FLOW MEASUREMENTS IN PASSAGES OF DIFFERENT DIFFUSERS OF A CENTRIFUGAL COMPRESSOR AT DESIGN CONDITION

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Abstract

Flow field measurements in the passages of different types of diffusers of a centrifugal compressor are presented in this paper. The measurements are carried out using a precalibrated three hole pressure probe at the design condition. The measurements are carried out in the passages of the following diffusers: vaneless, vane, low solidity vane and partial vane diffusers. The results are presented as contours, axially averaged and mass averaged flow parameters. The partial vane diffuser shows slightly improved flow field.

Nomenclature

b	= diffuser width (m)
C	= absolute velocity (m/s)
C_m	= meridional velocity (m/s)
h	= diffuser vane height (m)
p_a	= atmospheric pressure (Pa)
p_o	= total pressure (Pa)
p_s	= static pressure (Pa)
Q	= any flow parameter
R	= radius ratio = r/r_2
r	= radius (m)
s	= vane spacing = $2\pi r/Z$ (m)
U	= blade sped (m/s)
V	= volume flow (m^3/s)
W	= specific work (m^2/s^2)
X	= non-dimensional axial distance = x/b (X = 0 at shroud and X = 1 at hub)
x, θ	= axial and tangential directions
Z	= number of vanes

Greek Letters

α	= flow angle (deg)
$\Delta\phi_{max}$	= $\phi_{max\ VLD}$ - ϕ_{max}
$\Delta\psi_{max}$	= (ψ_{max} - $\psi_{max\ VLD}$)
ϕ	= flow coefficient = $V/\pi D_2 b_2 U_2$
ϕ_{max}	= maximum flow coefficient
ϕ_{op}	= operating range (ϕ_{max}- ϕ at ψ_{max})
σ	= solidity=chord/pitch
ψ	= energy coefficient = $2W/U_2^2$
ψ_d	= energy coefficient at ϕ=0.34
ψ_{max}	= maximum energy coefficient
ψ_o	= total pressure coefficient=$2\,(P_o - P_a)/\rho\,U_2^2$
ψ_s	= static pressure coefficient=$2\,(P_s - P_a)/\rho\,U_2^2$

Subscripts

2	= impeller exit

Superscript

-	= axially averaged value
=	= mass averaged value

Introduction

In a centrifugal compressor the flow leaves the impeller with high absolute velocity and inclined at a large angle to the radial direction. The role of the diffuser is to decelerate the flow while it is passing through a divergent passage. Thereby the kinetic energy of the flow is transformed to pressure energy. Centrifugal compressor diffusers can be broadly classified into two types (i) Vane diffuser (VD) (ii) Vaneless diffuser (VLD). In a centrifugal compressor, it is well established that conventional vane diffusers exhibit higher performance (i.e. efficiency

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Manuscript received on 09 Mar 2007; Paper reviewed, revised and accepted on 01 Sep 2007

and static pressure rise vs. mass flow) than vaneless diffuser, but with the compromise of reduced operating range. The factor favouring a vaneless diffuser is that of low cost and it can accept a wider range of inlet flow variations without a severe performance impact. The use of conventional vane diffusers in the process applications carries greater risk with respect to performance aspects. Senoo [1] reported a new type of diffuser vane called low solidity vane diffuser (LSVD). The major advantage of the low solidity vane diffuser is that it does not have a throat between vanes. Hence the diffuser passage is not choked. The low solidity vane diffusers provide a higher performance than the vaneless diffusers and a larger flow range than the vane diffusers.

Yoshinaga et al. [2] reported improved performance of a centrifugal compressor, when diffuser vanes with height less than the passage width, named, partial vane diffuser (PVD) were fixed to the shroud. However no systematic and detailed investigations on the comparative merits of these diffusers are reported in literature. Hence the present investigation is undertaken.

Objective

The major objective of the present research is to systematically investigate the flow phenomena in different types of diffusers used in centrifugal compressor namely, vane, vaneless, low solidity vane and partial vane diffusers. The ultimate aim is to improve pressure rise, efficiency and operating range of the centrifugal compressor by judiciously combining two types of diffusers, namely low solidity vane (LSVD) and partial vane (PVD) diffusers. To achieve the objective, a low specific speed compressor is tested with vane, vaneless, low solidity vane and partial vane diffusers of cambered constant thickness vanes. Extensive performance measurements are carried out by systematically varying the vane height and position (hub, shroud or both hub and shroud) in vane diffuser and low solidity vane diffuser configurations.

Also static pressure measurements on the hub and shroud are measured. These results are reported earlier in Issac et. al [3] and Sitaram et. al [4]. From these measurements a partial vane diffuser with vane height of 0.3 times the diffuser width with 11 numbers of vanes fixed on the hub and shroud is found to give best performance. This diffuser is denoted as 11PVD3HS. Flow field measurements in the vane passages of 11PVD3HS, VLD, VD and LSVD at design condition are reported and compared in the present paper.

Experimental Facility and Instrumentation

Experimental Facility

A low speed single stage centrifugal compressor was used for the present experimental investigations. The meridional view of the facility is shown in Fig.1. The compressor is driven by a 50 kW D.C. motor with a separate exciter through a step up gear of 2.5:1 ratio. The speed of the compressor can be maintained constant within ± 1 rpm. The design details of the compressor are given below:

Pressure ratio, P_{01}/P_{02}	= 1.08
Mass flow, $\dot{m}$	= 0.84 kg/s
Design speed, n	= 4500 rpm
Shape number = $n\sqrt{V}/\left[60W^{3/4}\right]$	= 0.0843
Inducer hub diameter, D_{ih}	= 0.110m
Inducer tip diameter, D_{it}	= 0.225m
Vane angle at inducer hub, β_{ih}	= 45°
Vane angle at inducer tip, β_{it}	= 29°
Impeller exit diameter, D_2	= 0.393 m
Vane angle impeller exit, β_2	= 90°
Number of impeller vanes, Z	= 20
Vame diffuser L.E. diameter, D_3	= 0.432 m
Diffuser width, b_3	= 0.020 m
Vaneless diffuser exit diameter, D_5	= 0.600 m

The angles are measured w.r.t. tangential direction. The meridional view of the compressor is shown and major components are identified in Fig.1.

Design of Low Solidity Vane Diffuser

The method of Eynon and Whitfield [5] is followed for the design of the vane of the low solidity vane diffuser. The following parameters are specified: inlet radius ratio, vane solidity, number of vanes, leading edge and trailing edge angles. Then it is possible to determine the diffuser exit radius and the radius of the vane camber line. A vane solidity of 0.7 is chosen, as it is most commonly used value for LSVD. At the outset it was decided to use same profile and other geometrical details except solidity for both VD and LSVD to minimise fabrication work and also the performance is effected by solidity only, but not other geometric parameters. The impeller has 20 vanes. To avoid resonance, the VD should have one vane less or more than that of the impeller. However the LSVD have one half of vanes of the VD. Hence an even number of vanes higher than that of impeller is chosen, i.e. 22 nos.

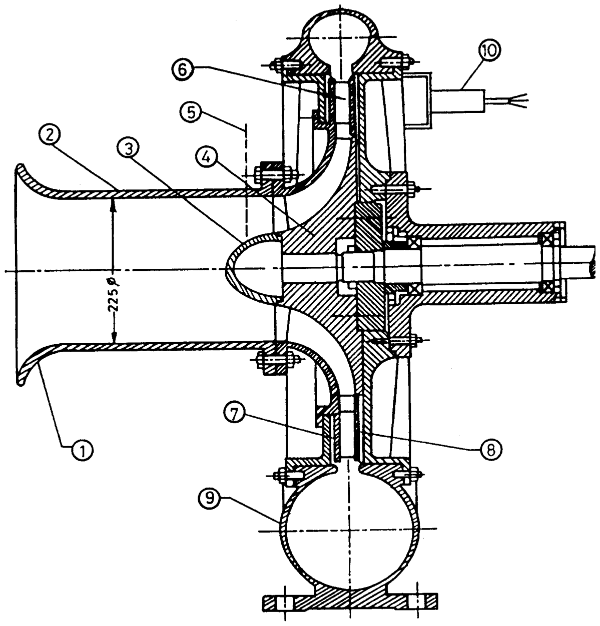


Fig.1 Meridional view of the centrifugal compressor

1.Inlet Nozzle; 2.Inlet Duct; 3. Hub; 4. Impeller; 5. Inlet Transverse Station; 6. Vane Diffuser; 7. Diffuser Shroud; 8. Diffuser Hub; 9. Scroll Casing; 10. Exit Transverse Mechanism

Thus LSVD have 11 no. of vanes, having a solidity of 0.7. The leading and trailing edges are made semi elliptical with the major axis equal to four times the minor axis. The minor axis is equal to the vane thickness and is equal to 3 mm. Kmecl e.t al [6] also selected a semi elliptical leading edge of 4:1 ratio after carrying out numerical studies with leading edges of different elliptic shapes. The vane diffuser configuration is obtained by inserting vanes in the centre of the passages of the low solidity vane diffuser. Fig. 2 shows different types of diffusers tested and Table-1 gives their major details.

Instrumentation

The compressor performance with different diffusers was determined from average wall static pressures from the inlet duct and exit duct. A lightweight probe traversing mechanism is used to measure the flow at six radial stations and three to nine circumferential locations (shown in Fig.3) in the diffuser passage with a precalibrated three hole probe. The radial positions are upstream of the vane leading edge (LE), near LE, mid passage, near trailing edge (TE), downstream TE and far downstream. The radial distances as percentage of radius difference of LE and TE is also shown in the third column. The probe measurements can be carried out in two passages of the vane diffuser. This serves two purposes, viz. (i) to check the flow periodicity in the vane passages and (ii) flow measurements in one low solidity vane diffuser passage. These two passages are situated far away from the volute

Table-1 : Details of geometry of difusers tested

Diffuser Type	VLD	VD	LSVD	11PVD3HS
Solidity, σ	-	1.4	0.7	0.7
No. of vanes	-	22	11	11 + 11
R_3	1.0000	1.1000	1.1000	1.1000
R_4	1.2514	1.2514	1.2514	1.2514
R_5	1.5267	1.5267	1.5267	1.5267
Chord, Ch (mm)	-	86.07	86.07	86.07
α_3 (Deg)	-	15	15	15
α_4 (Deg)	-	25	25	25
R_3 and R_4 - Vane inlet and exit radius ratios				
α_3 and α_4 - Vane inlet and exit angles (Deg)				
The angles are measured w.r.t. tangential direction				
11PVD3HS - 11 number of partial vanes of h/b of 0.3 fixed on hub and shroud staggered at half the vane spacing				

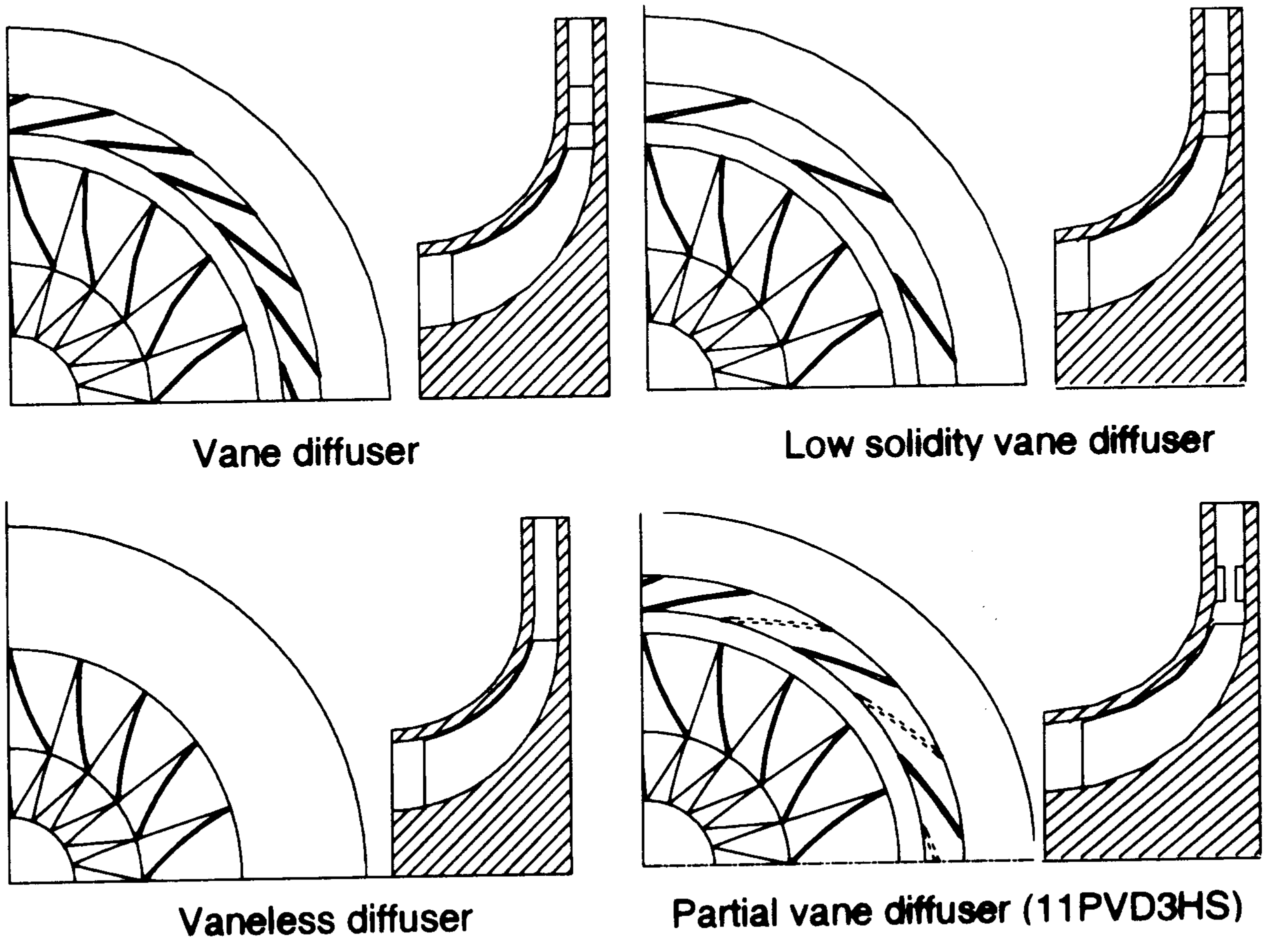
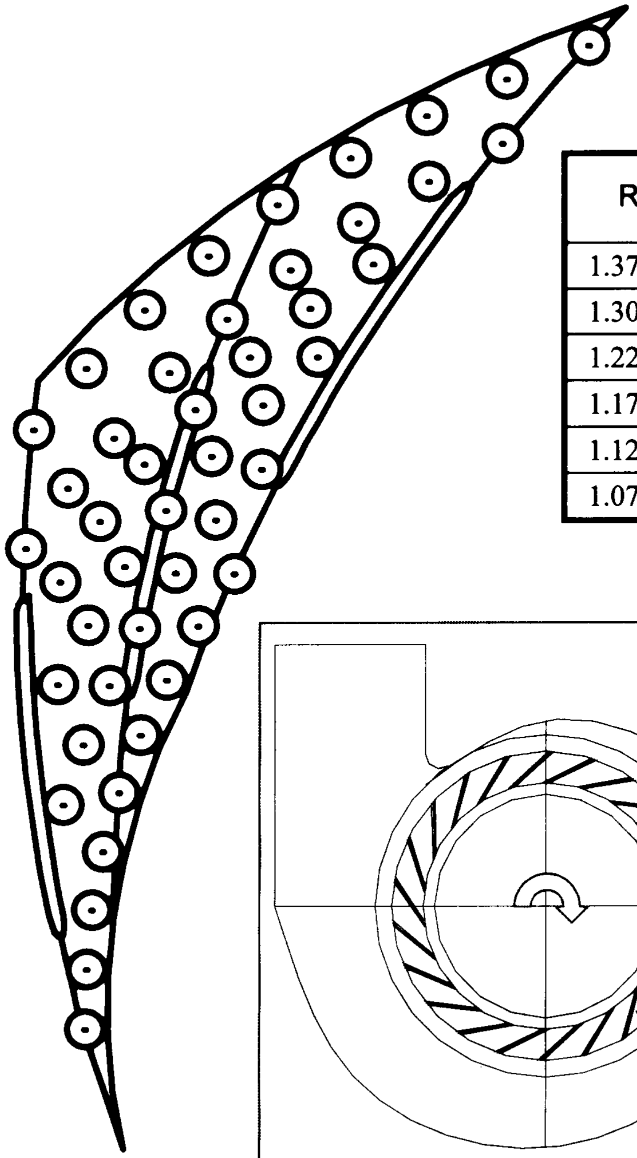


Fig.2 Schematic views of centrifugal compressor with different types of diffusers

Table-2 : Performance comparison of vane, vaneless, low solidity vane and partial vane diffusers

Configuration	VLD	VD	LSVD	11PVD3HS
ψ_{max}	1.50	1.68	1.60	1.56
ϕ_{max}	0.95	0.60	0.68	0.93
ϕ at ψ_{max}	0.34	0.23	0.25	0.33
ψ_d	1.50	1.54	1.56	1.57
ψ at ϕ_{max}	0.48	0.19	0.24	0.47
$\Delta\psi_{max}$	0.00	0.12	0.07	0.04
$\Delta\psi_{max}/\psi_{maxVLD}$	0.0%	8.0%	4.7%	2.7%
$\Delta\phi_{max}$	0.00	-0.37	-0.28	-0.02
$\Delta\phi_{max}/\phi_{maxVLD}$	0%	-39%	-30%	-2%
ϕ_{op}	0.61	0.37	0.43	0.60
$(\phi_{op}-\phi_{opVLD})/\phi_{opVLD}$	0%	-39%	-30%	-2%



R	Position	$\frac{(R-R_3)}{(R_4-R_3)}$ x100
1.3791	Far downstream	184%
1.3027	Beyond TE	134%
1.2265	Near TE	84%
1.1756	Mid chord	50%
1.1247	Near LE	16%
1.0712	Upstream of LE	-19%

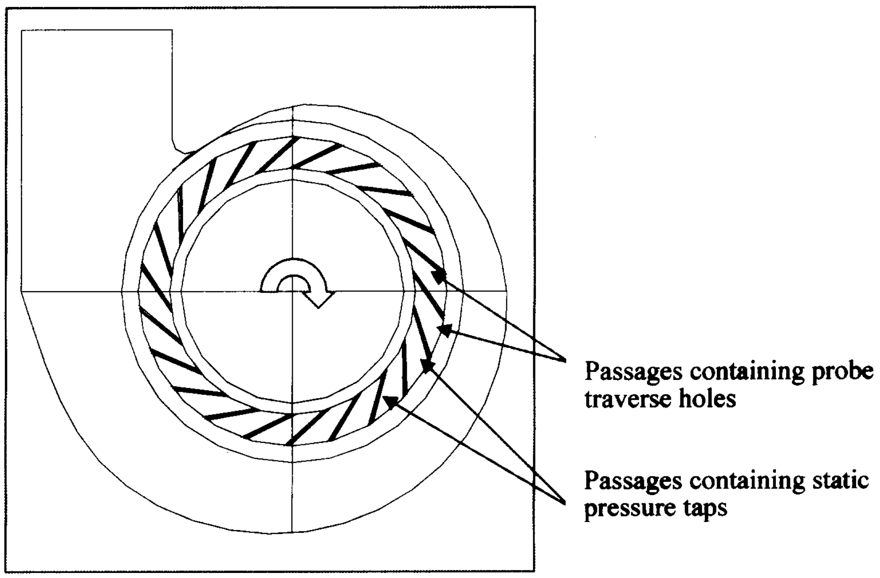


Fig.3 Probe traverse locations on diffuser hub for two vane diffuser passages

tongue as shown in inset of Fig.3, to minimize the influence of volute tongue on the measured pressures. At each traverse locations, flow measurements are taken at thirteen axial locations. Near the hub and shroud measurements are taken at 1 mm intervals. All the pressure tapings are connected to a scanning box (FCO 91-3) manufactured by M/s. Furness Control Ltd., UK, and measured with a micro manometer (FCO12 Model 4, range ± 1999 mm of WC, accuracy ± of full scale reading) manufactured by M/s. Furness Control Ltd., UK.

Results and Discussion

Because of large amount of data acquired, only typical results obtained from the present experimental investigation are presented and interpreted in the following sections. All the data are presented in Issac [7].

Performance Characteristics of the Compressor

The performance of the compressor with the four types of diffuser is compared in Fig.4. Major performance parameters of the four diffusers are given in Table 2. From the figure and table it is observed that the performance of

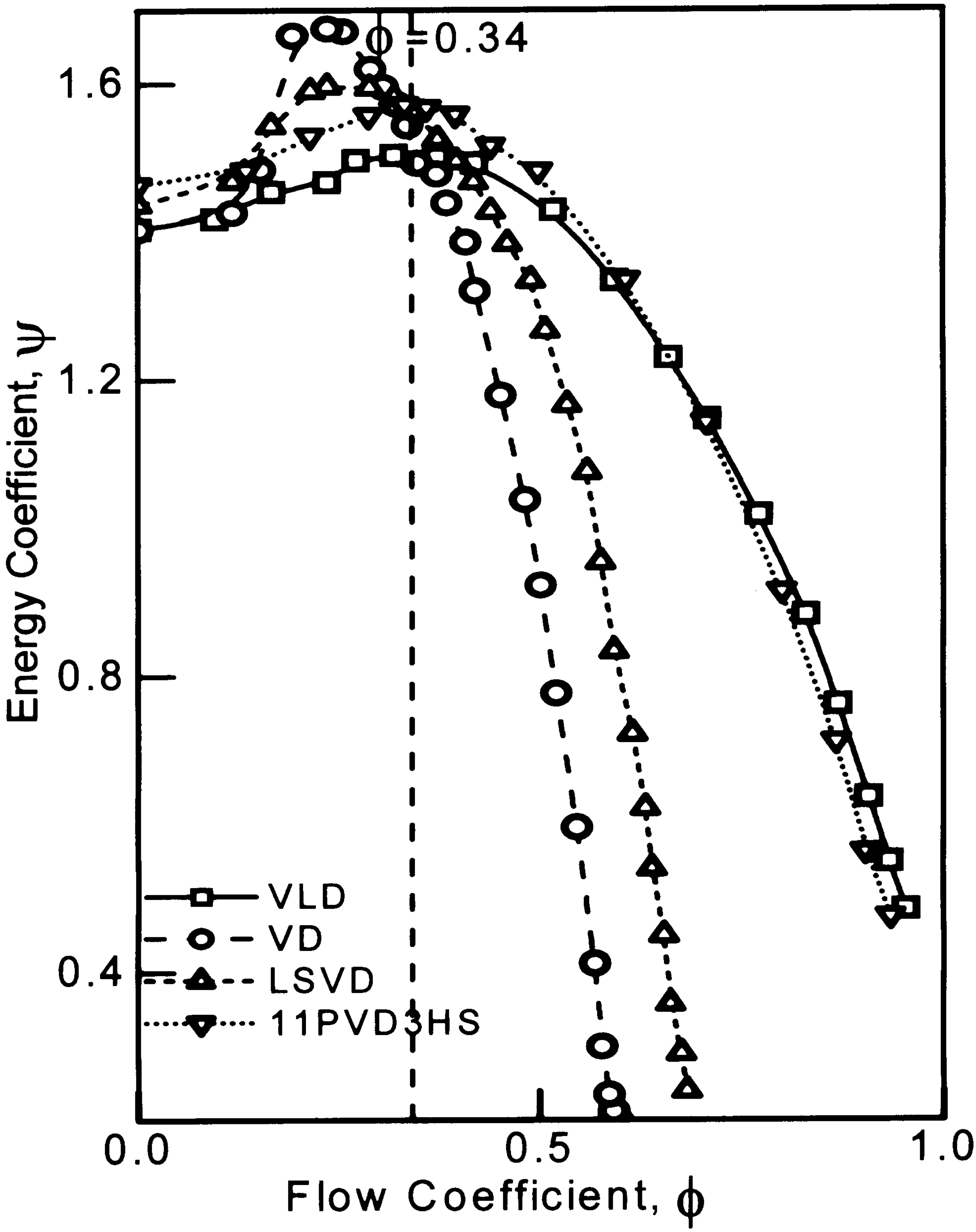


Fig.4 Compressor performance with VLD, VD, LSVD and 11PVD3HS

11PVD3HS is superior compared to that of the other diffusers. Hence flow field measurements are carried out in this diffuser and compared with those in vaneless, vane and low solidity vane diffusers.

All the flow field measurements are carried out with the compressor running at a speed of 3000 ± 1 rpm. Earlier it was found that the effect of Reynolds number on the compressor performance is small, as long as the speed is 3000 rpm or higher (Issac [7]). The measurements are carried out at three flow coefficients (design, $\phi = 0.34$ and off design conditions, $\phi = 0.23$, below design volume and $\phi = 0.60$, above design volume). However the data at design flow coefficient only are presented and interpreted in this paper.

Diffuser Vane Passage Flow Measurements

The flow parameters inside the diffuser passage of VD, VLD and LSVD and partial vane (11PVD3HS) diffusers for design flow coefficient, namely, $\phi = 0.34$ are presented and interpreted in the following sections. The locations for the traverse are shown in Fig.3. For the sake of brevity only typical results are presented.

For each flow parameter, contours are presented at axial stations near the hub, midspan and near the shroud. Axially averaged contours are also presented. These are followed by radial variation of mass averaged values. Axially averaged value of any flow parameter is defined as follows:

$$\bar{Q} = \int_0^b Q\, C_m\, dx \Big/ \int_0^b C_m\, dx$$

Total Pressure Coefficient

Contours of total pressure coefficients at X = 0.1 (near shroud), 0.5 (midspan) and 0.9 (near hub), along with axially (hub to shroud) averaged total pressure contours at $\phi = 0.34$ for VLD, VD, LSVD and 11PVD3HS are shown in Fig. 5.

The distribution of total pressures near hub and shroud shows lower values compared to that at midspan, indicating losses due to boundary layers, secondary and tip clearance flows. In the VLD and 11PVD3HS, the circumferential variation of total pressure is less. However the total pressure is circumferentially non-uniform in the VD and LSVD. For the LSVD, the total pressure has large gradients near the trailing edge on the pressure surface. The gradients are higher at shroud compared to those at hub and midspan. At the shroud, the losses are high due to boundary layers, secondary and tip clearance flows and their interaction with the main flow. The total pressure in VD at any radius is slightly lower than that in other diffusers

The axially averaged total pressure distributions for the vaneless and partial vane diffusers are uniform in circumferential direction. Moreover, the decrease in total pressure is also less when compared with that of VD and LSVD diffusers. This indicates the losses (frictional and incidence) occurring in vaneless and partial vane diffuser are lower.

Static Pressure Coefficient

Contours of static pressure coefficients at X = 0.2 (near shroud), 0.5 (midspan) and 0.8 (near hub), along with axially (hub to shroud) averaged static pressure contours at $\phi = 0.34$ for VLD, VD, LSVD and 11PVD3HS are shown in Fig. 6. The circumferential distribution of static pressure coefficient is uniform for the VD and 11PVD3HS. Near the pressure surface at the trailing edge of the LSVD, static pressure gradients are high. The gradients are higher at the shroud, compared to those at hub and midspan. As mentioned earlier the flow in the shroud region is highly viscous due to the boundary layers, secondary and tip clearance flows and their interaction with the main flow. This causes large gradients in total pressure and velocity. Hence large gradients occur in static pressure also. The vane diffuser shows somewhat uniform static pressure distribution in the circumferential direction. This may be due to reduced vane loading. In addition the static pressure in VD at any radius is slightly higher than that in other diffusers. The axially averaged static pressure distribution shows similar trends.

Flow Angle

Contours of flow angle at X = 0.1 (near shroud), 0.5 (midspan) and 0.9 (near hub), along with axially (hub to shroud) averaged flow angle contours at $\phi = 0.34$ for VLD, VD, LSVD and 11PVD3HS are shown in Fig.7. The flow angles are uniform in the circumferential direction for the VLD and 11PVD3HS. For the VD and LSVD, the flow angles are non-uniform even after the vane trailing edge. Near the trailing edge on the pressure surface flow angle shows large variation for the VD and LSVD. This phenomenon is highly visible near the hub and shroud. This

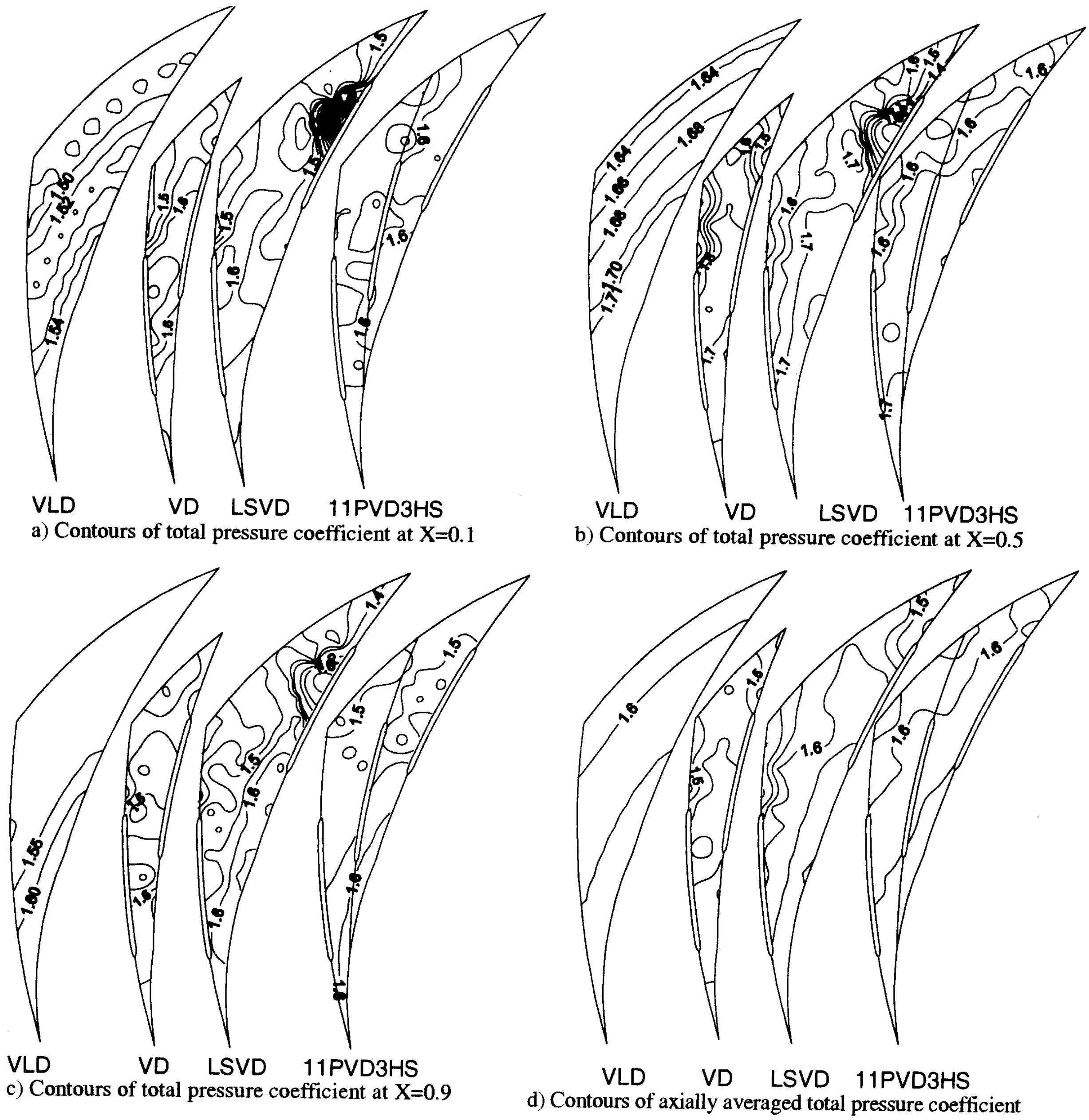


Fig.5 Contours of total pressure coefficients at ϕ = 0.34

can be attributed to the large incidences in the boundary layers that occur near the hub and shroud. The vane inlet angle is kept constant along its span. However near the hub and shroud, the flow leaves the impeller with large spanwise gradients in velocity and flow angle. Hence the incidence changes substantially, causing large changes in the diffuser flows in these regions. This phenomenon is more predominant in the LSVD compared to that in the VD. The VD has higher number of vanes and gives better flow guidance, whereas the LSVD gives poor guidance to the flow, because of lesser number of vanes. Also the magnitudes of flow angles are nearly same in the VLD and 11PVD3HS and lower compared to those in the VD and LSVD. This is due to the guidance offered by the full height vanes of the VD and LSVD. The circumferentially averaged flow angles show similar trends. Furthermore the flow angle changes are high in the hub and shroud

a) Contours of static pressure coefficient at X=0.2

b) Contours of static pressure coefficient at X=0.5

c) Contours of static pressure coefficient at X=0.8

d) Contours of axially averaged static pressure coefficient

Fig.6 Contours of static pressure coefficients at ϕ = 0.34

region of the vane diffuser, whereas the changes are nominal at midspan and axially averaged values.

Variation of Mass Averaged Flow Parameters with Radius

The radial variation of the mass averaged flow parameters at three flow coefficients is shown in Fig. 8. Mass averaged flow parameter any flow parameter is defined as follows:

$$\bar{\bar{Q}} \int_0^s \int_0^b Q\, C_m \, dx\, d\theta \Big/ \int_0^s \int_0^b C_m \, dx\, d\theta$$

Mass Averaged Total Pressure Coefficient

The mass averaged total pressure coefficient decreases as radius increases for all flow coefficients. The decrease

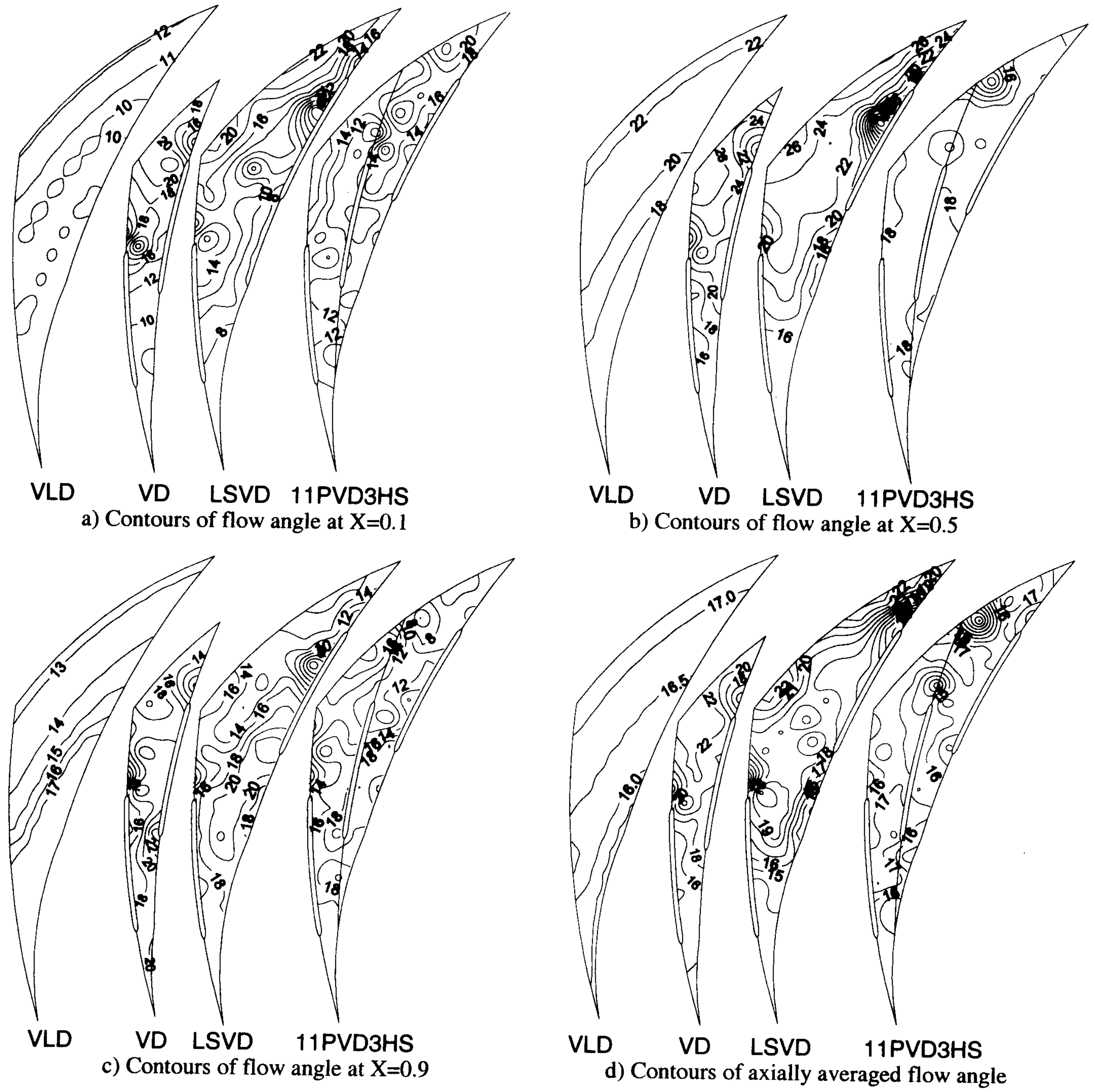


Fig.7 Contours of flow angles at $\phi = 0.34$

in total pressure indicates the amount of losses occurred in the flow passage. Both the vane and low solidity vane diffusers show nearly same total pressure drop, but lower than that in the vaneless and partial vane diffusers. The radial variation of the mass averaged total pressure coefficient in these diffusers is almost same. The total pressure coefficient is nearly equal in the four diffusers upto R=1.2265, i.e. upto the vane TE. However the total pressure drop is more beyond this radius in the vane and low solidity vane diffusers, compared to that in the vaneless and partial vane diffusers. After the exit of diffuser vane, the low solidity vane diffuser shows slightly higher pressure drop than the vane diffuser.

Mass Averaged Meridional Velocity

Meridional velocity decreases for all diffusers with increase of radius. Area of the flow passage also increases

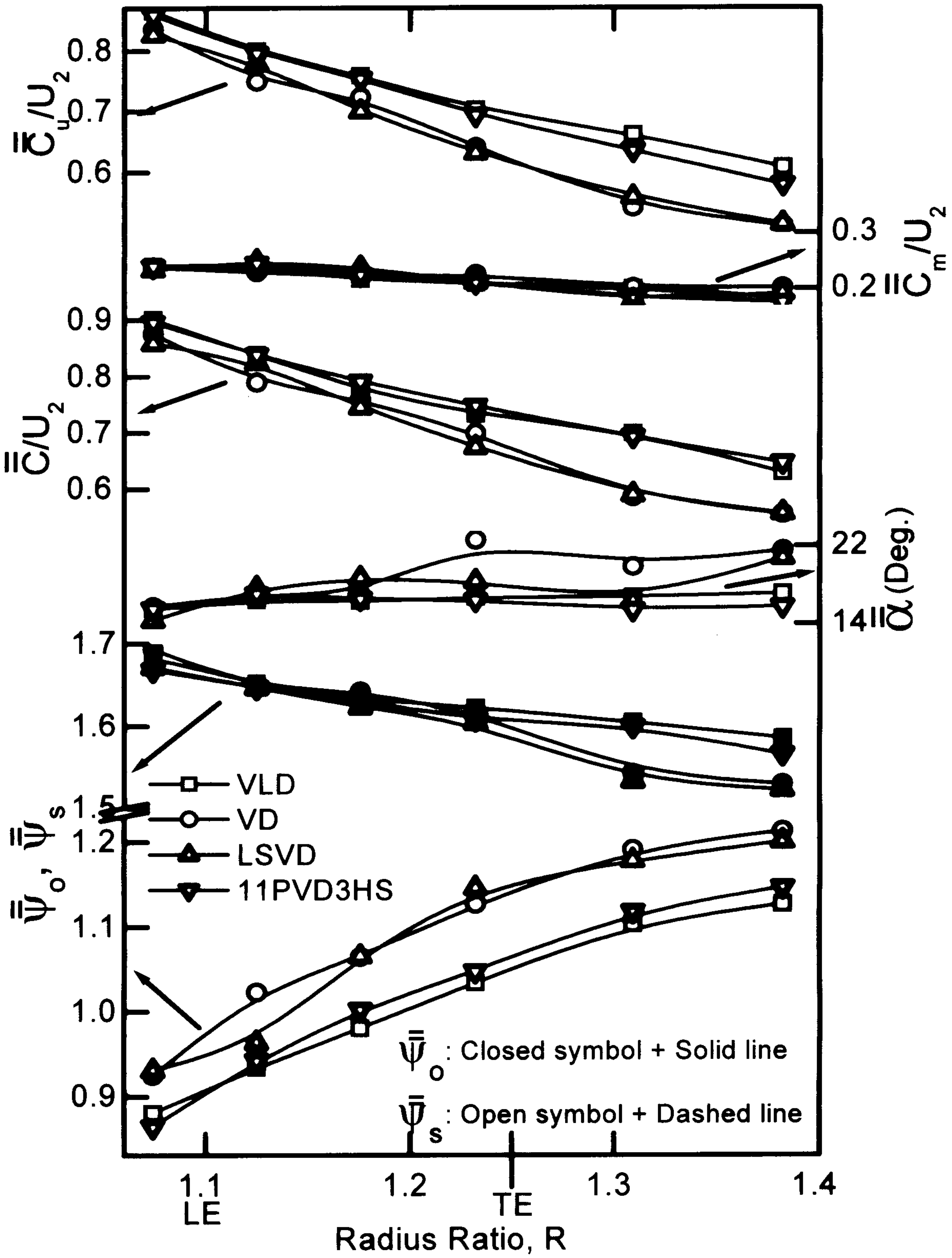


Fig.8 Variation of mass averaged flow parameters with radius ratio at ϕ = 0.34

with increase in radius. Therefore, to maintain continuity of the flow, meridional velocity is reduced.

From the above graph, it can be interpreted that the performance of the vaneless and partial vane diffusers is almost identical. But 11PVD3HS has an added advantage that the vane orientation on the hub and shroud can be independently varied, so that the vane incidence is nearly zero at all flow coefficients, to give higher performance than that of VLD throughout the operating range.

Mass Averaged Static Pressure Coefficient

As expected the vane diffuser shows higher static pressure rise and the vaneless diffuser shows lowest static pressure rise. Partial vane diffuser shows slightly higher pressure rise than the vaneless diffuser but lower than that of low solidity vane diffuser. Inside the vane passage of the vane, low solidity vane and partial vane diffusers, the rate of increase of static pressure coefficient is high, compared with that in the vaneless space after the diffuser. Static pressure rise in the vane and low solidity vane diffusers is almost equal.

Mass Averaged Flow Angle

The mass averaged flow angle of the vaneless and partial vane diffusers remains constant as radius increases. This indicates that flow through these diffusers is free vortex type and the fluid path is logarithmic spiral. For the vane and low solidity vane diffusers, flow angle is nearly constant inside the vane passage. The flow angle increases slightly from radius ratio 1.1 to 1.22. This is due to the presence of the vane, which guide the flow between the diffuser vane passages. After the vane exit the flow angle again increases as the radius further increases.

Mass Averaged Velocity

As radius increases velocity decreases faster for the vane diffuser followed by the low solidity vane, partial vane and vaneless diffusers. This indicates the order of pressure rise. That is the vane diffuser gives higher pressure rise whereas, the vaneless diffuser shows lowest pressure rise. Initially the velocity decrease is almost equal for all diffusers. After the vane LE, velocity in the vane and low solidity vane diffusers decreases rapidly compared to that in the vaneless and vane diffusers. For the partial vane diffuser, decrease in velocity is slightly lower than that of the vaneless diffuser.

Mass Averaged Tangential Velocity

Tangential velocity is nearly same for the vane and low solidity vane diffusers. Similarly partial vane diffuser and vaneless diffuser also show similar variation, but slightly higher than the vane and low solidity vane diffusers.

Conclusions

The following major conclusions are drawn from the present investigation.

- The partial vane diffuser (11PVD3HS) shows 2.7 percent higher peak energy coefficient than that of vaneless diffuser. In addition the partial vane diffuser (11PVD3HS) shows perceivable higher peak energy coefficient than that of vaneless diffuser throughout the useful operating range.

- The vane diffuser gives a higher peak energy coefficient (12 percent higher than VLD). However both the operating range and useful operating range are substantially reduced. The low solidity vane diffuser shows a higher operating range than the vane diffuser and the peak energy coefficient is higher than that of the partial vane and vaneless diffusers near design condition.

- Total pressure contours are uniform in the circumferential direction at all axial stations for the VLD and 11PVD3HS. The total pressure reduction is also less when compared with that of VD and LSVD. This indicates that the losses occurring in the VLD and 11PVD3HS are less.

- Static pressure and flow angle contours are nearly uniform in the circumferential direction at all axial stations for the VLD and 11PVD3HS. Near the pressure surface at the trailing edge of the VD and LSVD, near the hub and shroud, both static pressure and flow angle show large variations. In case of the LSVD, this phenomenon is more predominant than the VD. The VD has higher number of vanes and gives better flow guidance, whereas the LSVD gives poor guidance to the flow, because of lower number of vanes.

- The mass averaged total pressure in the VLD and 11PVD3HS is higher compared to that in VD and LSVD.

- The mass averaged static pressure in the VD and LSVD is higher compared to that in VLD and 11PVD3HS.

Accordingly velocity and tangential component of velocity are lower in these diffusers.

Acknowledgement

Financial support from the Council for Scientific and Industrial Research (CSIR) under the Project "Diffusers for Energy Efficient Centrifugal Compressors" (Scheme No.: 22(0325)/01/EMR-II) is gratefully acknowledged.

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