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Investigation of Flows in Rectangular Diffusers with Inlet Flow Distortion

The results of an experimental study on the influence of severely distorted velocity profiles on the performance of a straight two-dimensional diffuser are reported. The data cover entry Mach numbers ranging from 0.1 to 0.6 and several inlet distortion levels. The pressure recovery progressively deteriorates as the inlet velocity is distorted.

NOTATION

A_i area under the velocity profile above the diffuser centre line as shown in Fig.3 (m^2)

A_{ii} area under the velocity profile below the diffuser centre line as shown in Fig.3 (m^2)

AR area ratio - exit area/throat area

AS aspect ratio (b/W_1)

b distance between parallel walls (m)

CP pressure recovering coefficient $(P_2-P_1)/(P_{01}-P_1)$

CP_{REF} pressure recovery coefficient for symmetrical velocity profile at the diffuser throat

L axial length from the throat to the exit section (m)

M Mach number (space averaged)

P static pressure (N/m^2)

P_o total pressure (N/m^2)

Re Reynolds number at entry (space averaged)

U velocity of flow (m/s)

W depth of diffuser (m)

θ half divergence angle (deg)

λ distortion parameter $\dfrac{\frac{1}{b/2}\int u\,db\Big|_i}{\frac{1}{b/2}\int u\,db\Big|_{ii}} = \dfrac{A_i}{A_{ii}}$

ψ CP/CP_{REF}

SUBSCRIPTS

1 diffuser inlet (throat)

2 diffuser exit

INTRODUCTION

In some applications of straight rectangular diffusers, the flow entering the diffuser throat may be severly non uniform. It is generally accepted that a distorted velocity profile, compared with a uniform profile at the same flow rate, will possess excess kinetic energy flux. This excess of energy will tend to increase as the flow advance into the diffuser and the velocity differences are accentuated due to increasing adverse pressure gradient. Hence static pressure rise, which is a function of the reduction in the kinetic energy-flux, must be adversely affected by distortion of the inlet velocity profile. However quantitative data showing the effect of inlet flow distortion on pressure recovery is scarce. Waitman et al |1| gave a few data where the inlet flow was distorted by obstructions. The pressure recovery coefficient (CP) was found to change due to inlet distortion of the main stream before the throat and the magnitude and direction of the change in CP and changes in the flow regime depended strongly on the type of obstruction and its location. Livesey and Turner |2| studied the effect of velocity profile decay on shear flow in diffusers. Their main conclusion was that in turbulent flow a velocity profile would not be completely specified by shape alone. The rate at which the profile develops or decays, determined by the turbulent structure originating in its past history or method of generation, was of equal importance. Furthermore if the entry profile was in a rapid state of decay

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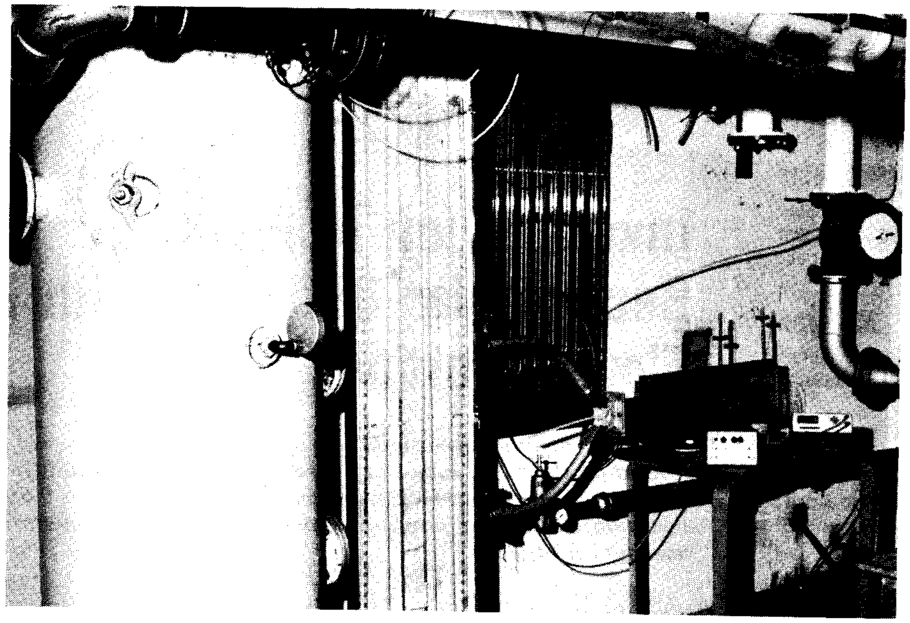

Fig. 1 (a) General view of the apparatus

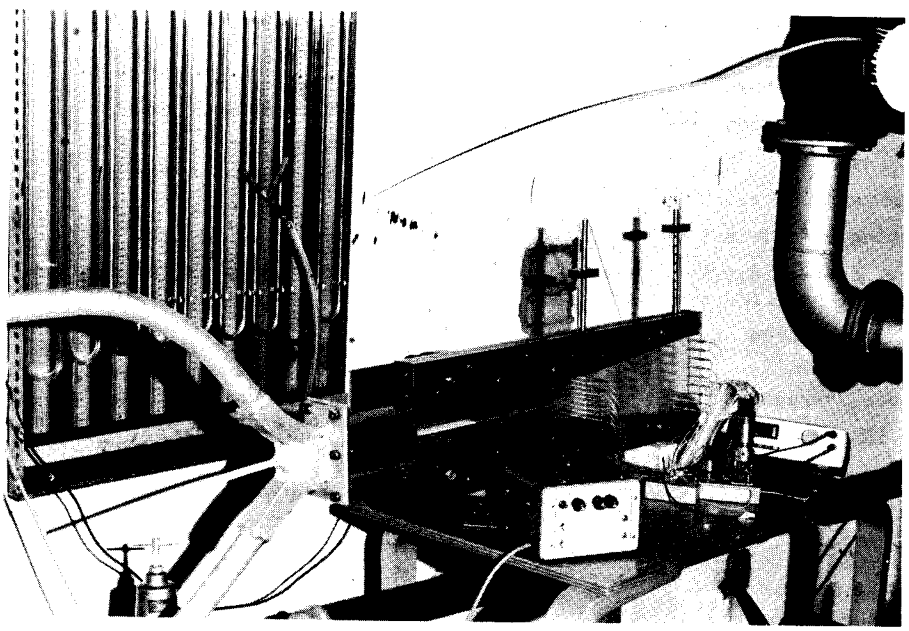

Fig. 1 (b) A close up of diffuser and instrumentation then this instability might be a major factor influencing the outlet velocity profile, consequently the theoretical prediction of the profile would not be accurate. However it should be noted that although turbulent boundary layers on the walls of the constant section entry ducts of various lengths may produce non-uniform inlet velocity, the velocity profiles would be essentially symmetrical. Tyler and Williamson |3| tested a series of conical and annular diffuser geometries for non uniform inlet velocity distribution and found that there was a marked influence of inlet flow distortion on optimum diffuser geometry. A distortion factor, defined as the ratio of maximum to mean velocity in the inlet cross-section was found to be applicable to the pressure recovery in diffusers and diffuser exit settling pipes. The flow Mach number, based on maximum velocity in the inlet plane, did not exceed 0.35. Wolf and Johnston |4| investigated the effect of non uniform inlet velocity profiles on flow regimes and performance in two-dimensional diffusers. Experimental data were collected for two general types of inlet flows : (i) simple uniform shear flows in the core, and (ii) severly non uniform shear flows of the wake, jet and step shear type. It was concluded that in general, for equivalent or nearly equivalent total non-uniformity parameters, such as K_{E1}, B_1, U_{1-max}/U_{1-min}, etc, and equally thin boundary layers, the diffuser performance would deteriorate as the inlet profile was changed from wake flow to jet flow and finally to step shear flow. The distortion parameters B_1 and K_{E1} were defined as follows :

B_1 = total blockage factor at inlet

= 1 - (effective area/geometric area)

K_{E1}= kinetic energy flux coefficient at inlet

$$= \frac{1}{A}\int_A \left(\frac{u}{\bar{u}}\right)^3 dA$$

The results of Wolf and Johnston are very comprehensive but they cover only the incompressible flow case.

In this paper the results of an experimental study on the influence of velocity profiles and mixing lengths on diffuser performance are reported. The tests were carried on a straight two-dimensional diffuser for entry Mach number ranging from 0.1 to 0.6 and several inlet distortion levels. A distortion parameter has been defined to facilitate comparisons between the symmetrical non uniform and severly distorted asymmetric flows at the throat.

DESCRIPTION OF EXPERIMENTAL APPARATUS

Two photographs of the test apparatus are shown in Figs 1a and 1b. Important details of the diffuser are given below :

Area ratio AR = 1.855
Aspect ratio AS = 0.245
Length to width ratio L/W_1 = 4
Divergence angle 2θ = 12 Deg.

The constructional data of the diffuser assembly are shown in Fig.2.

Compressed air is supplied to the diffuser from a large settling tank shown on the left of Fig.1a, via the two rectangular section ducts with independently controlable values. The diffuser proper and

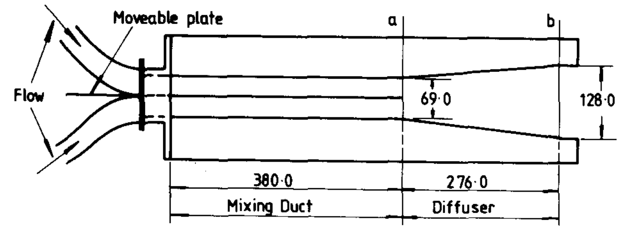

FIG.2 SCHEMATIC REPRESENTATION OF TEST SECTIONS
a. Measurement station for P_1 & P_{01}
b. Measurement station for P_2 & P_{02}

the constant area duct upstream of the diffuser throat are made from perspex. A thin plastic strip divides the entry duct into two equal parts and can be moved to alter the mixing length upstream of the diffuser throat. The desired velocity profile can be obtained by simultaneously manipulating the flow rates in the two ducts and the dividing strip.

The diffuser is instrumented for static and total pressure measurements. As can be seen from Fig.1b static pressure (wall tapping) tubes are connected to a scanivalve. Total pressures are read using two single hole cylindrical probes which can be traversed across the throat and the exit section in pre-determined steps. The mass flow rate is measured by means of a British Standard Orifice, which is installed upstream of the settling tank. During the tests, the settling tank was charged continuously with compressed air to maintain steady conditions of pressure and temperature.

PROCEDURE

Tests were carried out for symmetrical velocity profiles at the diffuser throat to obtain reference data. This condition corresponded to equal flows in both branches leading to the constant area entry duct. In subsequent tests, the position of the movable strip and the flow rates in the two branches were adjusted together to obtain different velocity profiles and at the same time, as far as practical, similar boundary layer displacement thicknesses at the throat section.

Experimental data which included total pressures scans at entry and exit sections and static pressure measurements as shown in Fig.1b for a range of entry Mach numbers and velocity profiles.

DISCUSSION OF RESULTS

The performance of diffusers is usually given in terms of pressure recovery coefficient, geometrical data, and the entry conditions defined by such parameters as Mach number, Reynolds number, blockage etc. When the entry flow is non-uniform, the Mach number and Reynolds number may be based on either maximum or mean values of the entry parameters. In this paper space averaged mean values have been used.

The inlet flow distortion has been quantified generally as the ratio U_1 - min/U_1 - max. Clearly this definition is unsatisfactory as it is possible to produce a large number of entirely different velocity profiles which can have the same U_1 - min/U_1 - max values.

In this study a new distortion parameter λ was used. The definition of λ is as follows :

$$\lambda = \frac{\frac{2}{b}\int^{b/2} U db \Big|_{i}}{\frac{2}{b}\int^{b/2} U db \Big|_{ii}} = \frac{A_i}{A_{ii}}$$

The areas A_i and A_{ii} are shown in Fig.3.

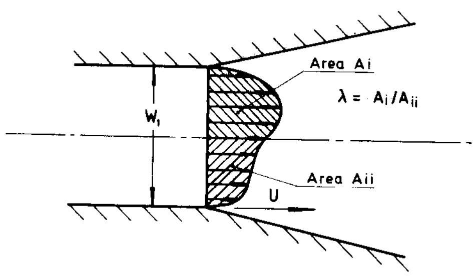

FIG.3 : TYPICAL NON-UNIFORM VELOCITY PROFILE

The values of CP vs M_1 for λ, shown in Fig.4, were used as the reference data for comparing the results obtained for severely distorted entry profiles.

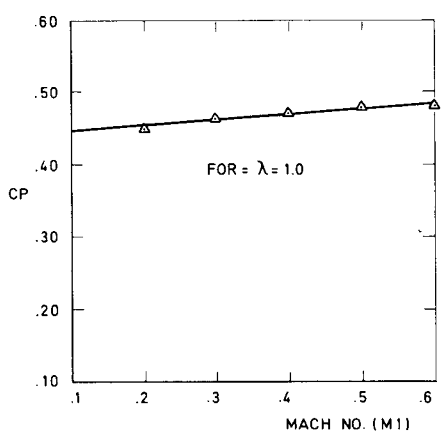

FIG.4 : PRESSURE RECOVERY COEFFICIENT VS ENTRY MACH NUMBER FOR λ = 1

Fig.5 shows graphs of ψ vs M_1 for a range of values of λ. It can be seen that pressure recovery coefficient decreases quite significantly as the inlet distortion parameter is increased. It should be noted that for each space averaged value of M_1 CP_{REF} was obtained from Fig.4.

The graphs of ψ vs Re, shown in Fig.6, are similar to those given in Fig.5. The effect of inlet distortion on pressure recovery is quite significant, but for the same value of the distortion parameter, the pressure recovery coefficient ratio is only slightly dependent on the Reynolds number.

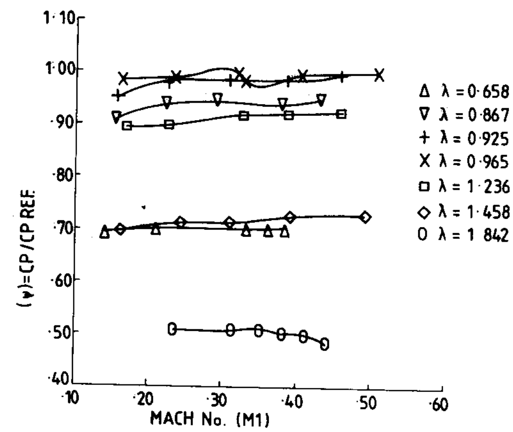

FIG.5 : PRESSURE RECOVERY RATIO (ψ) AGAINST MACH N° (M1)

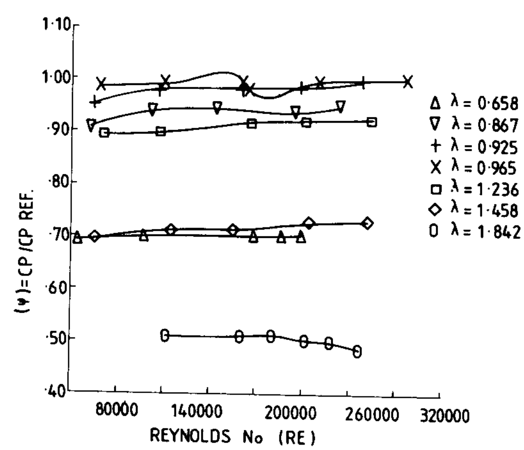

FIG.6 : PRESSURE RECOVERY RATIO (ψ) AGAINST REYNOLDS N° (Re)

Fig.7 shows the variation of ψ with λ for the entry Mach numbers ranging from 0.1 to 0.6. It can be seen that for severely distorted flows, λ = 1.8, the pressure recovery may be reduced by as much as 50%.

Finally it should be mentioned that pressure recovery coefficient was calculated according to the following equation :

$$CP = \frac{P_2 - P_1}{P_{01} - P_1}$$

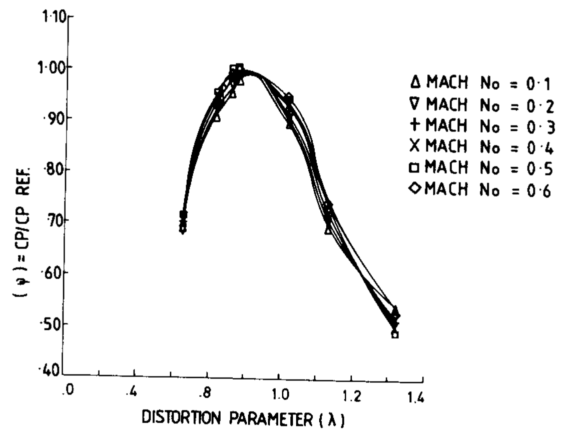

FIG.7 : PRESSURE RECOVERY RATIO (ψ) AGAINST DISTORTION PARAMETER (λ)

The uncertainty in the pressure recovery due to measurement tolerances are approximately ± 3% to 6.5% over the full range.

The entry Mach number M_1 is calculated from the measured values of P_{o1} and P_1 in accordance with the following equation :

$$M_1 = \sqrt{\frac{2}{\gamma - 1}\left\{\left(\frac{P_1}{P_{o1}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right\}}$$

CONCLUSION

1. Experimental results are reported to show the effect of inlet flow distortion on the performance of straight rectangular diffusers.
2. Serious degradation in pressure recovery is produced by severely distorted asymmetric inlet velocity profiles.
3. The results may have some application to the vane diffusers of centrifugal compressors as the flow entering the diffuser channels is usually severely distorted because of the jets and wakes discharged by the impeller. It must emphasize however that the data presented in the paper were obtained under steady conditions. The flows in the diffuser channels of a centrifugal compressor would be time dependent unless the diffuser vanes are far removed from the impeller tip.

ACKNOWLEDGEMENTS

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REFERENCES

1. Waitman B.A., Reneau L.R. and Kline S.J. : "Effects of inlet conditions on performance of two-dimensional subsonic diffusers", ASME trans. Series D, Journal of Basic Engineering, Vol.83 N°3, Sept. 1961, pp. 349-360.
2. Livesey J.L. and Turner J.T. : "The effect of velocity profile decay on shear flow in diffusers", Int. J. Mech. Sci. Pergamon Press Ltd., 1964, Vol.6, pp. 371-379.
3. Tyler R.A. and Williamson R.G. : "Diffuser performance with distortion inflow", Proc. Inst. Mech. Engrs, 1967-68, Vol. 182, Pt.3D, Paper 11.
4. Wolf S. and Johnston J.P. : "Effects of non-uniform inlet velocity profiles on flow regimes and performance in two-dimensional diffusers", ASME Trans. Series D, Journal of Basic Engineering, Sept. 1969, pp. 462-474.