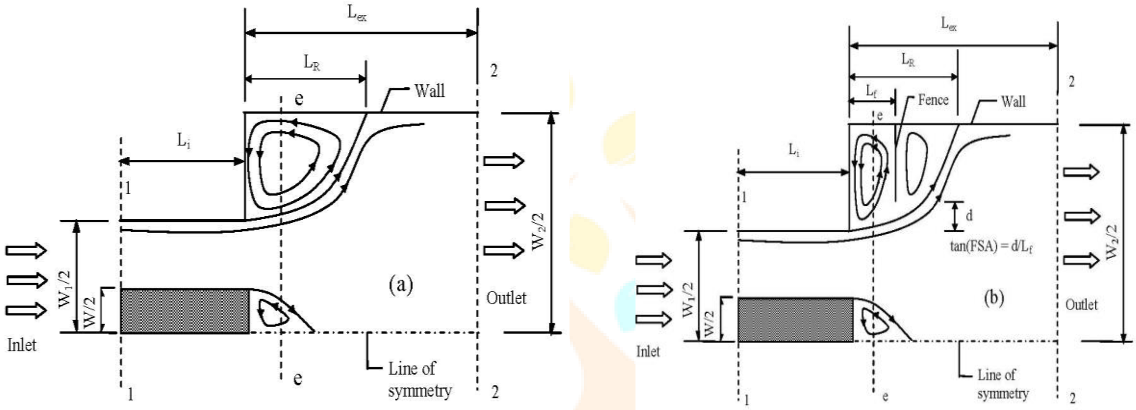

Figure 1. Schematic diagram of the computational domain (a) sudden expansion with central restriction only (Model-1) (b) sudden expansion with central restriction and fence (Model-2)

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

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

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

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

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., $u^* = 1.5\left[1-(2y^*)^2\right]$.
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 [10]. 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. The distribution of grid nodes is non-uniform and staggered.

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 to 6
3. Central restriction from 10% to 40%
4. Fence subtended angle, FSA = 10 deg
5. Distance of fence from throat, $L_f^* = 1$

3.1 Variation of Average Stagnation Pressure drop at the location where static pressure rise becomes maximum

Stagnation pressure is very important parameter on which the overall cycle performance of gas turbine engine depends. 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 computation of average stagnation pressure at any section should take into considerations of the direction of the velocity vector particularly in a flow situation, like the present case where the flow is the recirculating type. An attempt has been made to compute the average stagnation pressure at any section by the following expression:

$$P_{sav} = \frac{\int_{A_e} \left(p_e + \frac{1}{2}\rho \overline{V_e}^2 \right) u_e dA_e}{\int_{A_e} u_e dA_e} \qquad \text{-----------} \quad (5)$$

Where the subscript 'e' refers to the plane of measurement.

Maximum average static pressure has immense importance for assessing the performance of gas turbine equipments. Therefore, in this section, we have computed the average stagnation pressure drop at the location where static pressure rise becomes maximum ($P^*_{sav-drop}$). Fig. 2 represents the variation of average stagnation pressure with axial distance for Model – 1 and Model – 2 (FSA of 10 deg and L_f^* of 1) with 10, 20, 30 and 40 percent central restrictions for typical Reynolds number of 200 and an aspect ratio of 2. The general behaviour of all curves is drooping characteristics for both the models.

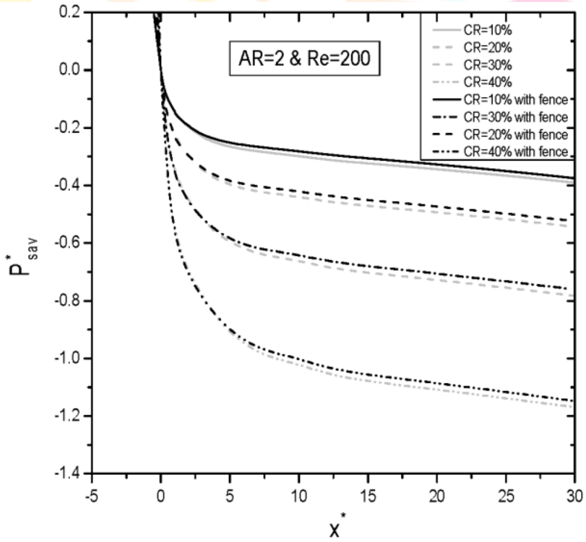

Fig. 2 Effect of central restriction on average stagnation pressure distribution

From the figure, it is seen that average stagnation pressure drop increases at any section with increase in percentage of central restriction for a fixed value of Reynolds number for both the models. It is also observed that, at a particular value of Reynolds number and central restriction, less stagnation pressure drop occurs at a section when a fence is placed at the downstream of the throat in case of Model – 2. The probable reason behind this may be that the presence of fence causes increased diffusion which decreases the stagnation pressure drop at any section. Maximum average static pressure rise is of prime importance for assessing the performance of gas turbine equipments. Again this should be achieved with minimum stagnation pressure loss.

Table 1 Average stagnation pressure drop at the location where static pressure rise becomes maximum ($P^*_{sav-drop}$) for Re=200 and AR=2

	Model-1	Model-2
CR=10%	0.6204	0.5823
CR=20%	0.9192	0.8753
CR=30%	1.3888	1.3372
CR=40%	2.1490	2.1005

Therefore, in Table 1, we have computed the average stagnation pressure drop at the location where static pressure rise becomes maximum ($P^*_{sav-drop}$), considering the same condition used in fig. 2. Fig. 3 shows that $P^*_{sav-drop}$ increases with increase in percentage of central restriction for a fixed value of aspect ratio. This is occurring because the viscous dissipative effect of the central zone dominates the diffusion effect, resulting in the drop of stagnation pressure at a particular section.

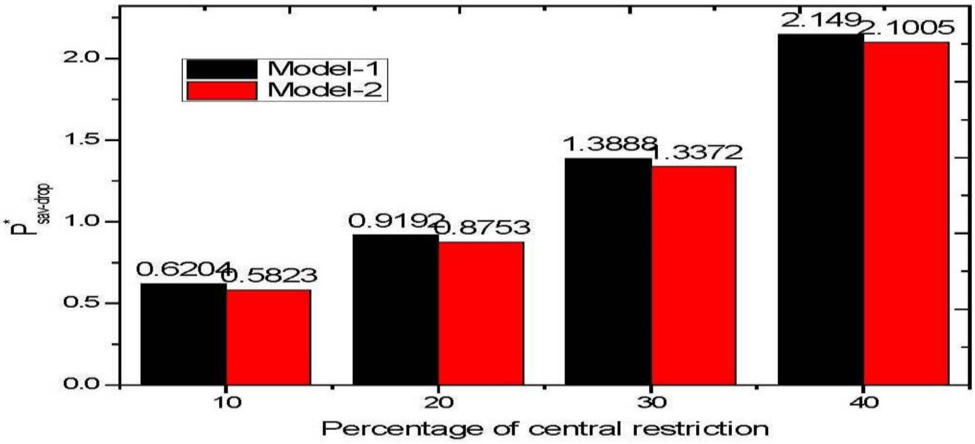

Fig. 3 Variation of $P^*_{sav-drop}$ with percentage of central restriction for Re=200 and AR=2

Fig. 4 illustrates the effect of Reynolds number on average stagnation pressure drop at the location where static pressure rise becomes maximum for Model - 1 and Model - 2 with typically 40% central restriction. The Reynolds numbers of 50, 100, 150 and 200 are considered for each case for a constant aspect ratio of 2. From the figure, it is observed that average stagnation pressure drop at the section of maximum static pressure rise decreases with increase in Reynolds number. It is also noted that the average stagnation pressure drop at a section is always less in case of Model - 2 compared to the case of Model – 1.

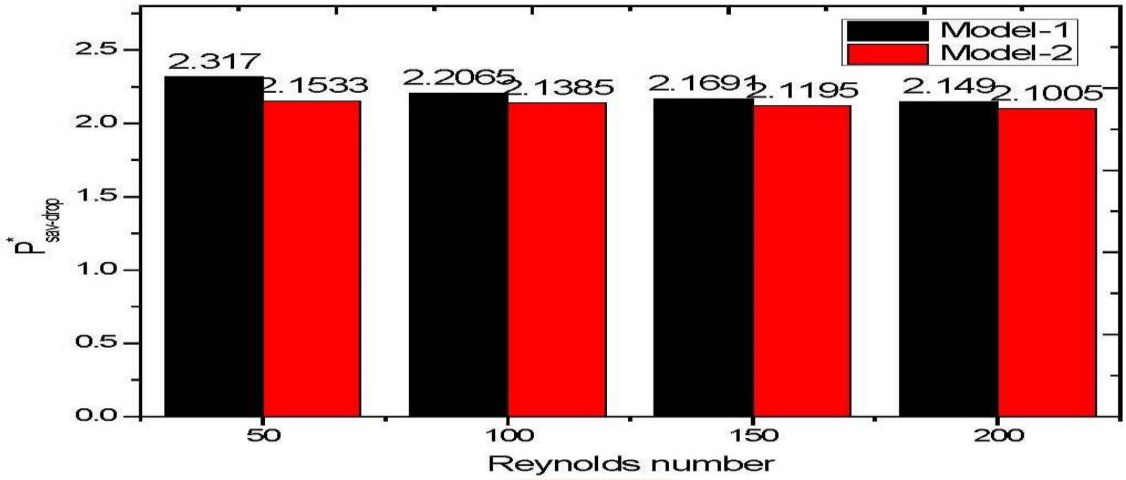

Fig. 4 Variation of $P^*_{sav-drop}$ with Reynolds number for CR=40% and AR=2

The effect of aspect ratio on average stagnation pressure drop at the location of maximum static pressure rise for Model - 1 and Model – 2 with different aspect ratios of 1.5, 2, 3, 4, 5 and 6 is shown in fig. 5. In each case, a fixed Reynolds number of 100 and 40% central restriction is considered.

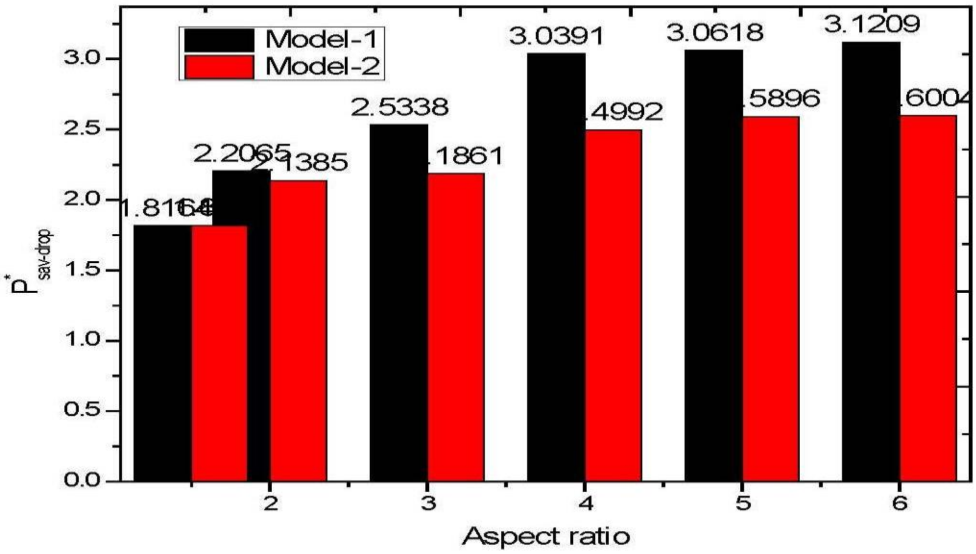

Fig.5 Average stagnation pressure drop at the location where static pressure rise becomes maximum ($P^*_{sav-drop}$) from throat for CR=40% and Re=100

From the figure, it is seen that average stagnation pressure drop at the section of maximum pressure rise is less at lower aspect ratio for both the configurations. The reason is that as aspect ratio increases diffusion at corner region increases, simultaneously the viscous dissipative effect also increases. The ultimate result is the enhancement of stagnation pressure drop at a particular section with increase in aspect ratio. When all the considered conditions are fixed, it is noted that average stagnation pressure drop at a section is less in case of Model - 2 compared to the configuration of Model - 1.

IV. CONCLUSION

The effect of aspect ratio, central restriction and Reynolds number on average stagnation pressure drop at the location of maximum average static pressure rise ($P^*_{sav-drop}$) have been investigated for two modified sudden expansion configurations. This leads to the following important observations;

i) Average stagnation pressure drop at the section of maximum static pressure rise decreases with increase in Reynolds number.

ii) This drop increases with increase in percentage of central restriction for a fixed value of Reynolds number and aspect ratio for both the models. This $P^*_{sav-drop}$ is less at higher Reynolds number when all other condition remains same.

iii) This $P^*_{sav-drop}$ increases with increase in aspect ratio for a fixed percentage of central restriction and a constant value of flow Reynolds number

iv) $P^*_{sav-drop}$ is always less for Model-2 in comparison with Model-1.

From the study, it may be concluded that Model – 2 with higher flow Reynolds number, lower percentage of central restriction and aspect ratio of 2 offers more benefit in terms of average stagnation pressure drop at the location of maximum average static pressure rise compared to Model – 1.

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
L_f	Distance of fence from throat
P or p	Static pressure, [N/m^2]
P^*_{av}	Dimensionless average static pressure
P^*_{sav}	Dimensionless average stagnation pressure
s^*	Dimensionless distance along the wall
Re	Reynolds Number
u	Velocity in x-direction, ms^{-1}
U	Average velocity, ms^{-1}
v	Velocity in y-direction, ms^{-1}
$\overline{V_e}$	Velocity vector at section e-e, 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}
Ψ	stream function

Subscripts

*	Dimensionless terms
1-1	Inlet
2-2	Exit
e	pertaining to section e-e

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