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EFFECTS OF INLET FLOW FIELD CONDITIONS ON THE PERFORMANCE OF CENTRIFUGAL COMPRESSOR DIFFUSERS
PART 2: STRAIGHT-CHANNEL DIFFUSER

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ABSTRACT

This is Part 2 of an examination of influence of inlet flow conditions on the performance and operating range of centrifugal compressor vaned diffusers. The paper describes tests of straight-channel type diffuser, sometimes called a wedge-vane diffuser, and compares the results with those from the discrete-passage diffusers described in Part 1. Effects of diffuser inlet Mach number, flow angle, blockage, and axial flow non-uniformity on diffuser pressure recovery and operating range are addressed.

The straight-channel diffuser investigated has 30 vanes and was designed for the same aerodynamic duty as the discrete-passage diffuser described in Part 1. The ranges of the overall pressure recovery coefficients were 0.65-0.78 for the straight-channel diffuser and 0.60-0.70 for the discrete-passage diffuser; the pressure recovery of the straight-channel diffuser was roughly 10% higher than that of the discrete-passage diffuser. Both types of the diffusers showed similar behavior regarding the dependence on diffuser inlet flow angle and the insensitivity of the performance to inlet flow field axial distortion and Mach number. The operating range of the straight-channel diffuser, as for the discrete-passage diffusers was limited by the onset of rotating stall at a fixed momentum-averaged flow angle into the diffuser, which was for the straight-channel diffuser, $\alpha_{crit} = 70° \pm 0.5°$.

The background, nomenclature and description of the facility and method are all given in Part 1.

1 INTRODUCTION

In Part 1, we examined the influence of inlet flow field conditions on the performance of discrete-passage diffusers. In Part 2 we present the results of investigations of this topic for straight-channel diffusers as well as compare the two types of radial diffusers. Effects of diffuser inlet Mach number, flow angle, axial flow non-uniformity and blockage on diffuser pressure recovery and onset of instability are addressed. The test facility, instrumentation, and parameters used are described in Part 1.

Straight-channel diffusers are used by a large number of turbomachinery companies. The configuration is both simple to manufacture and yields good performance (Krain (1984), Kano et al. (1982), Rodgers (1982)). The starting point for the design of the straight-channel test diffuser is often a diffuser map (e.g. Reneau et al. (1967)) for single channel 2D-diffusers to select geometrical diffuser parameters: diffuser channel divergence angle 2θ, area ratio AR and length-to-width ratio LWR. Selected diffusers are often designed very close to the line of maximum pressure and in the flow regime of no appreciable stall. According to the measurements by Yoshinaga et al. (1980), the optimal diffuser divergence angle for straight-channel type radial diffuser is in the range 8° to 10°.

To make direct use of single channel diffuser performance data, the blockage at inlet should be given. Investigations for single channel diffusers had shown that diffuser pressure recovery decreases significantly as inlet blockage increases, for example Runstadler and Dean (1969), Runstadler and Dolan (1973). The diffuser pressure recovery coefficient used by Runstadler is based on dynamic pressure calculated from the velocity at the center of the inlet section. For the same diffuser geometries as Runstadler, Dong (1996) recalculated the pressure recovery coefficient based on mass-averaged total pressure at diffuser inlet and found that the dependence of pressure recovery on inlet blockage is much less (see for comparison Fig. 1). Recently Yaras

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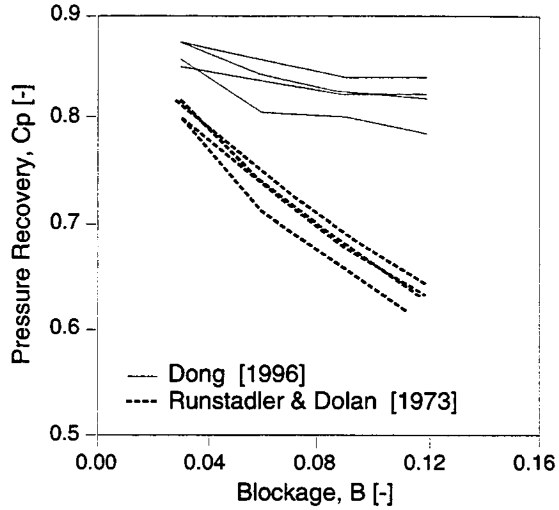

Figure 1: Pressure recovery coefficient, Cp, as a function of inlet blockage, B_1, for single channel diffusers with different area ratios and divergence angles; comparison of the data from Dong (1996) (Cp is based on mass-averaged diffuser inlet total pressure) and Runstadler and Dolan (1973) (Cp is based on diffuser inlet centerline total pressure).

(1996) also investigated the effects of inlet conditions on the flow in a fishtail curved diffuser and found that both the pressure recovery coefficient based on mass-averaged inlet total pressure and mass-averaged total pressure losses through the diffuser are observed to be relatively insensitive to variations in the diffuser inlet boundary layer.

For centrifugal compressor vaned diffusers blockage should be defined at the diffuser throat, because the channel part of the centrifugal compressor vaned diffuser is geometrically similar to single channel diffusers. There is almost never experimental data available at diffuser throat, but the throat blockage can be estimated (if it can be defined at diffuser inlet) by assuming isentropic flow from diffuser inlet to throat. It is also sometimes estimated from measurements of the diffuser pressure recovery from the diffuser inlet to the throat, adopting the approach which was first suggested by Kenny (1972), to derive a correlation between throat blockage and pressure rise. Calculation of throat blockage for the straight-channel diffuser tested here and performance comparisons with single channel diffuser data can be found in Deniz (1997).

An important aim of the straight-channel investigations was to compare the performance of the straight-channel diffuser to that of the discrete-passage diffuser. The overall inlet conditions for the straight-channel diffuser design, i.e. the mean inlet flow angle, α, the number of vanes, vaneless space radius ratio, and the axial depth, b, and throat area, A_{th}, were therefore chosen to be similar to those of the discrete-passage diffuser, reported in Part 1. The main dimensions of the straight-channel diffuser and discrete-passage diffuser are given in Table 1. Fig. 2 shows straight-channel diffuser geometry and the locations of channel centerline, vaneless and quasi-vaneless space static pressure taps.

In Part 1 different definitions for averaging the non-uniform total pressure at inlet to the diffuser and the pressure recovery coefficient were described. Depending on the method used, the data can collapse into a narrow trend, or spread in a manner that is difficult to understand. The availability-averaged total pressure was selected as the most physically appropriate one to be used in defining the diffuser pressure recovery coefficient, but it was also found that mass-averaged total pressure gave similar values and is easier to use. In Part 1 the difference between availability and mass-averaged diffuser inlet dynamic total pressure was found to be no more than 1.6% and for the measurements in this part the difference is no more than 1%. The mass-averaged pressure recovery coefficient is sufficiently close to the availability-averaged pressure recovery coefficient so that it will be used throughout Part 2.

The ranges of blockage, flow non-uniformity, and other parameters achieved include values above and below of those produced by typical centrifugal compressor impellers. They can be summarized for the straight-channel diffuser as follows:

- Diffuser inlet flow angle, α_1, 63°-71°
- Diffuser inlet Mach number, M_1, 0.2-1.15
- Velocity profile axial-distortion (uniform and non-uniform pro-

Table 1: Parameters for straight-channel and discrete-passage diffuser

	Straight-Channel Diffuser	Discrete-Passage Diffuser
Diffuser Channel Divergence Angle, 2θ	8°	
Area Ratio, AR	2.34	4.29
Length-to-Width Ratio, LWR	9.574	8.75
Number of Diffuser Channels, Z_v	30	30
Aspect Ratio, AS	0.643	
Diffuser Axial Width, b	9.0 mm	9.0 mm
b/r_1	0.044	0.044
$r_1/r_{1'}$	1.10	1.10
$r_2/r_{1'}$	1.64	1.52
Throat Area, A_{th}	0.00013 m^2	0.00013 m^2
Diffuser Centerline Design Angle	69°	69°
Wedge Angle of Diffuser Vane, β	4.0°	

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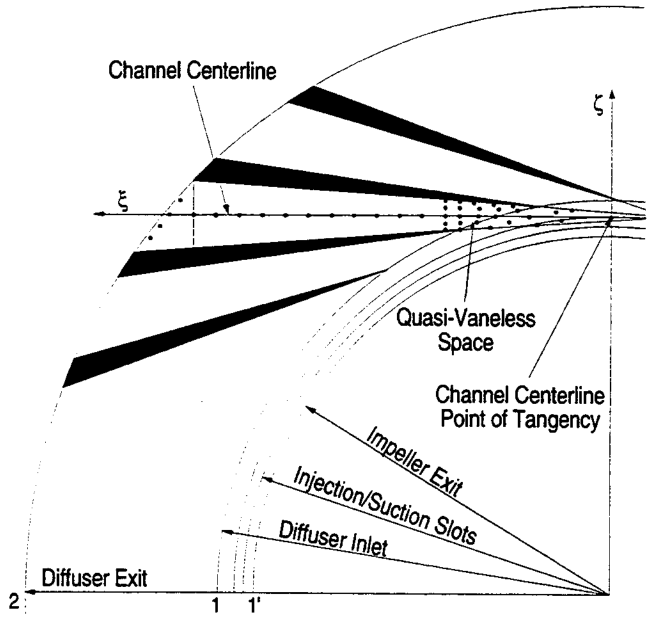

Figure 2: Straight-channel diffuser geometry and static pressure tap locations.

files, inlet flow angle differences up to 45° between diffuser rear and front walls)

- Diffuser inlet blockage, B_1, 2-35%
- Diffuser inlet Reynolds number, Re_1, $0.4 \cdot 10^5$ - $2.5 \cdot 10^5$.

2 RESULTS

2.1 Baseline Inlet Flow Field Data without Air Injection/Suction

The results of four separate data sets are presented. The first data set or baseline (denoted with number I) was carried out without air injection/suction. The diffuser inlet flow angle and Mach number axial profiles were measured for every operating point. For the baseline case (no injection/suction) examples of axial distributions of flow angle and Mach number are shown in

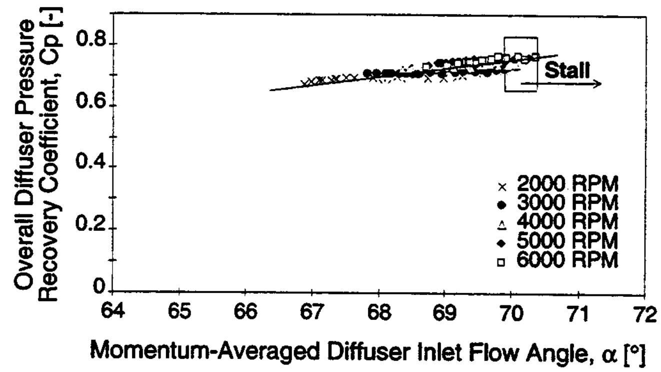

Figure 4: Mass-averaged overall straight-channel diffuser pressure recovery coefficient, Cp, versus momentum averaged diffuser inlet flow angle, α, for different corrected impeller speeds (no/injection/suction).

Figures 3a and 3b for different corrected impeller speeds from 2000 RPM to 6000 RPM and a constant atmosphere-to-plenum ratio. The profiles of flow angle and Mach number are fairly symmetrical at diffuser inlet, although there is an influence of the labyrinth seal leakage shown in the flow angles near the front wall (x/b = 0). In Fig. 3b, the diffuser inlet Mach number increases as impeller rotational speed increases and the maximum Mach number achieved at the diffuser inlet was 1.15.

For the baseline case (no injection/suction), the overall diffuser pressure recovery coefficient versus inlet flow angle is shown in Fig. 4. The figure includes all the different corrected impeller speeds examined and data from maximum flow rate to the onset of rotating stall. The pressure recovery coefficient is based on mass-averaged inlet total pressure and the inlet flow angle is the momentum-average. For all speeds the overall diffuser pressure recovery increases from 0.67 to 0.77 as the flow is reduced from maximum ($\alpha \approx 67°$) to the near stall operating point ($\alpha \approx 70.5°$). (For constant impeller speed, lower mass flow rate implies lower radial velocity and therefore increasing flow angle

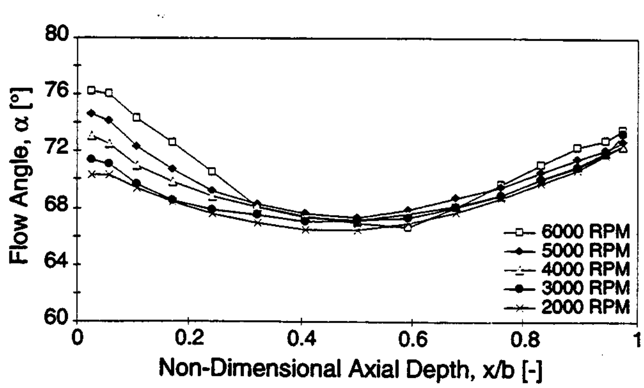

Figure 3a: Axial distributions of flow angle, α, at the straight-channel diffuser inlet for different corrected impeller speeds (no injection/suction).

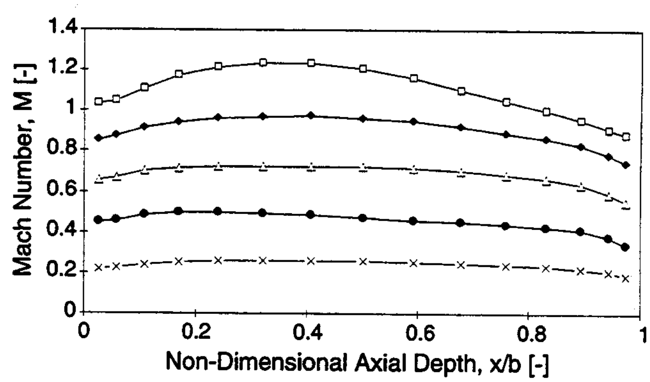

Figure 3b: Axial distributions of absolute Mach number, M, at the straight-channel diffuser inlet for different corrected impeller speeds (no injection/suction). (Same legend as Fig. 3a)

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at the diffuser inlet.) Rotating stall appeared when α was between 70° and 70.5° for all impeller speeds investigated.

The effect of inlet Mach number on the mass-averaged overall diffuser pressure recovery coefficient is shown in Fig. 5. In this figure, the absolute Mach number at diffuser inlet varies from 0.2 to 1.15 and there is little influence on the mass-averaged overall diffuser pressure recovery coefficient. The observed insensitivity of diffuser pressure recovery on the diffuser inlet Mach number is in accordance with other vaned diffuser investigations, such as Krain (1984) (straight-channel diffuser), Hunziker (1993) (cambered-vane diffuser), Japikse and Osborne (1986) (different vaned diffusers).

2.2 Influence of Inlet Flow Conditions (Data with Air Injection/Suction)

Three series of experiments were undertaken with air injection/suction through the profile control slots in the vaneless space. The three data series are denoted with the numbers II, III, and IV in the legend of Figures 6 and 7. Inlet conditions to the diffuser include low and high Mach numbers, symmetric and asymmetric profiles, with high and low distortions and blockage levels (see Fig. 6). In the legend of Fig. 6a, b, and c the average value of the presented flow angle distribution is given together with the flow angle non-uniformity, α_n.

For data series II and III, two constant corrected impeller speeds were chosen, a low speed N = 2000 RPM (Mach number at diffuser inlet $M_1 \approx 0.2$ to 0.4) and a high speed N = 5000 RPM (Mach number at diffuser inlet $M_1 \approx 0.7$ to 1.0). For data series II, for a constant corrected impeller speed and throttle valve position the applied injection and suction rates were at the same amount (maximum 10% of venturi mass flow rate), so that the venturi mass flow rate, $\dot{m}$, remained nearly constant with and without injection suction. The data series (II) thus did not have a high level of velocity non-uniformity at the diffuser inlet as seen in Fig. 6a, where the difference of inlet flow angle between front and rear sides of the diffuser was smaller than 10°.

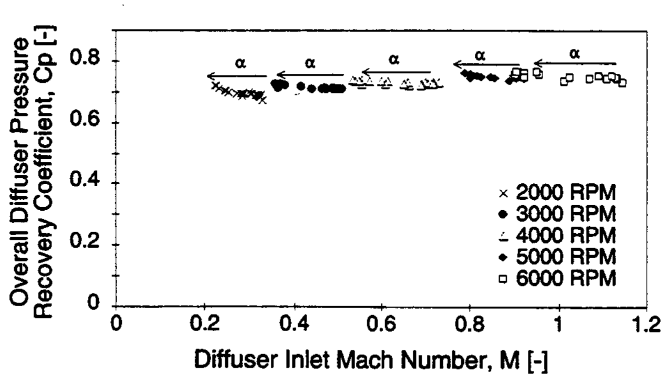

Figure 5: Mass-averaged overall straight-channel diffuser pressure recovery coefficient, Cp, versus diffuser inlet Mach number, M, for different corrected impeller speeds (no/injection/suction).

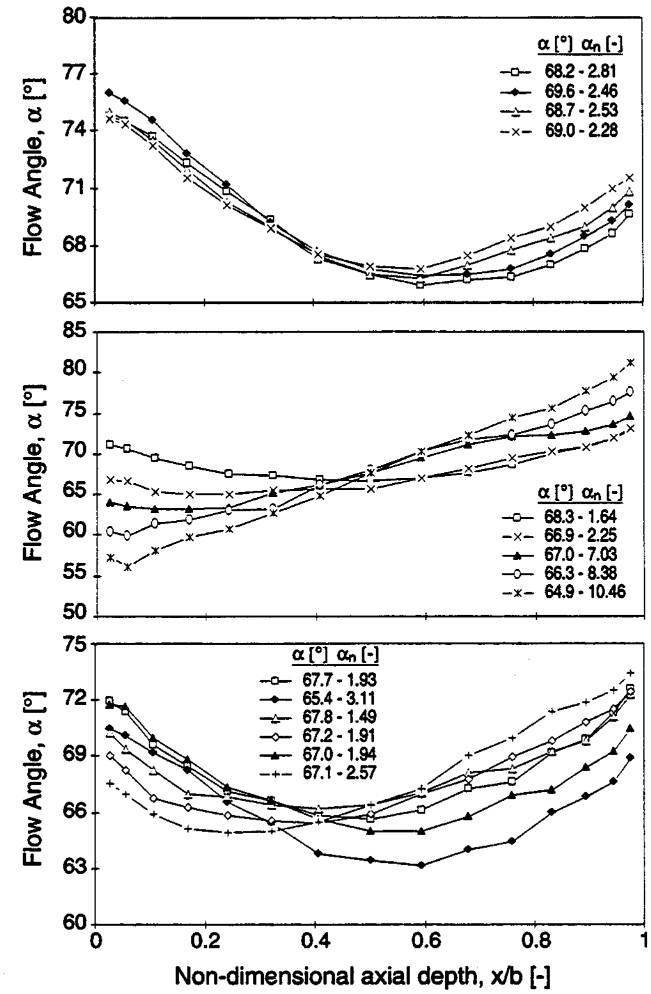

Figure 6: Examples of flow angle, α, axial distribution at the straight-channel diffuser inlet (with injection/suction): a) Series II, N = 5000 RPM, b) Series III, N = 2000 RPM, c) Series IV, N = 4000 RPM.

High levels of distortion at the diffuser inlet were obtained in data series III, where inlet distortion was varied from a symmetrical relatively flat distribution to an asymmetrical triangular distribution. Up to 45° difference of inlet flow angle between front and rear sides of the diffuser was achieved. Examples of the measured flow angle distributions are shown in Fig. 6b.

Data series IV contains three different impeller speeds, 2000, 4000, and 6000 RPM. At the lowest speed the Mach number range at inlet to the diffuser is 0.2 to 0.4, whilst at the highest speed it is in the range 0.8 to 1.15. In the series IV data, asymmetrical, distorted velocity profiles and also symmetrical velocity profiles with different boundary layer blockage levels were applied at the diffuser inlet with both side injection or suction. Some examples of the measured flow angle distributions of series IV are shown in Fig. 6c for N = 4000 RPM. A full list of conditions is given in Deniz (1997).

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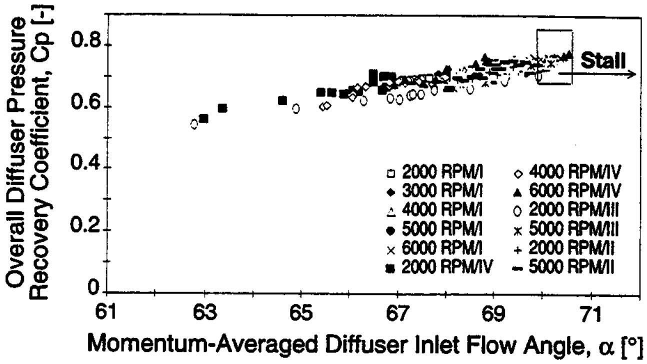

Figure 7: Mass-averaged overall straight-channel diffuser pressure recovery coefficient, Cp, versus momentum averaged diffuser inlet flow angle, α, for different corrected impeller speeds and data series (I, II, III, IV) with and without injection/suction.

Figure 7 shows mass-averaged overall pressure recovery coefficient for the straight-channel diffuser as a function of momentum-averaged flow angle into the diffuser for various impeller speeds, throttle valve positions and inlet distortion parameter levels. The magnitude of the diffuser pressure recovery and operating range are essentially functions of inlet flow angle alone; the onset of rotating stall for the investigated straight-channel diffuser occurred at a momentum-averaged flow angle (70° ±0.5°) independent of the inlet flow field distortion and Mach number. For all data series, with and without injection/suction, the maximum diffuser pressure recovery was achieved just before the rotating stall threshold.

As discussed in the introduction, the conventional view of diffuser performance puts great emphasis on the inlet blockage. Normally it is hard to know the magnitude of the blockage, but in these tests with the straight-channel diffuser it was measured. Figure 8 plots mass-averaged overall diffuser pressure recovery coefficient versus straight-channel diffuser inlet blockage. A

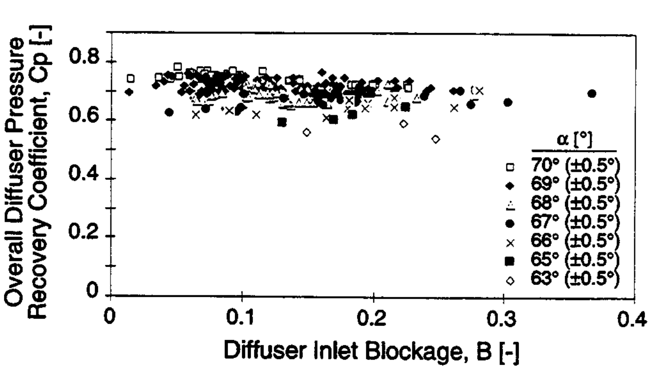

Figure 8: Mass-averaged overall straight-channel diffuser pressure recovery coefficient, Cp, versus diffuser inlet blockage, B, with and without injection/suction.

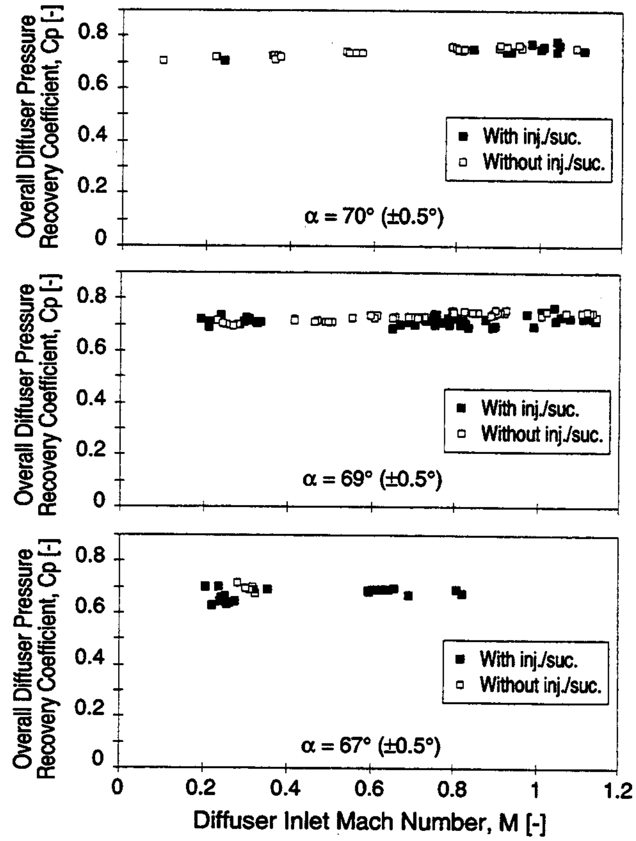

Figure 9: Mass-averaged overall diffuser pressure recovery coefficient, Cp, versus diffuser inlet Mach number, M, represented for constant diffuser inlet flow angles.

slightly decreasing trend of the mass-averaged pressure recovery with increasing diffuser inlet blockage can be observed in Fig. 8. Note, however, that the lower pressure recovery coefficient values in Fig. 8 cannot be attributed to inlet blockage alone, because the points of lower pressure recovery are also points of lower inlet flow angle in Fig. 7.

The main trend of the Fig. 7 is that the performance of the vaned diffusers of centrifugal compressors can be correlated using one main parameter, the average inlet flow angle. For a given flow angle, mass-averaged overall diffuser pressure recovery coefficient is essentially independent of diffuser inlet conditions. To isolate the influence of parameters associated with the inlet flow field, the data in Figures 7 and 8 are presented for constant flow angles in Figures 9 through 11. Figures 9a, 10a, and 11a are for a high flow angle ($\alpha = 70°$) near to the rotating stall onset; Figures 9b, 10b, and 11b are for the straight-channel diffuser metal angle ($\alpha = 69°$); and Figures 9c, 10c, and 11c are for a lower flow angle ($\alpha = 67°$). In each of these the ordinate is the overall diffuser pressure recovery coefficient based on the mass-averaged inlet total pressure. Figure 9 has *inlet Mach number* as abscissa, Fig. 10 has *inlet blockage*, and Fig. 11 *flow angle non-*

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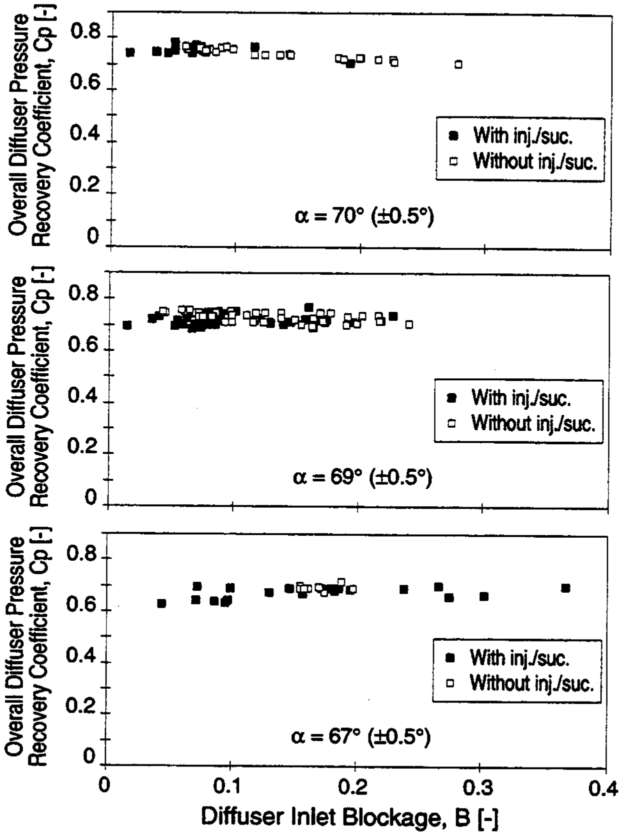

Figure 10: Mass-averaged overall diffuser pressure recovery coefficient, Cp, versus diffuser inlet Blockage, B, represented for constant diffuser inlet flow angles.

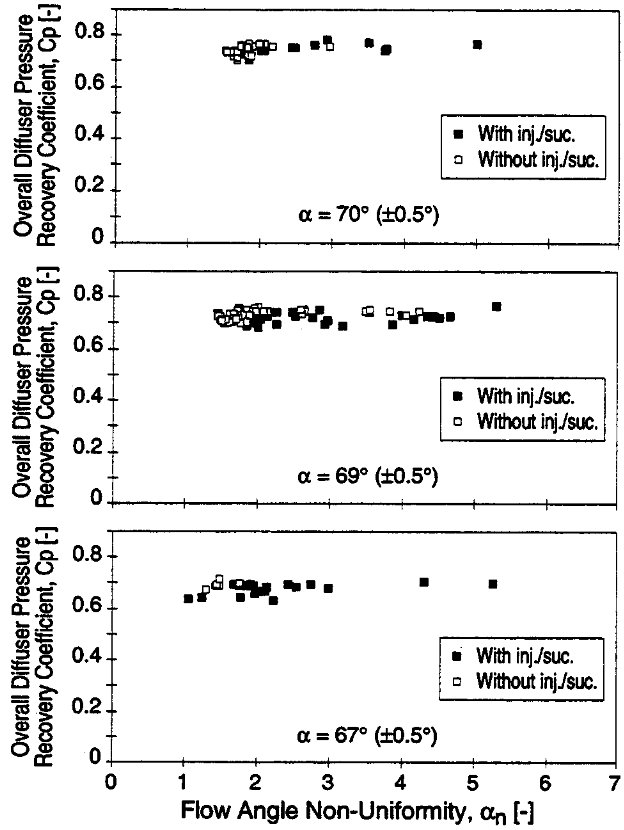

Figure 11: Mass-averaged overall diffuser pressure recovery coefficient, Cp, versus diffuser inlet flow angle non-uniformity, α_n, represented for constant diffuser inlet flow angles.

uniformity. (The axial variation in the velocity distribution at the diffuser inlet is expressed in term of the flow angle non-uniformity.) Figures 9 through 11 confirm that there is no significant dependence of mass-averaged pressure recovery on these parameters. This observation is also true for the other constant inlet flow angles, see Deniz (1997). The mass-averaged overall diffuser pressure recovery is overwhelmingly determined by the inlet flow angle.

An example of static pressure distribution along the centerline of one diffuser channel is plotted in Fig. 12 for experiments with injection/suction. This figure shows a constant speed (N = 2000 RPM) case with different inlet flow field distortion levels and flow angles. The average values of inlet flow angles are 63.0°, 64.8°, 68.4°, 68.9°, and 70.0° and there is significant difference in the pressure recovery between pressure rise curves of different flow angles. The slope of the pressure rise in the channel diffuser part is similar for all inlet flow angles, but the achieved overall diffuser pressure recovery is different. The reason for the different overall diffuser pressure recovery is the changes in pressure rise at the diffuser inlet region. In Fig. 12 the highest pressure recovery is for $\alpha = 70.0°$, which is close to the onset of rotating stall. Curves for flow angles 68.9° and 68.4° are near the diffuser inlet metal angle. For inlet flow angles equal or greater than the diffuser metal angle (70.0°, 68.9° and 68.4°) there is a substantial fraction of the pressure rise, which occurs in the diffuser inlet region, in quasi-vaneless space after the leading edges and immediately upstream of the diffuser throat. In the channel part of the diffuser, the slope of the pressure rise decreases in the flow direction so lengthening of the diffuser is likely to produce small additional gains. More than 60 % of the overall diffuser pressure static rise occurs within the first 30% of the diffuser channel length.

Decreasing the inlet flow angle to $\alpha = 64.8°$ reduces the slope of the pressure rise in the diffuser inlet region, whilst decreasing the inlet flow angle further to $\alpha = 63.0°$ results in a fall in static pressure in the diffuser inlet region (quasi-vaneless space), with an acceleration of flow until flow enters the channel part of the diffuser. The overall diffuser pressure recovery is consequently low for $\alpha = 63.0°$, but choking of the flow, which occurred for the 30 passage discrete-passage diffuser at low diffuser inlet flow angle region, was not observed for the straight-channel diffuser, because the Mach number at the diffuser inlet was, for example only 0.3 for $\alpha = 63.0°$. Unfortunately test data at the low diffuser inlet flow angle region with high Mach numbers at diffuser inlet was not obtained for the straight-channel diffuser investigations.

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2.3 Comparison with Discrete-Passage Diffuser Results

The test results of the investigations with discrete-passage diffusers (see Part 1) showed that overall diffuser pressure recovery coefficient based on suitably averaged inlet stagnation pressure correlates well with an average inlet flow angle and is insensitive to axial distortions of the diffuser inlet flow field and Mach number. The results of the experiments with the straight-channel diffuser presented in Sections 2.1 and 2.2 show similar behavior.

The achieved overall diffuser pressure recovery levels of straight-channel and discrete-passage diffusers are compared in Fig. 13. The straight-channel diffuser shows ~10% higher pressure recovery. At operating points near the design point, the pressure recovery coefficient (mass or availability-averaged) for straight-channel diffuser is around 0.65 - 0.78 and for discrete-passage diffuser around 0.60 - 0.70. The variation in the pressure recovery coefficient with inlet flow angle (momentum-averaged) is similar for both types of diffuser. Figure 13 shows that the critical inlet flow angle for the onset of rotating stall for the straight-channel diffuser is 70° ±0.5° and that for the discrete-passage diffuser is 73.5° ±0.5°. This is not an obvious advantage because the range of flow angles tolerated as operating range is about 5° for both design and the whole operating range of the straight-channel diffuser is at smaller flow angles than that of the discrete-passage diffuser. Put differently, the straight-channel diffuser used for this experiment will accept a higher impeller mass flow. Perhaps surprisingly the optimum mass flows for the straight-channel diffuser and discrete-passage diffuser are not equal even when the geometric throat area and the inlet metal angle are the same.

3 SUMMARY and CONCLUSIONS

An experimental investigation has been carried out on performance, operating range and fluid dynamic phenomena of a straight-channel diffuser typical of high performance centrifugal compressor stages. The influences of inlet flow field conditions, including Mach number, flow angle, fluid dynamic blockage, and flow non-uniformity in the axial direction on the pressure recovery and stability of a straight-channel diffuser were investigated on a centrifugal compressor diffuser test facility. The range of inlet conditions included Mach numbers from 0.2 to 1.15, flow angles from 63° to 71°, blockage levels from 3 to 35% and high levels of axial flow field distortion, e.g. up to 45° flow angle difference between front and rear walls at the diffuser inlet.

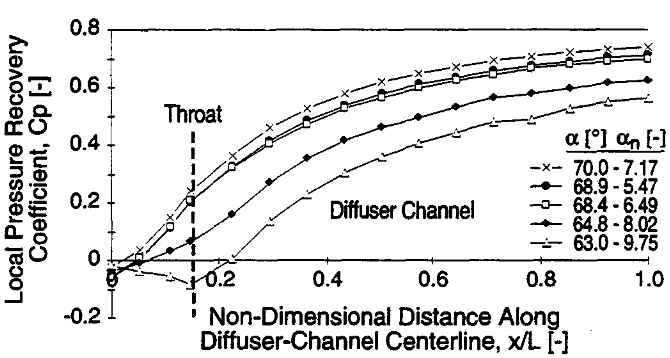

Figure 12: Static pressure distribution along the centerline of a straight-channel diffuser channel for different flow angles at a constant impeller speed N = 2000 RPM (with injection/suction).

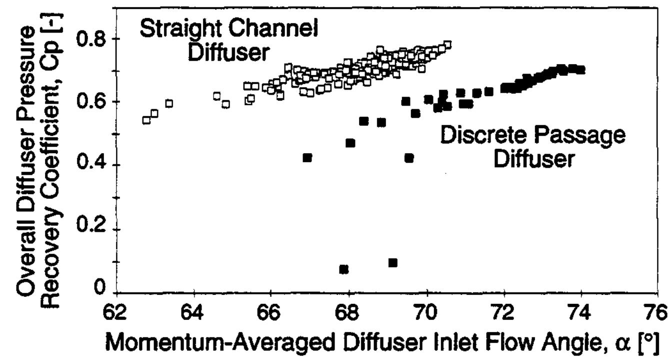

Figure 13: Comparison of mass-averaged overall diffuser pressure recovery coefficient, Cp, for straight-channel and discrete-passage diffusers.

The main conclusions of this investigation are as follows:

(1) The pressure recovery coefficient for either discrete-passage or straight-channel diffusers is virtually a unique function of inlet flow angle. This requires a suitable average to be used for the inlet total pressure in calculating the pressure recovery coefficient and a suitable average flow direction to be used for the flow angle. It is then found that the dependence on Mach number (even at supersonic levels), blockage, and various inlet distortions is negligible.

(2) It has been found that either an availability-averaged total pressure or a mass-averaged total pressure is satisfactory in correlating pressure recovery. The availability-average can be shown to be better theoretically, but in practice the mass-average is equally satisfactory.

(3) The inlet flow direction should be based on the momentum-averaged flow angle.

(4) The straight-channel diffuser was found to give pressure recovery coefficients in the range 0.65-0.78 (proportional to inlet flow angle) whereas the discrete-passage diffuser gave lower values in the range 0.60-0.70.

(5) The performance of the discrete-passage diffuser was essentially the same with 30 or 38 passages.

(6) The onset of rotating stall was found in both types of diffusers to occur at a fixed value of inlet flow angle (based on the momentum-average). The actual magnitude of the critical angle depends on the type (and on the design) of diffuser. The presence of a total pressure/flow angle probe at diffuser inlet

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was found in one case examined to have caused stall at an diffuser inlet flow angle approximately 0.45° smaller.

(7) The insensitivity of the diffuser performance to details of the flow such as Mach number, blockage and velocity profile distortion suggests that a strong mixing process is at work in the quasi-vaneless space and throat region. What controls the performance is the overall mass flow, momentum and energy of the flow entering the diffuser. By using suitable averages for inlet stagnation pressure and flow direction it appears that most of the essential information has been included. This deserves further study. A paper demonstrating the importance of flow angle on radial diffuser performance by means of CFD will be published soon. This prospective paper will also be including a comparison between CFD predictions for the straight-channel diffuser and experimental results presented for the same diffuser in this paper.

(8) It appears plausible to suggest that the approach to compressor diffuser performance estimation and design, which rests on the determination of blockage at the diffuser inlet or the throat, is unnecessary. This approach fails to take account of the mixing processes referred to in (7) above, which appear to be an important aspect in determining the overall diffusion capability.

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