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An Experimental Investigation to Control the Flow Emerging From a Wide Angle Diffuser

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Abstract: - *In the absence of any flow control, the flow through a wide-angle diffuser consists of a narrow axial jet surrounded by regions of separated flow, which persists downstream. The results of an experimental investigation into the use of perforated plates to control the velocity profile emerging from wide-angle diffuser are reported here. Geometry has an important influence on the flow features for short wide-angle diffuser. The incorporation of perforated plates has a considerable influence on the flow properties within the diffuser.*

Tests were undertaken using different perforated plates in an axisymmetrical type of wide-angle diffuser, having rectangular cross-section with area ratio 10 and total included angle 60^0. Without the use of perforated plates to control the flow, highly non-uniform velocity profiles occur. Depending upon the porosity of the screens and their locations within the diffuser, different types of exit velocity profile were found.

However the most important finding of the work is that with appropriate choice of porosity and location of the minimum two perforated plates, mean velocity profile could be achieved which avoided flow separation and displayed a high degree of flow uniformity. These results extent significantly the range of the area ratio in which minimum two perforated plates are necessary to ensure uniformity of the velocity profile at the exit plane of wide-angle diffuser.

1. Introduction

Diffusers find extensive application in turbo machinery, in jet propulsion engines and in wind tunnels for the purpose of decelerating confined fluid flows. In practice various types of diffusers are used such as conical diffuser, annular diffuser, rectangular diffuser, curved diffusers of circular cross section, rectangular cross section etc.

Although diffusers are widely used, their flow characteristics are still not fully known. The flow through a diffuser inevitably depends on its geometry, which is defined by the area ratio, wall expansion angle, cross-sectional shape and wall contour. Other parameters such as conditions at entry and exit and boundary layer control devices, if any, also affect the diffuser performance. With an arbitrary combination of these parameters, the flow through a diffuser becomes too difficult to predict in detail. The issue becomes complicated further by the occasional presence of boundary layer separation caused by the adverse pressure gradients necessarily present in diffusers. It was in fact this separation in a conical diffuser that inspired Prandtl and in 1904 the concept of boundary layers emerged.

Wide-angle diffuser is defined as a diffuser in which the cross-sectional area increases so rapidly that separation can be avoided only by using boundary layer control. A wide-angle diffuser should be regarded as a means of reducing the length of a diffuser of given area ratio, rather than a device to effect pressure recovery. Uniformity and steadiness of the flow at the diffuser exit are of prime concern since this affects the performance of vital components downstream.

The four most important parameters in a wide-angle diffuser are: -

(i) The area ratio, (ii) The diffuser angle, (iii) The number of screens/perforated plate within the diffuser, (iv) The total pressure drop coefficient of all screens.

1.1 Flow Separation in Wide-Angle Diffusers

In the absence of any form of flow control device, wide-angle diffusers experience separation, which starts just beyond the throat due to the substantial adverse pressure gradient occurring in that region. The broad pattern of flow under these conditions is an axial-flow jet together with large separated flow regions in the vicinity of the diffuser walls. It results a highly non-uniform velocity profile at the diffuser exit plane. In addition, large-scale turbulence fluctuations or flow pulsations may be present. In order to establish a uniform velocity distribution over the exit plane of the wide-angle diffuser, some form of control must be introduced. Devices, which have application in this context, include flow straighteners, splitters, vanes wire-mesh gauges and perforated plates. The present work focuses attention on the simple shaped wide-angle diffuser, which finds application in practical electrostatic precipitators.

1.2 Test Rig and Experimental Conditions

In order to carry the experimental tests on diffuser so as to study the performance of the diffuser without any flow control devices and the performance of the diffuser with flow controlling device like perforated plates, flow bench available at Defence Institute of Advanced Technology, Pune was used.

The Wide-angle diffuser designed was fitted to the outlet duct provided on the flow bench. Air was used as the working fluid for the tests. Air leaving the outlet box of the diffuser was freely discharged to the atmosphere. Multi-tube manometer was used for measuring the wall static pressures at different pressure tapping positions. Velocity measurements were made using Pitot-static tube.

1.3 *Description of the Model*

The physical model of a wide-angle diffuser is shown in fig. 1. The wide-angle diffuser is made of Perspex sheet with thickness of the sheet 6mm. The outlet area available from the airflow bench is of 50 X100 mm. The total divergence angle of the experimental wide-angle diffuser was $2\alpha= 60$. The resulting outlet to inlet area was therefore equal to 10. The diffuser was connected to the Airflow bench out let with a rectangular cross-section of dimensions 50 X 100mm, as seen schematically in fig. 1. The diffuser had a length L_1 of 130mm and the box had a length L_2 of 250 mm.

Four slots machined into the inner sides of the diffuser's Perspex wall allowed four perforated plates A, B, C and D to be rigidly clamped horizontally within the diffuser at locations $X/L_1=$ 0.05, 0.25, 0.59 and 0.95 respectively. The plates were perforated with circular holes and all had the same porosity (total open area to total plate area) of 40%. Each plate has been made of a flexible sheet of metal steel of 1 mm thickness.

The typical operating velocity at the diffuser inlet (M_1, fig.2) was 30 m/s, corresponding to a Reynolds number of Re = 1.14×10^5, based on the inlet hydraulic diameter.

Static pressure taps were installed on the wall and the box along the mid-vertical planes of the diffuser/box ducting in order to quantify wall static pressure variations in the down stream direction. The notations and locations of the pressure taps are presented in table 1. The pressure distribution was represented by the wall static pressure recovery coefficient, C_p, defined by

$$C_p=\frac{P-P_r}{\frac{1}{2}\rho\, U_1^{\,2}} \qquad (1)$$

Where P is the static pressure measured at a certain location, P_r is the reference pressure located upstream of the diffuser (here P_0), ρ is the air density, and U_1 is the average velocity determined at the diffuser inlet plane M_1.

Figure 1. Actual Experimental Setup for Velocity Readings

Table-1: Notations and positions of the wall static pressure probes

Position	**P_0**	**P_1**	**P_2**	**P_3**	**P_4**	**P_5**	**P_6**	**P_7**
X/L_1	-0.12	0.02	0.12	0.23	0.40	0.56	0.74	0.91

Position	**P_8**	**P_9**	**P_{10}**	**P_{11}**	**P_{12}**	**P_{13}**	**P_{14}**	**P_{15}**
X/L_1	1.18	1.37	1.55	1.78	2.01	2.20	2.39	2.56

Table-2: Locations of the velocity measurement sections

Position	M_0	M_1	M_2
X/L_1	-0.17	0	1.45

Figure 2. Details of Wide-Angle Diffuser

The flow uniformity could be assessed using the percent root mean square index determined from a number of measurements of local velocity distribution over a cross-section. It can be written as

$$\text{RMS\%} = 100 \left[\left(\frac{U_{RMS}}{U_{Ave}} \right)^2 - 1 \right]^{1/2} \qquad (2)$$

Where U_{Ave} is the average velocity through the cross-section and U_{RSM} is the local RMS value of the mean velocity given by

$$U_{RMS} = \left[\frac{1}{n} \sum_{1}^{n} U^2 \right]^{\frac{1}{2}} \qquad (3)$$

Where U is the mean velocity and n is the number of probe locations used at the measurement plane.

A good degree of flow uniformity corresponds to a value of RMS% less than 15%. For values between 15% and 25% the system performance can be deemed satisfactory, however for values larger than 35%, flow uniformity is considered poor.

The axial velocity U (X) distribution measurements were made at different locations in both the diffuser and the rectangular box. The velocity measurements were carried out using different uniform rectangular mesh grids at each location, varying from 11 X 6 points in the (Y-Z) plane at M_0 to 26 X 11 at M_3 where additional points were added around the outside of the mesh grid used at M_0. The averaged velocity through the measuring section U_{Ave} normalized all measured velocity components.

In present study, seven experimental arrangements for each porosity i.e. 40% and 50% were investigated where, in each of them, plate D was fixed and other plates were moved from one position to another. The arrangements were denoted according to the plate used i.e. D, AD, BD, CD, ABD, ACD and BCD.

2. Results

Velocity measurements were made across the entrance duct over the full measuring cross-section M_0 and M_1. It was observed that the diffuser inlet velocity was essentially uniform. Measurements of the velocity distribution upstream of diffuser confirmed that it remained uniform, as shown in figure 3 and figure 4.

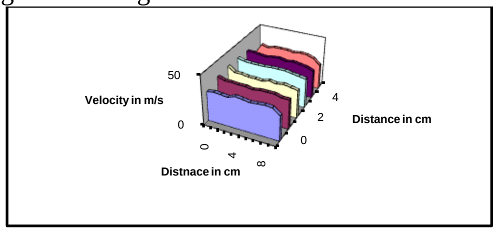

Figure 3. Velocity distribution over the full measuring section M_0 for empty diffuser

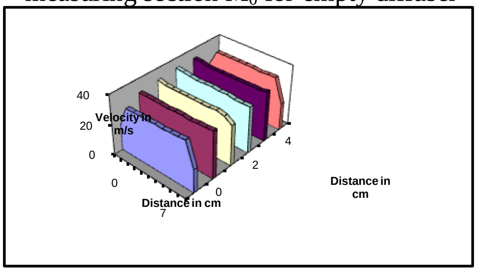

Figure 4. Velocity distribution over the full measuring section M_1 for empty diffuser

2.1 Velocity Distributions at the Diffuser Exit

2.2 The empty diffuser configuration

The empty wide-angle diffuser has flow separation, which is seen from the literature, so it is necessary to see actual velocity profile at exit of the diffuser without any flow control system. Figure 5 shows the velocity profile over the full measuring cross-section M_2 for empty diffuser. The flow remains uniform over the half cross-section of plane M_0. After this the flow velocity suddenly increases with a high central core region with excessive flow separation or the reverse flow near the walls of the diffuser. RMS% value calculated for the diffuser was very high which is not desirable and hence the flow is highly non-uniform.

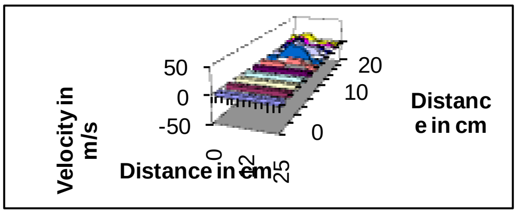

Figure 5. Velocity distribution over the full measuring section M_2 for empty diffuser

2.3 The diffuser with perforated plates of 40% porosity

To control the flow in the diffuser perforated plates are used with various configurations i.e. location of one plate at the exit was fixed and other plates were moved at various location in the diffuser. In the various configurations for porosity 40% the best result obtained with two perforated plates B-D is shown in the figure 6. Here the velocity profile observed is considerably uniform over the measuring plane. Here the RMS% of the velocity was 35.9%, which is very less than the other configurations and it is very near to the desirable value. Here the flow remains attached to the walls of the diffuser and there is very less variation in the flow in central core region.

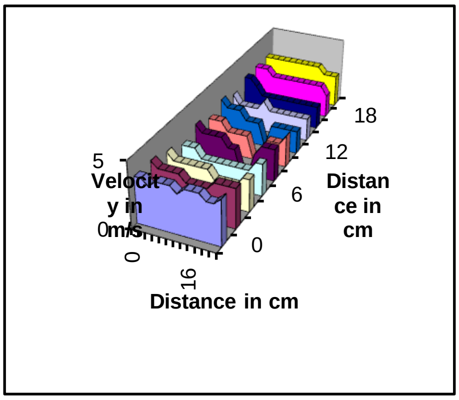

Figure 6. Velocity distribution over the full measuring section M_2 for configuration BD with 40% porosity

2.4 The diffuser with perforated plates of 50% porosity

Similarly for perforated plates with porosity 50% the velocity profiles at the exit of the diffuser were drawn. From various combinations the most desirable configuration obtained was the combination of perforated plates B-C-D having porosity. The velocity profile observed is considerably uniform over the measuring plane. Here the RMS% of the velocity was 31.096%, which was very less than other configurations of porosity 50% and it is very near to the desirable value. Here the flow remains attached to the walls of the diffuser and there is very less variation in the flow in central core region

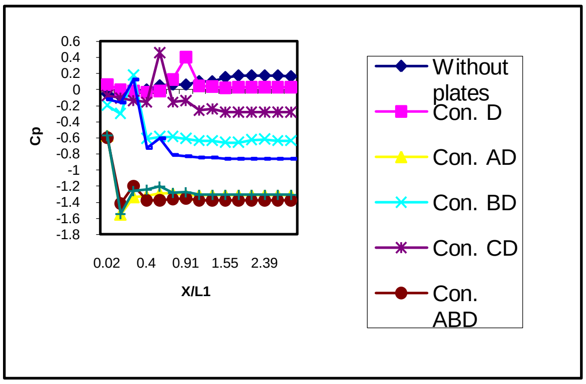

Figure 7. Velocity distribution over the full measuring section M_2 for configuration BCD with 50% porosity

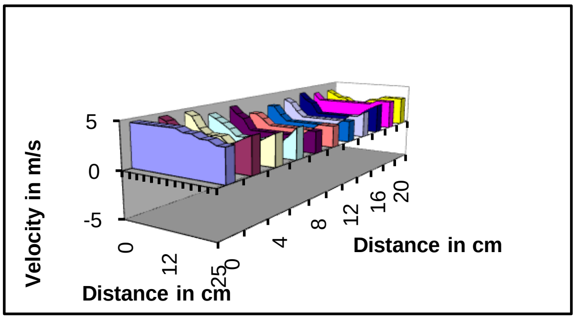

Figure 8. Wall static pressure recovery coefficient Cp profile in the downstream direction from the diffuser to the outlet of the box (Plates with porosity 40%)

The wall static pressure recovery coefficient Cp profile in the downstream direction from the diffuser to the outlet of the box (Plates with porosity 40%) is shown in figure 8. Cp for the empty diffuser configuration that is without plates, the wall static pressure distribution show drop in pressure in the vicinity of the throat but thereafter reflect the large region of stalled fluid within the diffusing passage by remaining largely unchanged. Configuration D does not show any change in Cp profile and is almost same as that for empty diffuser. In configuration AD, the effect of presence of plate A was to prevent the flow from separating at the diffuser inlet. Although the velocities at diffuser inlet were highest, the flow through the plate A caused high pressure losses translated by negative value of the Cp as seen in fig. 8. In BD configuration, in the absence of plate A, the wide wall divergence angle caused separation of the boundary layer at the inlet of the diffuser. However with the presence of plate B, the flow is recovered from separation as shown in above figure. In configuration CD, first upstream plate C could not prevent the flow from separating, since a large recirculation zone still existed at the exit of diffuser. Configuration CD returned the highest positive value of Cp.

In the three perforated plate combination ABD and ACD, it returned the negative values of pressure recovery coefficients due to presence of plate A at the inlet of diffuser. This indicates that the effective outlet area, which is the actual area less the viscous blockage, was smaller than the inlet area caused by the presence of plate A, which added more blockage to the flow downstream. This resulted in an outlet pressure lower than inlet one and a negative value of Cp. In configuration BCD, value of Cp decreases in upstream side and then remains almost constant. Here the values of Cp are negative.

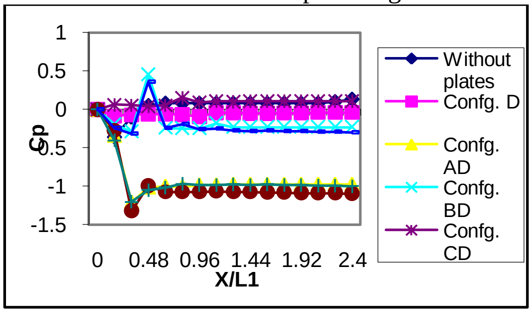

Figure 9. Wall static pressure recovery coefficient Cp profile in the downstream direction from the diffuser to the outlet of the box (Plates with porosity 50%)

The wall static pressure recovery coefficient Cp profile in the downstream direction from the diffuser to the outlet of the box (Plates with porosity 50%) is shown in figure 9. Cp for the empty diffuser configuration that is without plates, the wall static pressure distribution show drop in pressure in the vicinity of the throat but thereafter reflect the large region of stalled fluid within the diffusing passage by remaining largely unchanged. Configuration D does not show any change in Cp profile and is almost same as that for empty diffuser. In configuration AD, the effect of presence of plate A was to prevent the flow from separating at the diffuser inlet. Although the velocities at diffuser inlet were highest, the flow through the plate A caused high pressure losses translated by negative value of the Cp. In BD configuration, in the absence of plate A, the wide wall divergence angle caused separation of the boundary layer at the inlet of the diffuser. However with the presence of plate B, the flow is recovered from separation as shown in above figure. In configuration CD, first upstream plate C could not prevent the flow from separating, since a large recirculation zone still existed at the exit of diffuser. Configuration CD returned the highest positive value of Cp.

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3 Conclusions

Measurements of velocity distribution and wall static pressure distribution along the diffuser have been presented in order to provide an improved understanding of the physical features of the flow in a wide angle diffuser combined with perforated plates.

The magnitude of the plate porosity and the location of the plate within the diffuser influence the pressure losses. Perforated plates of 40% and 50% porosity are tested. It is observed that with changing location and porosity of the perforated plates, three flow regimes frequently occurred they are,

i) A cruciform flow pattern with depleted corner regions

ii) A regime of high velocity wall-layers and a depleted core and

iii) A regime where the flow passage was completely filled and flow separation avoided.

From the experimental results obtained, for diffusers of area ratio about ten and included angle 600 the use of two perforated plate of about 40% porosity or three perforated plates of about 50% porosity are advised. The upstream-perforated plate should be set at X/L_1 =0.25 whilst down stream perforated plate should be located at approximately X/L_1 = 0.95 for 40% and for 50% third perforated plate at X/L_1 = 0.59 is to be located between perforated plates which are at same location as in case of 40% porosity.

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