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Pressure characteristic study in a configuration of sudden expansion with central restriction

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Abstract
In this paper, a numerical study on pressure characteristics of fluid passing through a configuration of sudden expansion with central restriction 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% and for an aspect ratio (AR) from 1.5 to 6. The effect of each variable on maximum average static pressure rise and 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 magnitude of maximum average static pressure rise initially increases with increase in aspect ratio, and then it decreases. The peak value of maximum average static pressure rise magnitude is achieved at an aspect ratio of 2. This magnitude also increases with increase in Reynolds number and percentage of central restriction. Average stagnation pressure drop at the location of maximum average static pressure rise is less at lower aspect ratio and lower percentage of central restriction.
Keywords: *Stagnation Pressure drop, Static Pressure rise, Central Restriction, Sudden Expansion*.

I. INTRODUCTION

Massive improvements, in recent years, in the technology of different components of air-craft gas turbine have placed a greater emphasis upon the requirement and consequently the development of efficient diffuser that has the primary function of increasing static pressure rise and reducing air velocity to ensure efficient combustion in the combustor at a low pressure loss. In this research activity, the pressure characteristics study has been performed in terms of maximum average static pressure rise and average stagnation pressure drop considering a modified sudden expansion configuration by incorporating some central restriction in the inlet zone.

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 first work in the field of plain sudden expansion configuration was carried out by Macagno and Hung [1]. During flow visualization study, they have seen clear cellular eddies at a Reynolds number of 36. These are formed behind the sudden expansion and these are symmetric in nature. Vogel and Eaton [2] have experimentally presented the detailed heat transfer and relevant fluid dynamic data for the investigation of the near wall region downstream of a sudden expansion configuration. They have seen that turbulent mixing in the separated free shear layer is very strong except close to the step. Kwon et al. [3] have experimentally observed unusual structures of premixed flames in a sudden expansion tube. In their experimental study, they have considered four different expansion ratios which are 1.2, 1.4, 1.6 and 2. Schreck and Schafer [4] have numerically studied bifurcation phenomena in three dimensional sudden channel expansions. In their numerical approach, they have used steady incompressible Navier-Stokes equation and SIMPLE algorithm. They have considered Reynolds number ranging from 70 to 105 for an expansion ratio of 1:3. They have studied bifurcation from the steady symmetric solution to steady asymmetric solutions. Guo et al. [5] have performed numerical simulation of unsteady turbulent flows behind axisymmetric sudden expansion configuration. They have considered expansion ratio (E) in the range from 1.96 to 6.0. They have concluded that a critical Reynolds number occurs which is correlated with the expansion ratio. Chakrabarti et al. [6] 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 $20 \leq \mathrm{Re} \leq 100$, aspect ratio from 1.5 to 4. They have studied the effect of Reynolds number, aspect ratio, inlet length and inlet velocity distribution on the wall pressure, average static pressures, stagnation pressure drop gradient and diffuser efficiency in detail. Neofytou [7] 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 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. Ternik [8] has numerically investigated the shear thinning viscous effect on the development of phenomenon of flow asymmetry in a 1:3 planar symmetric sudden expansion channel. He has observed that purely viscous shear-thinning behavior yields greater pressure gradients, overall pressure drop and flow resistance in comparison to the Newtonian fluid. 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. 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 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 is not addressed. Therefore it has motivated author to study systematically the effect of Reynolds number, percentage of central restriction and aspect ratio on maximum average static pressure rise and average stagnation pressure drop of fluid passing through a configuration of sudden expansion with central restriction.

II. MATHEMATICAL FORMULATION

2.1 Governing Equations

A schematic diagram of the computational domain for flow through sudden expansion with central restriction 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: $p^* = p/\rho U^2$

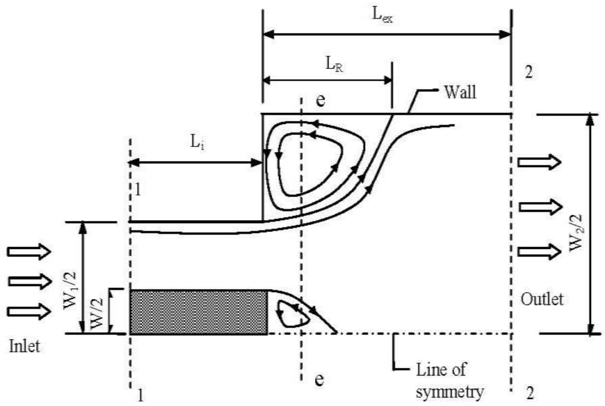

Figure 1 : Schematic diagram of the computational domain for the configuration of sudden expansion with central restriction

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

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

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

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

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. RESULT 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) Aspect ratio, AR = 1.5 to 6
(2) Central restriction from 10% to 40%
(3) Reynolds number, $50 \le \text{Re} \le 200$

3.1 Variation of Maximum Average Static Pressure Rise

The static pressure rise is considered to be an important parameter in assessing the performance of various components of gas turbine engine such as diffuser, combustor etc. A high static pressure rise should be achieved with minimum stagnation pressure loss. In the present work, the average static pressure at any cross section is determined by the following expression:

$$\mathrm{P_{av}} = \frac{\int \mathrm{pdA}}{\int \mathrm{dA}} \qquad \text{------------} \quad (4)$$

Fig. 2(a) shows the variation of maximum average static pressure rise with aspect ratio for sudden expansion with typically 10%, 20%, 30% and 40% central restrictions for fixed flow Reynolds number of 100. In each case, aspect ratio is considered as 1.5, 2, 3, 4, 5 and 6. The result shows that the maximum magnitude of average static pressure rise initially increases with increase in aspect ratio, and then it decreases for the case of 10% and 20% central restrictions. The peak value of maximum average static pressure rise magnitude is achieved at aspect ratio of 2 and at higher percentage of central restrictions (i.e. CR=30% and 40%), the maximum magnitude of average static pressure rise decreases gradually with increase in aspect ratio.

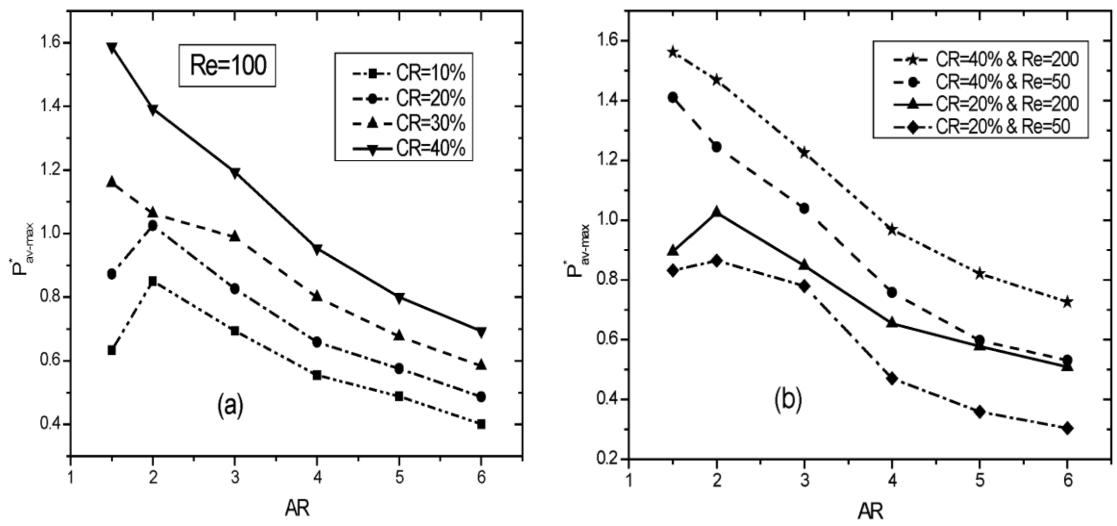

Figure 2: Variation of maximum average static pressure rise with aspect ratio

The variation of maximum average static pressure with different aspect ratio for two limiting cases of Reynolds number of 50 and 200 for typical central restrictions of 20% and 40% is shown in fig. 2(b). For all the cases, aspect ratio is considered as 1.5, 2, 3, 4, 5 and 6. From the figure, it is noted that the maximum magnitude of average static pressure rise increases with increase in Reynolds number for a particular aspect ratio and fixed percentage of central restriction. The reason is that at higher Reynolds number kinetic energy diffusion both at corner and central region increases which enhances the maximum average static pressure rise magnitude. The figure also depicts that the effect of Reynolds number remains unaffected when aspect ratio changes for a fixed percentage of central restriction i.e., at higher central restriction, for both high and low Reynolds number, magnitude of maximum average static pressure rise decreases gradually with increase in aspect ratio. Naturally for this case, the choice may be of using aspect ratio as 1.5 to obtain the higher benefit in terms of maximum average static pressure rise. But, in case of 10% or 20% central restriction, the optimum aspect ratio of 2 is achieved in obtaining higher magnitude of maximum average static pressure rise.

3.2 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 ($P^*_{sav-drop}$). The variation of $P^*_{sav-drop}$ with aspect ratio for different central restriction configurations (CR=10%, 20%, 30% and 40%) for a constant Reynolds number of 100 is shown in fig. 3(a). For all the cases, aspect ratios are considered as 1.5, 2, 3, 4, 5 and 6. It is observed that $P^*_{sav-drop}$ increases with increase in aspect ratio for a fixed percentage of central restriction. 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.

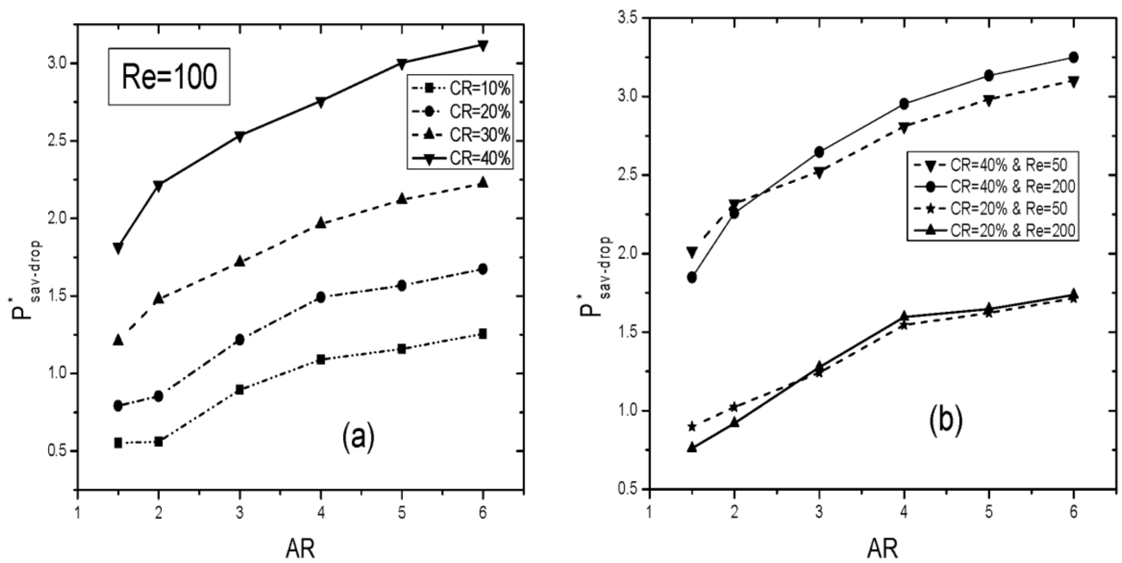

Fig. 3 Variation of average stagnation pressure drop at the location when static pressure rise becomes maximum with aspect ratio

From the fig. 3(a), it is also noted 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(b) represents the variation of average stagnation pressure drop with aspect ratio for two limiting cases of Reynolds number (Re=50 and 200) for 20% and 40% central restrictions. Different aspect ratios are considered as 1.5, 2, 3, 4, 5 and 6. From the figure, it is observed that up to aspect ratio of 2; $P^*_{sav-drop}$ is less at higher Reynolds number of 200 for both the considered central restrictions. Then, this drop becomes more at higher Reynolds number of 200 compared to the lower Reynolds number of 50. The reason is that as Reynolds number increases, the corner recirculating bubble size increases but side by side the viscous dissipative effect also increases. This viscous dissipative effect again becomes more as aspect ratio increases.

IV. CONCLUSION

The effect of aspect ratio, central restriction and Reynolds number on maximum average static pressure rise, average stagnation pressure drop at the location of maximum average static pressure rise have been investigated for sudden expansion with central restriction configuration. This leads to the following important observations;

i) At lower percentage of central restriction (CR=10% and 20%), the maximum magnitude of average static pressure rise initially increases with increase in aspect ratio, and then it decreases. The peak value of maximum average static pressure rise magnitude is achieved at aspect ratio of 2. But, the maximum magnitude of average static pressure rise decreases gradually with increase in aspect ratio at higher percentage of central restrictions (i.e. CR=30% and 40%).

ii) The effect of Reynolds number remains unaffected when aspect ratio changes for a fixed percentage of central restriction i.e., at higher central restriction, for both high and low Reynolds number, magnitude of maximum average static pressure rise decreases gradually with increase in aspect ratio.

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

Therefore, it may be concluded that better performance in terms of maximum average static pressure rise and $P^*_{sav-drop}$ is achieved at higher flow Reynolds number with aspect ratio of 2 for the case of 10% or 20% central restriction.

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^*_{av-max}	Dimensionless maximum average static pressure rise
P^*_{sav}	Dimensionless average stagnation pressure
$P^*_{sav-drop}$	Dimensionless average stagnation pressure drop at the location of maximum average static pressure rise
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 $m^{-1}s^{-1}$

Subscripts

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

REFERENCES

[1]. Macagno, E.O., and Hung, T.K., 1967, Computational and Experimental study of a Captive Annular Eddy, J. Fluid Mech., 28, 43 – 64.

[2]. Vogel, J. G. and Eaton J. K., 1985, "Combined Heat Transfer and Fluid Dynamic Measurements Downstream of a Backward-Facing Step", *ASME, Journal of Heat Transfer*, 107:922-929.

[3]. Kwon, M. J., Lee, B. J. and Chung, S. H., 1996, "An Observation of Near-Planar Spinning Premixed Flames in a Sudden Expansion Tube", *Combustion and Flame*, 105:180-188.

[4]. Schreck, E., and Schafer, M., 2000, "Numerical study of bifurcation in three-dimensional sudden channel expansions", *Computers & Fluids*, 29:583-593.

[5]. Guo, B., Langrish, T. A. G. and Fletcher, D. F., 2001, "Numerical Simulation of Unsteady Turbulent Flow in Axisymmetric Sudden Expansions", *ASME, Journal of Fluids Engineering*, 123:574-587.

[6]. Chakrabarti S., Ray S. and Sarkar A., 2003, "Low Reynolds number flow through sudden expansion - from a diffuser viewpoint", *J. Energy, Heat and Mass Transfer*, 25:46-66.

[7]. Neofytou, P., 2006, "Transition to asymmetry of generalised Newtonian fluid flows through a symmetric sudden expansion", *J. Non-Newtonian Fluid Mech.* 133:132–140.

[8]. Ternik, Primo Ž , 2009, "Planar sudden symmetric expansion flows and bifurcation phenomena of purely viscous shear-thinning fluids", *J. Non-Newtonian Fluid Mech.*, 157:15–25.

[9]. Tuncer, O., Kaynarogˇlu, B., Karakaya, M. C., Kahraman, S., Yıldırım, O. C. and Baytas C., 2014, "Preliminary investigation of a swirl stabilized premixed combustor", *Fuel*, 115: 870–874.

[10]. S. V. Patankar, Numerical Heat Transfer and Fluid Flow, Hemisphere Publication, 1980.