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Performance Comparison of Straight and Curved Diffusers

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Abstract. Experimental studies have been carried out to compare the performance of two dimensional straight and curved diffusers of same area ratio and effective divergence angle in the Reynolds number range of 7.8×10^5 to 1.29×10^6. Free stream turbulence effects have also been studied at the increased turbulence level to 3.4per cent. The results indicate that straight diffuser pressure recovery is slightly higher as compared to the curved diffusers. However, stream turbulence, which improves the pressure recovery in both cases, has been observed to have greater effect in case of curved diffuser. Boundary layer velocity profiles on the diffuser surfaces have also been presented at various streamwise stations. It is observed that the growth of inner surface boundary layer has a major effects on losses in case of a curved diffuser.

Nomenclature

C_p = static pressure recovery $(\bar{P}_2 - \bar{P}_1)/\frac{1}{2}\,\rho\,\bar{V}_1^2$

$\bar{P}$ = arithmetic average static pressure at the cross-section

R = Radius

Re = Reynolds number $\bar{V}_1\,\bar{W}_1/\nu$

$\bar{V}$ = mass averaged velocity

W = diffuser width

ρ = fluid density

ν = kinematic viscosity

Subscripts

1 = inlet to the diffuser

2 = any other station

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1. Introduction

In fluid flow systems, it is often necessary to decelerate and turn the fluid simultaneously. Among other applications, curved diffusers are used in vaned diffusers of centrifugal compressor stages, in steam turbine exhaust hoods, and in the inter-connecting ducting between the components of gas turbines. The performance of diffuser is generally evaluated in terms of pressure recovery. The main problem in achieving a high pressure recovery is the flow separation which results in non-uniform flow distribution and excessive losses. Moore & Kline[1] have shown that the flow regimes of a simple diffuser depend on the total divergence angle, wall-length to throat-width ratio and the inlet free stream turbulence. The variations in throat-width, Reynolds number, and the throat aspect ratios normally encountered had little or no effect on flow regimes. Fox Kline[2] have systematically investigated the flow regimes for curved diffuser passages. The gross geometry of curved diffusers may be described in terms of three parameters[3], the inlet length to width ratio, area ratio, and the turning angle. Fox & Kline[2] have also presented experimental results showing the effect of the parameters on curved diffuser performance and flow regimes. It was noted that there was a rapid drop-off in allowable area ratio for the first stall limit as the turning angle increased. Sagi & Johnston[3] have qualitatively explained this rapid drop-off in performance and the area ratio (for first stall limit) in terms of less favourable inner wall boundary layer growth characteristics. The inner wall is subjected to following curvature induced effects : (i) increased potential flow loadings along the wall, (ii) increased thickening of the inner wall boundary layer caused by secondary flows off the end walls and (iii) reduced turbulent mixing along the inner wall.

A complete specification of diffuser inlet conditions is as important to the designer of a diffuser as is the knowledge of the important relationships between stall flow regime limits and performance[4,5].

Howard[6] et al. have done experimental investigations of secondary flows in ducts. Boundary layer turning on the end walls and the passage vortex roll up on the suction surface and wall corner were observed in the circular arc duct.

Recently Ichiro[7] et al. have tested circular arc center line diffuser with three different effective divergence angles and have presented the distribution of pressure coefficient on the inner (i.e. suction side) and outer walls (i.e. pressure side) versus angular position of stations. Assuming approximate displacement thickness, a theoretical distribution of pressure coefficient was calculated which agreed with the measurements.

In the present investigations, the performance of curved and straight diffusers of same area ratio have been compared for the identical inlet conditions. The other aspects of study include the effect of free stream turbulence level on the performance and the growth of boundary layer on the diffuser walls. The higher inlet turbulence level of 3.4 per cent has been obtained by use of a turbulence grid. The Reynolds number range of experiments is 7.8 × 10^5 to 1.29 × 10^6 and the chosen turning angle of curved diffuser is 55°.

2. Experimental Procedure

The experiments have been carried out on a cascade tunnel which had a nozzle exit cross-section of 304 × 381 mm. The diffusers were fixed at the nozzle exit. The tunnel had a speed range from 25 to 54.0 m/s at the nozzle exit. The straight and curved diffusers are shown in Figs. 1 and 2.

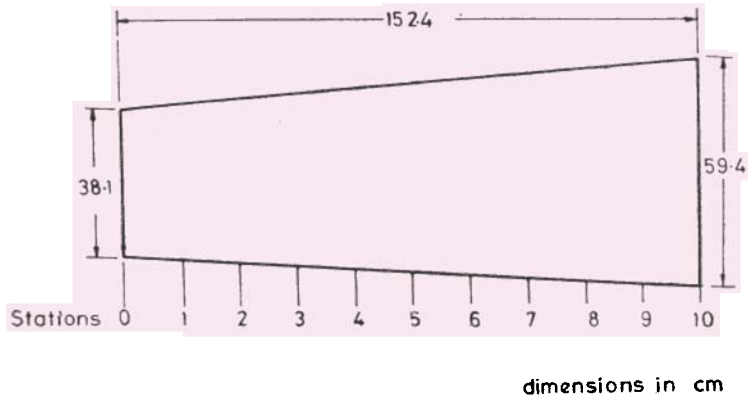

Figure 1. Two dimensional straight diffuser.

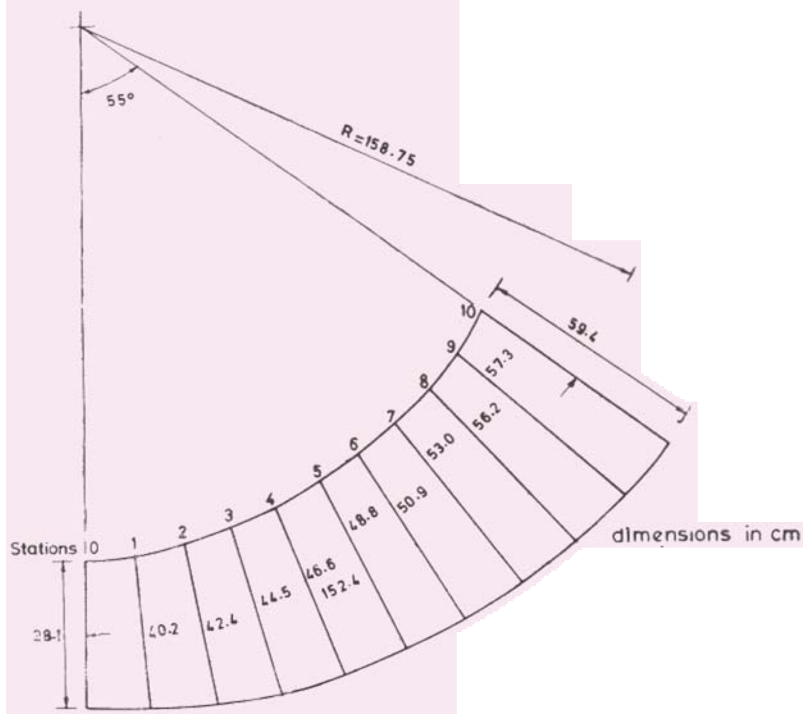

Figure 2. Two dimensional curved diffuser.

The centre line of the curved diffuser is a circular arc. The turning angle of 55° is chosen from considerations that there is no appreciable stall at the exit[2]. The divergence is only in the horizontal plane and the inlet width of diffuser is 381 mm which increases to 594 mm at the exit. The arc length is 1.524 m. Based on the inlet and outlet dimensions and the arc length, the corresponding diffuser angle for straight diffuser was 8°. The straight diffuser was therefore designed for this divergence angle and the same area ratio as for the curved diffuser. The inner and outer surfaces of the curved diffuser were made of perspex while the straight diffuser was made of smooth plywood. The pressure tappings were provided at the intervals of 11.0° for the curved diffuser with first station at 5.5° from the inlet. The straight diffuser had similar pressure tappings at stations having similar area ratio as correspond to curved diffuser stations. The pressure tappings were of 2 mm diameter at 37.5 mm spacing on bottom and side surfaces of both the diffusers. Circular holes were provided at locations intermediate to the above stations for inserting the probe for velocity distribution measurements.

Multitube manometers were used for wall static pressure measurements. The tubes had inclination of 60° with horizontal. The pressure measurements had an accuracy of 1 mm of water. DISA A10 constant temperature hot wire anemometer was used for turbulence measurements. The velocity measurements were taken using a three hole null type yaw probe with an overall diameter of 3 mm. A traversing mechanism was used for traversing the probe for boundary layer measurements.

To increase the level of free stream turbulence, a turbulence grid was put just at the nozzle exit. The grid consisted of steel bars of 12.7 mm diameter in a square of 51 × 51 mm. The length of the duct before the diffuser was 800 mm. A stream turbulence level of 3.4 per cent was obtained at the exit of the duct (inlet of the diffuser). In both cases, the diffuser discharged air directly into the atmosphere. The turbulence level at the nozzle exit (without the grid) was 0.7 per cent.

3. Results and Discussion

The pressure recovery in case of straight diffuser with and without increased free stream turbulence is shown in Fig 3. There is a distinct increase in pressure coefficient, at different measuring stations with increased free stream turbulence level. The reason for this increase appears to be the better mixing at higher stream turbulence levels. The upstream static pressure is measured just before the inlet of the diffuser in all cases.

Figure 4 shows similar plot for the case of curved diffuser. The effect of free stream turbulence in this case is even more pronounced. The increase is particularly pronounced at stations 7 and 9 where the inner surface boundary layer separation is imminent. It may be mentioned that C_p values are calculated based on the average of static pressure from inner to outer surface of the diffuser.

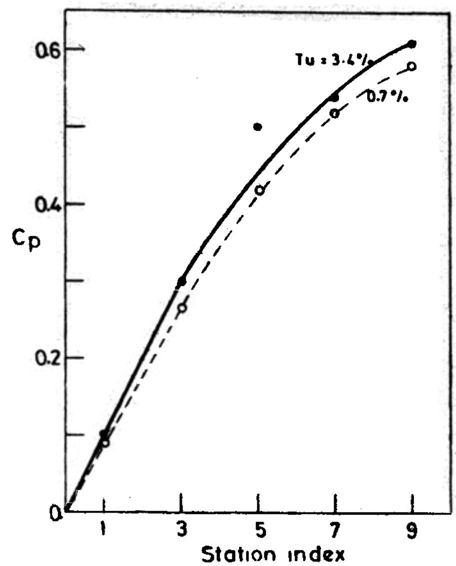

Figure 3. Pressure recovery in a straight diffuser.

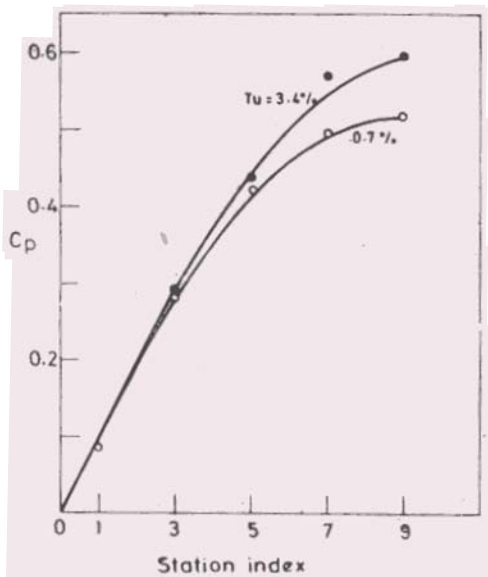

Figure 4. Pressure recovery in a curved diffuser.

Figure 5 compares the pressure recovery of straight and curved diffusers without the turbulence grid. The difference is apparent only at stations 7 and 9. The inner surface boundary layer is subject to higher potential flow loading in case of curved diffuser than the side walls of the straight diffuser. This results in a lower pressure recovery in case of curved diffusers.

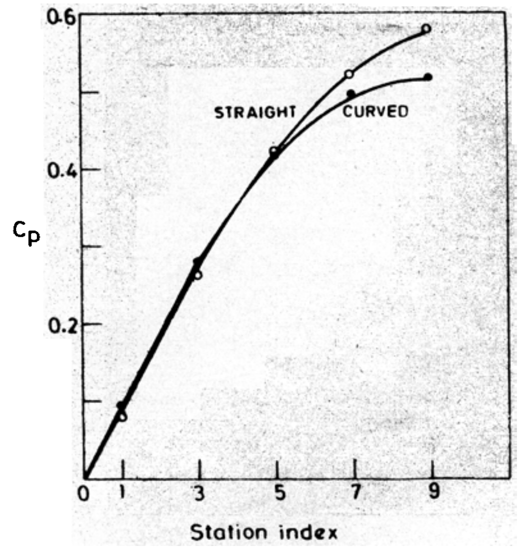

Figure 5. Comparison of pressure recovery in straight and curved diffusers (Tu = 0.7%).

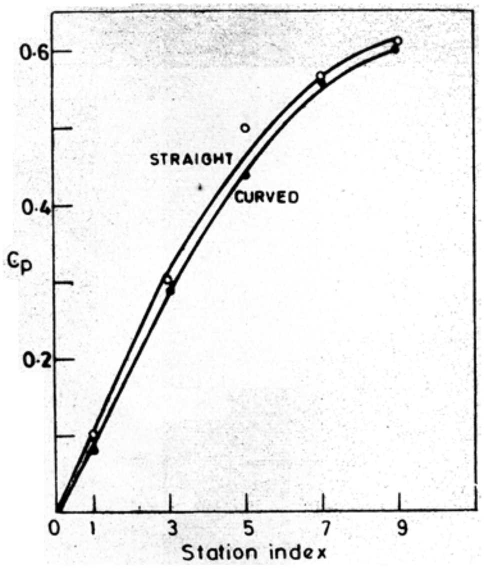

Figure 6. Comparison of pressure recovery in straight and curved diffusers (Tu = 3.4%).

Figure 6 compares the performance in two cases when the turbulence grid is used. Here the pressure recovery differs only slightly in two cases. This implies that relative improvement in performance is more for the curved diffuser. Fig. 7 shows the growth of the boundary layer on diverging walls of straight diffuser with and without increased free stream turbulence. There is a decrease in boundary layer thickness with increased turbulence. However, flow separation is absent in both cases for the straight diffuser.

The growth of boundary layer on inner and outer surfaces of the curved diffuser is presented in Fig. 8. The inner surface boundary layer is thicker than the outer surface. Flow separates on the inner surface before the last measuring station. This is a reason for lower pressure recovery in a curved diffuser as noticed in Fig. 5. It appears from the boundary layer velocity profiles that the flow separation gets

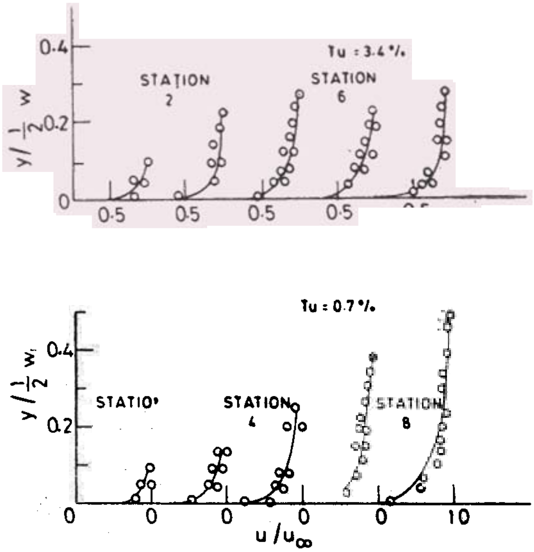

Figure 7. Boundary layer velocity profiles in a straight diffuser.

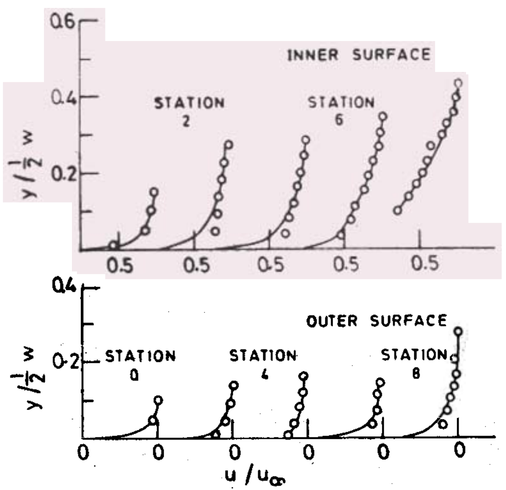

Figure 8. Boundary layer velocity profiles in a curved diffuser (Tu = 0.7%).

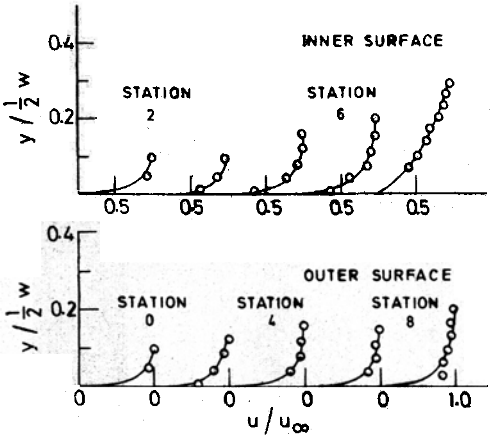

Figure 9. Boundary layer velocity profiles in a curved diffuser (Tu = 3.4%).

delayed when free stream turbulence is increased (Fig. 9). The boundary layer thickness is now less on both the inner and outer surfaces.

It has been emphasised[8] that the inlet momentum thickness plays a significant role in diffuser pressure recovery. The inlet momentum thickness was calculated for the two cases using the measured inlet velocity distributions. The momentum thickness ranged from 0.008 to 0.01. The effect of this variation is not expected to be significant on pressure recovery of the diffusers. Therefore the difference in pressure recovery in two cases is due primarily to the effect of free stream turbulence. Mooref Kline[1] have also observed that increasing turbulence level (with the ratio of wall-length to throat diameter held constant) delays the onset of two dimensional steady separation. In the Reynolds number range of present investigations, no significant effect of Reynolds number was observed.

4. Conclusions

Experiments have been carried out to evaluate and compare the performance of straight and curved diffusers of identical area ratio of 1.56 in the Reynolds number range of 7.8×10^5 to 1.29×10^6. The effect of increased inlet stream turbulence level has also been studied by increasing stream turbulence level to 3.4 per cent by using a grid.

The comparative study shows that higher values of pressure coefficient are attainable with straight diffusers for the same area ratio and effective divergence angle. Increasing the level of free stream turbulence has a favourable effect on diffuser performance. A study of boundary layer growth in curved diffuser reveals that major losses arise due to inner surface boundary layer. As free stream turbulence affects the growth of this boundary layer, the improvement in the performance in case of curved diffuser is more pronounced at increased turbulence level.

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