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STUDY ON THE VARIATION OF EFFECTIVENESS, EFFECTIVE LENGTH OF DIFFUSER AND STAGNATION PRESSURE, WITH THE CONFIGURATION OF A SUDDEN EXPANSION WITH TWO FENCES

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ABSTRACT

In this paper, an attempt has been made to study the effects of Reynolds number (Re) and the distance of second fence (L_{f2}^*) from the first fence, on effectiveness, effective length and variation of stagnation pressure of the configuration of a sudden expansion with two fences viewed as a diffuser, for Re from 20 to 160, L_{f2}^* from 0.2 to 1, an aspect ratio (AR) of 2 and fence subtended angle (FSA) of 10^0. During the computation distance of first fence (L_{f1}^*) from the throat is considered as 1. The two dimensional steady differential equations for conservation of mass and momentum are solved by finite difference method. The flow is steady, two dimensional and laminar. The fluid is Newtonian and incompressible. From the computations, it has been revealed that at higher Reynolds number, sudden expansion with two fences offers better performance. Stagnation pressure drop depends on Re and L_{f2}^*.

Keywords: Stagnation Pressure, Effectiveness, Effective Length.

1. INTRODUCTION

Diffuser is a device for reducing the velocity and increasing the static pressure of a fluid passing through a passage. It transforms kinetic energy of flow to potential energy. They play a vital role in many fluid machines to convert kinetic energy into pressure energy. Among its many applications, one of the most important applications of a diffuser is to use it ahead of the combustion chamber of an aircraft gas turbine unit. The presence of a diffuser ahead of the gas turbine combustor results not only in lowering the subsequent pressure losses, but also reduces the velocity of air at the exit of the axial flow compressor, to such a value that helps to sustain a stationary flame in the combustor. In aircraft system, deceleration of flow and recovery of average static pressure need to be executed in a very short length due to space limitation. Literature is rich with theoretical and experimental studies on different types of diffusers.

First work in the field of sudden expansion was carried out by Abbott and Kline[1]. They studied separated regions of turbulent, subsonic fluid flow system downstream of two-dimensional, backward-facing steps for the Reynolds number range of $2x10^4$ to $5x10^4$. Durst et al. [2] carried out flow visualization studies and laser-anemometry measurements in the flow downstream of a plane 3:1 symmetric expansion in a duct. Sullery et al. [3] conducted their experimental investigations for fence subtended angles of 15^0, 20^0 and 25^0 respectively in the configuration of Vortex Controlled Diffuser. Tsui and Wang [4] numerically studied laminar separated flow in symmetric, two-dimensional, straight-walled diffusers considering Reynolds number 56 and 114. Alleborn et al. [5] investigated the two-dimensional laminar flow of an incompressible viscous fluid through a channel with sudden expansion. Chakrabarti et al. [6-7] made a numerical study of the performance of a vortex controlled diffuser (VCD) in low Re regime and investigated numerically the performance of the sudden expansion viewed as a diffuser. Walker et al. [8] made experimental and computational studies of hybrid diffuser for gas turbine installation. Chakrabarti et al. [9] carried out the numerical simulation of the performance of a sudden expansion with fence viewed as diffuser considering Reynolds number range from 20 to 100. Sullery et. al. [10] experimentally investigated the effectiveness of vortex generator jets in controlling secondary flows in two-dimensional *S*-duct diffusers. Majid Nabavi [11] numerically studied the three-dimensional laminar incompressible flow through a planar diffuser (gradual expansion) for different divergence half angles of the diffuser (θ) Reynolds numbers (Re), and aspect ratios (AR).

From the literature review given above, it is seen that no such work has been done on the configuration of a sudden expansion with two fences viewed as diffuser. In this paper, the effect of important parameters like Reynolds numbers and L_{f2}^*, dimensionless distance of 2nd fence from 1st fence, on effectiveness and effective length and variation of stagnation pressure, of the configuration of a sudden expansion with two fences have been studied in detail.

2. MATHEMATICAL FORMULATION

2.1 Governing Equations

The schematic diagram of the computational domain is illustrated in fig.1.The flow under consideration is assumed to be steady, two-dimensional and laminar. The fluid is considered to be incompressible and obeys Newton's law of viscosity. The following dimensionless variables are defined to obtain the governing conservation equations in the non-dimensional form:

Lengths: $x^* = x/W_1$, $y^* = y/W_1$, $L_{f1}{}^* = L_{f1}/W_1$, $L_{f2}{}^* = L_{f2}/W_1$
$L_i{}^* = L_1/W_1$, $L_{ex}{}^* = L_{ex}/W_1$,
Velocities: $u^* = u/V_1$, $v^* = v/V_1$
Pressure: $p^* = (p + \rho g y)/\rho V^2{}_{avg}$

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

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

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

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

Where the flow Reynolds number, $R_e = (\rho V_{avg} W_1)/\mu$

2.2 Boundary Conditions

i) At the walls: $u^* = 0$, $v^* = 0$ (No slip condition)

ii) At the inlet: $u^* = 1.5[1-(2y^*)^2]$, $v^* = 0$

iii) At the exit: $\frac{\partial u^*}{\partial x^*} = 0$, $\frac{\partial v^*}{\partial x^*} = 0$

iv) At the line of symmetry: $\frac{\partial u^*}{\partial y^*} = 0$, $v^* = 0$

The boundary conditions are as follows:

2.3 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 [12]. The discretised equations are solved iteratively by SIMPLE algorithm, using line-by-line ADI method. The convergence of the iterative scheme is achieved when the normalized residuals for mass and momentum equations summed over the entire calculation domain will fall below 10^{-8}.

In our numerical experimentation, the flow is assumed to be fully developed at the exit and hence, the exit is kept far away from the throat. For all the calculations, the inlet length and the exit length are kept 1 and 100 respectively in non-dimensional form. The distribution of grid nodes is non-uniform in both co-ordinate directions allowing higher grid node concentrations in the region close to the step, walls and fences of the duct. After performing extensive grid independence study, finally, at inlet section 21×29 grid nodes and at exit section 329 × 61 grid nodes are considered in the x and y directions respectively.

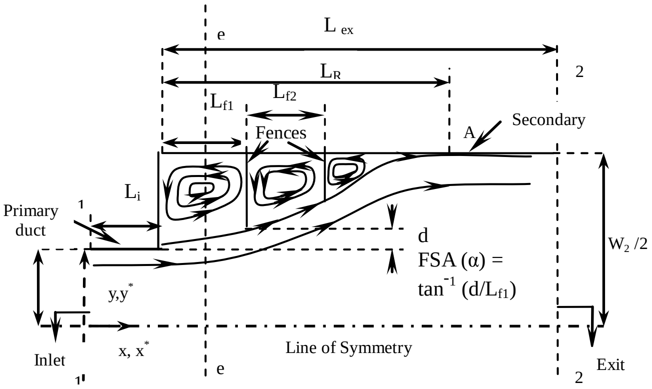


Fig.1. Schematic diagram of the computational domain

3. RESULTS AND DISCUSSION

3.1 Diffuser Effectiveness

Diffuser effectiveness is one of the vital parameter in the evaluation of diffuser performance. It is the ratio of actual increase in average static pressure and the average static pressure rise in the ideal diffusion process.

Here, computations for the diffusion effectiveness are done using the following non-dimensional expression:

$$(\eta_d)_{effective} = \frac{2\left(p_{2.avg}{}^* - p_{1.avg}{}^*\right)_{measured}}{1 - \frac{1}{\left(A^*\right)^2}} \tag{4}$$

Where, $p_{1.\,avg}$ *is the average value of static pressure at throat and is obtained by linear interpolation of the pressures at the nodes just before and after the throat, and $P_{2.\,avg}{}^*$ is the maximum average static pressure achieved after the throat.

The detailed derivation of equation (4) has been given in [7]. The numerator of expression (4) denotes the maximum actual static pressure rise that can occur in a diffuser. The denominator represents the static pressure rise experienced by an ideal fluid undergoing sudden expansion having an area ratio $A^*$of 2. The significance of the above expression is that it quantifies the amount of maximum static pressure rise with respect to the same for an ideal fluid passing through the diffuser.

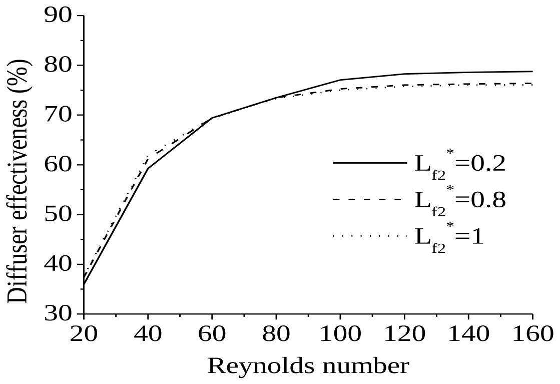
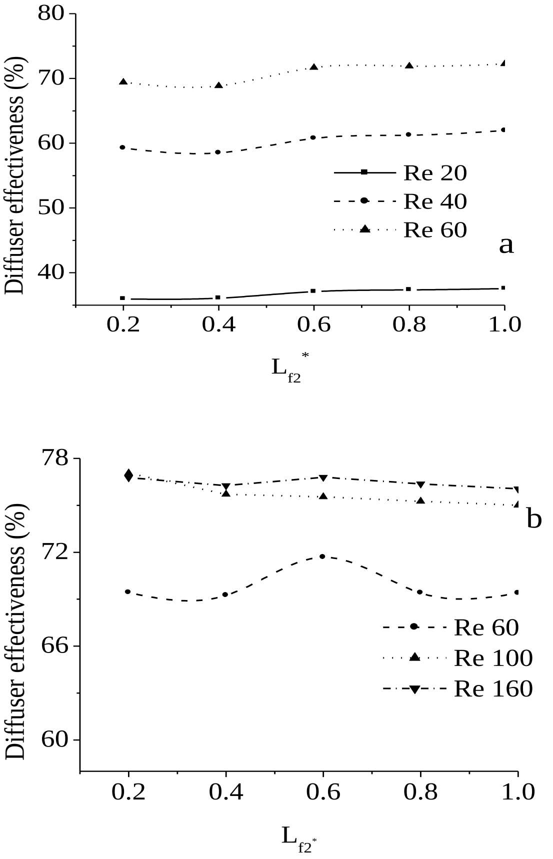


Fig. 2. Effect of L_{f2}^* on diffuser effectiveness with increasing Re showing a proper choice of L_{f2}^* can increase η_d even at lower Re.

The above figure describes the effect of Reynolds numbers and the variation of L_{f2}^* on diffuser effectiveness for fixed value of FSA of 10^0. The graph shows that, initially there is a rapid change in diffuser effectiveness as the Reynolds number increases and thereafter the effectiveness curve exhibits near asymptotic behavior. Hence we conclude that the diffuser effectiveness does not change appreciably in higher Reynolds number regime. The initial rapid increase in effectiveness is because, as Reynolds number increases, the diffusion of kinetic energy into the development of the static pressure head also increases. This gain is considerably greater than the eddy losses. Even at higher Reynolds number the diffusion of kinetic energy occurs but the gains are offset by the eddy losses. Thus at higher Reynolds number the effectiveness curves show asymptotic behavior.

At lower Reynolds number, for the L_{f2}^* values considered, two fences offer no benefit towards the diffuser effectiveness; rather the fences reduce the effectiveness. Similar observations were reported by Chakrabarti et al. [9]. But at a certain value of L_{f2}^*, diffuser effectiveness increases even for lower Reynolds number. These observations suggest that the exact value of Reynolds number where the fence starts becoming effective depends on the L_{f2}^* chosen for a fixed value of FSA. Figure 3 shows the variation of diffuser effectiveness with the Reynolds numbers for typical values of L_{f2}^* of 0.2, 0.8,1 respectively. It is seen that after a certain value of Reynolds number, efficiency is high at low value of L_{f2}^*. It is so happened due to formation of small recirculating zone which has less effect than the diffusion of kinetic energy. Therefore for lower Reynolds number, judicious position of the second fence can make the diffuser efficiency more effective. At lower Reynolds, the effect of variation of L_{f2}^* on diffuser efficiency is shown in figure 3(a). The graph represents, that, at lower Reynolds numbers cases, initially the diffuser effectiveness is more; thereafter it goes down and after a certain point the efficiency again begins to increase and reaches its maximum value, then it decreases in asymptotic manner. At higher Reynolds number for a particular L_{f2}^*, there is peak value of diffuser effectiveness which is shown in fig. 3(b). After the peak value is reached, the drop in effectiveness can be understood to be caused by the primary recirculating bubble occupying greater length of the diffuser for higher values of L_{f2}^*. Greater dimensions of this eddy cause more frictional dissipation and this reduces the effectiveness.



Figs. 3 (a-b). Variation of diffuser effectiveness with L_{f2}^* at low Re and high Re.

3.2 Distance of Maximum Average Static Pressure Rise from Throat

The primary reason of adopting a sudden expansion configuration is to achieve maximum pressure rise in the shortest possible space. The distance (L_p^*) between the throat and the location of maximum average static pressure, measured along the diffuser length, is an important parameter in the design of an efficient diffuser with minimum possible length. This distance is an important aspect in the design since it can be considered to be the effective length of the diffuser within which the diffusion process brings about maximum static pressure rise. Fig.4 shows the variation of Lp^* with L_{f2}^* for typical Reynolds numbers of 40,100 and 160. From the graph it is observed that the effect of L_{f2}^* on distance of maximum pressure rise from throat is negligible whereas the impact of Reynolds number on the Lp^* is more. The computational results show that as Reynolds number increases, the distance of maximum static pressure rise from the throat also increases.

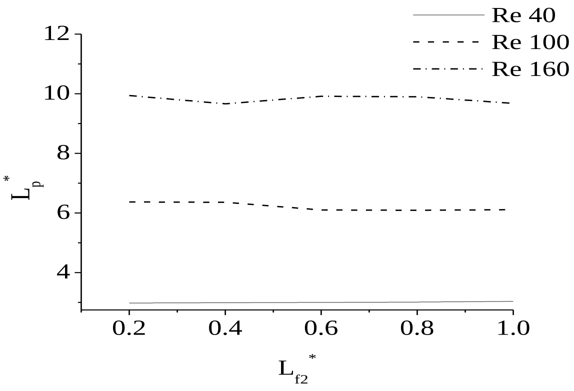


Fig 4. Variation of maximum pressure rise (L_p^*) with L_{f2}^*

3.3 Variation of Average Stagnation Pressure along the Length

Stagnation pressure is considered to be important to determine the performance of the various components of a gas turbine cycle as well as the performance of the cycle itself. The dimensionless form of the following equation is used to calculate the average stagnation pressure at a particular cross-section [7]:

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

Fig. 5 shows the variation of average stagnation pressure along the axial length for typical Reynolds numbers of 40,100,140 and 160 and typical values of L_{f2}* of 1. For all the cases we observe a gradual decrease in average stagnation pressure along the length of diffuser. Physically, we can argue that since symmetry conditions prevail in low Reynolds number, the flow along the length of diffuser may be considered as a streamline. Across this streamline there is no heat and work transfer, and because of the viscous dissipative effects, the stagnation pressure must fall along this streamline. It can be observed that, higher the Reynolds number, lesser is the corresponding pressure drop. This is explained by the fact that at low Reynolds number, the flow will have a tendency to ‘catch’ the surface of the outer duct much faster than flows with higher Re. So there is a greater transfer of mass towards the boundary, from the region surrounding the centerline. This causes a low-energy recirculating zone and thereby a lower value of the axial component of velocity leads to a sharp drop in the stagnation pressure around the throat region. This result is in confirmation with the results presented in [9].

Fig 6, shows the effect of L_{f2}^* on the stagnation pressure drop with Reynolds numbers. From this figure it is noticed that for a particular value of Reynolds number average stagnation pressure drop depends on the position of second fence L_{f2}^*. For Re 140 and 160, the average stagnation pressure drop initially decreases with the increase in the value of L_{f2}^*, and this pressure drop reaches to an optimum value at a certain value of L_{f2}^*, after that it again increases with further increase in the value of L_{f2}^*. For both the cases, the minimum average stagnation pressure drop takes place at L_{f2}^* of 0.4. In case of Re of 100, the minimum average stagnation pressure drop occurs at L_{f2}^* of 0.2.

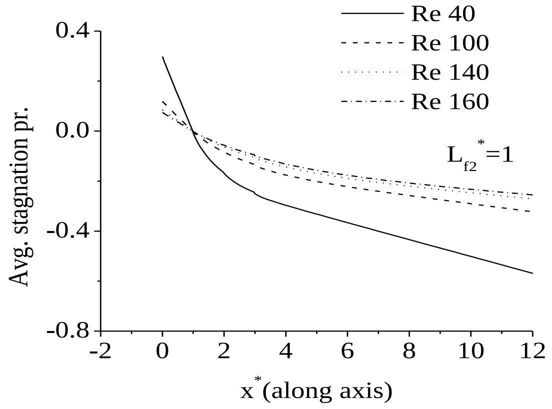


Fig.5. Effect of Re on variation of average stagnation pressure with axial distance.

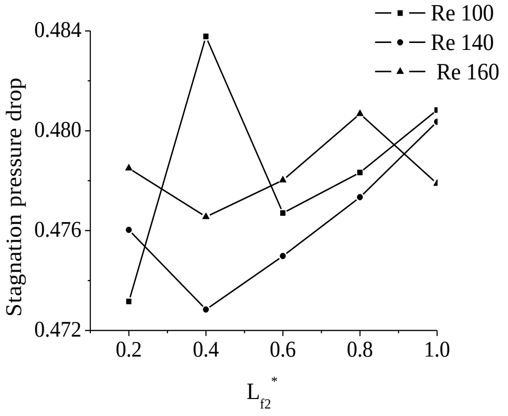


Fig 6. Effect of L_{f2}^* on variation of stagnation pressure drop with Re

5. CONCLUSIONS

In this study, performance analysis of sudden expansion with two fences in the Reynolds number range from 40 to 160 for the aspect ratio of 2 and fence subtended angle of 10^0 has been carried out from diffuser view point. The effects of Reynolds number (Re) and location of second fence from the first fence L_{f2}^* on diffuser properties have been investigated. From this investigation the following important points are made:

i) At higher value of Re, sudden expansion with two fences offers better result as far as diffuser effectiveness is concerned. But at lower value of Re this configuration may not always give higher benefit.

ii) Distance of maximum static pressure rise measured from throat is more or less indpendent of L_{f2}^* but dependent on the value of Re. The distance increases with the increase of Re.

iii) Stagnation pressure drop decreases with the increase of Re. But it also typically depends on the location of second fence. At Re of 100, the minimum average stagnation pressure drop occurs at L_{f2}^{*} of 0.2. For Re 140 and 160, the minimum average stagnation pressure drop takes place at L_{f2}^{*} of 0.4.

6. REFERENCES

1. Abbot, D. E., and Kline, S. J., 1962, “Experimental investigation of subsonic turbulent flow over single and double backward facing steps”, Journal of Basic Engineering, 84: 317-325.
2. Durst, F., Melling, A. and Whitelaw, J. H., 1974 “Low Reynolds number flow over a plane symmetric sudden expansion”, 64: 111-128.
3. Sullery, R. K., Ashoke, V., and Santharam, K. V., 1992, “Effect of inlet flow distortion on performance of vortex controlled diffusers”, 1992, ASME, Journal of Fluids Engineering, 114: 191-197.
4. Tsui, T. and Wang, C., 1995, “Calculation of laminar separated flow in symmetric two dimensional diffusers”, ASME, Journal of Fluids Engineering, 117: 612-616.
5. Alleborn, N., Nandakumar, K., Rasziller, H. and Durst, F., 1997, “Further contributions on the two-dimensional flow in a sudden expansion”, Journal of Fluid Mechanics, 330:169-188.
6. Chakrabarti, S., Ray, S. and Sarkar, A., 2002, “Numerical simulation of the performance of a vortex control diffuser in low Reynolds number regime”, International Journal of Numerical Methods for Heat and Fluid Flow, 12:224-240.
7. Chakrabarti, S., Ray, S. and Sarkar, A., 2003, “Low Reynolds Number flow Through Sudden Expansion from a Diffuser Viewpoint”,Journal of Energy Heat and Mass Transfer, 25:45-66.
8. Walker, A. D., Denman, P. A., and McGuirk, J. J., 2004, “Experimental and Computational Study of Hybrid Diffusers for Gas Turbine Combustors”, Journal of Engineering for Gas Turbines and Power, 126: 717-725.
9. Chakrabarti, S., Ray, S. and Sarkar, A., 2008, “Numerical Analysis for Sudden Expansion with Fence in Low Reynolds Number Regime”, Journal of Energy Heat and Mass Transfer, 30:131-148.
10. Sullery, R. K., and Pradeep, A. M., 2004, “Secondary flow control using Vortex Generator Jets”, Journal of Fluids Engineering, ASME, 126:650-657.
11. Majid, N., 2010, “Three-dimensional asymmetric flow through a planar diffuser: Effects of diverangence, Reynolds number and aspect ratio”, International Communications in Heat and Mass Transfer, 37: 17-20.
12. Patankar, S. V., 1980, Numerical Heat Transfer and Fluid Flow, Hemisphere.

7. NOMENCLATURE

Subscripts
1, i = Inlet 2= Outlet

Symbol	Meaning	Unit
A	Area at any section in	(m^2)
Re	Flow Reynolds number	
A^{*}	Aspect ratio, A_2/A_1	
x,y	Cartesian coordinate	
L_i	Inlet length	(m)
L_{ex}	Exit length	(m)
V_1	Mean inlet flow velocity	(m/s)
L_{f1}	Distance of 1st fence from throat	(m)
L_{f1}^{*} =	Dimensionless distance of 1st fence from throat	
L_{f2}^{*}	Dimensionless distance of 2nd fence from 1st fence	
W_1	Width of inlet duct	(m)
L_{f2}	Distance of 2nd fence from 1st fence	(m)
W_2= p^{*}	Width of outlet duct dimensionless static pressure	(m)
μ	Dynamic viscosity	(Ns/m^2)
ρ	Density of fluid	(kg/m^3)
u, v	Velocity components in x and y direction	(m/s)

L_{f1}^{*}	Dimensionless distance of 1st fence from throat	
L_{f2}	Dimensionless distance of 2nd fence from 1st fence	
L_R	Reattachment length measured from throat	(m)
d	Distance (perpendicular to axis) between inlet duct surface and fence	(m)
p_{avg}^{*}	Dimensionless average static pressure	
FSA	Fence subtended angle (α)	(radian)

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