TECHNICAL NOTE

FLOW MEASUREMENTS IN THE PASSAGES OF DIFFERENT TYPES OF DIFFUSERS OF A CENTRIFUGAL COMPRESSOR AT OFF DESIGN CONDITIONS

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Abstract

Flow measurements in the passages of different types of diffusers of a centrifugal compressor at off design flow coefficients are presented and compared with those at design flow coefficient in this paper. The measurements are carried out using a precalibrated three hole pressure probe. 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. At the above design flow coefficient, both vane and low solidity vane diffusers suffer large losses due to high incidences causing large drop in static pressure.

Keywords : Centrifugal compressor, Low solidity vane diffuser, Partial vane diffuser, Vane diffuser, Vaneless diffuser, Experimental investigations

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 (velocity, pressure, flow angle)
R = Radius ratio = r/r_2
Re = Reynolds number (See Table-1 for definition)
r = Radius (m)
S = Vane spacing = $2\pi r/Z$ (m)
U = Blade speed (m/s)
V = Volume flow rate (m^3/s)
W = Specific work (m^2/s^2)
X = Nondimensional axial distance = X/b
X=0 at shroud and X=1 at hub
x, θ = Axial and tangential directions
Z = Number of vanes
a = Flow angle (Deg)
$\Delta\phi_{max} = \left(\phi_{max} - \phi_{max\ VLD}\right) / \phi_{max\ VLD}$
$\Delta\psi_{max} = \left(\psi_{max} - \psi_{max\ VLD}\right) / \psi_{max\ VLD}$
f = Flow coefficient = $V / \pi D_2 b_2 U_2$
ϕ_{max} = Maximum flow coefficient
ϕ_{op} = Operating range $\left(\phi_{max} - \phi \text{ at } \psi_{max}\right)$
s = Solidity = chord/pitch
ψ = Energy coefficient = $2W / U_2^2$
ψ_d = Energy coefficient at $\phi = 0.34$
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
3 = Diffuser inlet

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Superscripts

- = Axially averaged value
= = Mass averaged value

Introduction

In a centrifugal compressor the flow leaves the impeller with high absolute velocity 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 a higher performance (i.e. efficiency and static pressure rise vs. mass flow) than vaneless diffuser, but with the compromise of reduced operating range. The factor favoring 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 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 diffusers vanes with height less than the passage width, named, Partial Vane Diffuser (PVD) were fixed to the shroud. However no systematic detailed investigations on the comparative merits of these diffusers are reported in literature. Hence the present investigation is undertaken.

Objective and Motivation

The major objective of the present research is to improve the 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, the flow phenomena in different types of diffusers used in centrifugal compressor namely, vane, vaneless, low solidity vane and partial vane diffusers is systematically investigated. 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 pressures on the hub and shroud walls are measured. These results are reported earlier [3, 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 measurements in the vane passages of 11PVD3HS, VLD, VD and LSVD at design condition are reported earlier [5]. Flow measurements in the vane passages of 11PVD3HS, VLD, VD and LSVD at off design conditions are reported in the present paper. These results are compared with results at the design condition.

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 within ± 1 rpm. Although the design speed is 4,500 rpm, the experiments are carried out at 3,000 rpm, as the Reynolds number effects on the performance are found to be negligible. The design details of the compressor are given in Table-1. The range of Reynolds number is also given in the table. Reynolds number for the impeller is based on the impeller blade tip speed, U_2, impeller exit width, b_3 (equal to impeller exit blade height and clearance) and kinematic viscosity at the impeller inlet, ν_1 as suggested by Casey [6]. Reynolds number for the diffuser is based on the diffuser inlet velocity, C_3, diffuser width, b_3 and kinematic viscosity at the impeller inlet, ν_1. As the flow is incompressible, the kinematic viscosity remains constant across the compressor.

The major components of the compressor are shown and identified in Fig.1.

Design of Low Solidity Vane Diffuser

The method of Eynon and Whitfield [7] 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. The selected diffuser vane geometrical parameters are given in Table-1. 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 et al [8] 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-2 gives their major details.

Instrumentation

A lightweight probe traversing mechanism is used to measure the flow at different radial and circumferential locations (shown in Fig.3) in the diffuser passage with a precalibrated three hole probe. 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 ± 0.1% of full scale reading) manufactured by M/s. Furness Control Ltd., UK.

Results and Discussion

Typical results obtained from the present experimental investigations are presented and interpreted in the following sections.

Performance Characteristics of the Compressor

The performance of the compressor with the four types of diffusers is shown in Fig.4. From the figure it is observed that the performance of 11PVD3HS is superior compared to the other diffusers. Partial vane diffuser

Table-1 : Design Details of the Performance Comparison of Vane, Vaneless, Low solidity Vane and Partial Vane Diffusers

Pressure ratio, P_{02}/P_{01}	1.08	Design speed, n	4500 rpm
Mass flow, m	0.84 kg/s	Shape Number, $N_{sh} = n\sqrt{V}/W^{3/4}$	0.0843
Inducer hub diameter, D_{ih}	0.110 m	Vane angle at inducer hub, β_{ih}	45°
Inducer tip diameter, D_{it}	0.225 m	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	Vane 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
Reynolds number based on impeller blade exit width = $U_2 b_3/\nu_1$	0.82×10^5	Reynolds number based on diffuser chord = $C_3 C_{h3}/\nu_1$	3.2×10^5 to 3.5×10^5
All angles are measured with w.r.t. tangential direction			

Table-2 : Details of Diffuser Geometry

Sl. No.	Name	Diffuser Type	Solidity, σ	No. of Vanes	R_3	R_4	Chord, Ch (mm)	α_3 (Deg)	α_4 (Deg)
1	VLD	Vaneless			1.0	1.5267			
2	VD	Vane	1.4	22	1.1	1.2514	86.07	75	65
3	LSVD	Low solidity vane	0.7	11	1.1	1.2514	86.07	75	65
4	11PVD3HS	Partial vane	0.7	11 + 11	1.1	1.2514	86.07	75	65
11PVD3HS	Partial vane diffuser with vane height of 0.3 times the diffuser passage width 11 number of partial vanes fixed on hub and shroud and staggered at half the vane spacing								

11PVD3HS has almost same volume flow range compared with that of VLD, but higher energy coefficient compared with that of VLD, particularly near design volume flow rate. Although partial vane diffuser 11PVD3HS has lower energy coefficient compared with that of VD and LSVD, particularly near design volume flow rate, the maximum volume flow rate for VD and LSVD is much lower compared with that of partial vane diffuser 11PVD3HS. Hence the useful range of both VD and LSVD is less than that of VLD and partial vane diffuser 11PVD3HS. The reason for this superior performance of partial vane diffuser 11PVD3HS is due to the reduced height of the diffuser vanes. Consequently, the incidence losses are reduced. Hence static pressure measurements on the diffuser walls and flow field measurements in the vane passages of these diffusers are made at design (ϕ = 0.34) and off-design conditions (ϕ = 0.23, below design value and ϕ = 0.60, above design value). The flow measurements at design condition are reported Sitaram et al [5]. The flow measurements at off design conditions are reported, interpreted and compared with those at the design condition 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 are measured using a calibrated three hole cobra probe at 3,000 rpm for three flow coefficients, namely, ϕ = 0.23, ϕ = 0.34 and ϕ = 0.60. The locations for the traverse are shown in Fig.3. Only typical results are presented below for the sake of brevity. All the results are available in Issac [9].

Axially Averaged Total Pressure : Contours of axially averaged total pressure at ϕ = 0.23, 0.34 and 0.60 for VLD, VD, LSVD and 11PVD3HS are shown in Fig.5. 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.

Axially Averaged Static Pressure : Contours of axially averaged static pressure at ϕ = 0.23, 0.34 and 0.60 for VLD, VD, LSVD and 11PVD3HS are shown in Fig.6. The circumferential distribution of static pressure coefficient is uniform for the vaneless diffuser. Near the pressure surface at the trailing edge of the VD and LSVD, the static pressure remains constant. This may be due to thicker boundary layer in this region; the effective flow area remains same, even though, radius and flow area increase. In case of the low solidity vane diffuser this phenomenon is higher than the vane diffuser. The vane diffuser has higher number of vanes and gives better guidance of flow, whereas the low solidity vane diffuser gives poor guidance to the flow because of lower number of vanes. Partial vane diffuser shows better circumferential uniformity when compared with VD and LSVD diffusers. At ϕ = 0.60, the vaneless diffuser shows higher static pressure than all the other diffusers. Both VD and LSVD diffusers suffered very high reduction in static pressure, near the leading edge.

Mass Averaged Total Pressure, Static Pressure Absolute Velocity and Flow Angle : The mass averaged total pressure, static pressure, absolute velocity and flow angle of VD, VLD and LSVD and partial vane diffusers are shown against radius ratio at flow coefficients, ϕ = 0.23, 0.34 and 60 in Fig.7. Mass averaged flow parameter any flow parameter is defined as follows:

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

where Q is P_o, P_s, C or α

The decrease in total pressure indicates the amount of losses occurring in the flow passage. At all flow coefficients, the total pressure decreases as radius increases. In VD and LSVD diffusers the total pressure drop is more from radius ratio 1.1 (Diffuser vane inlet) to 1.25 (Diffuser vane outlet), when compared with that of vaneless and partial vane diffusers. This may be due to higher frictional losses occurring in VD and LSVD diffusers. At ϕ = 0.60, the total and static pressure drop is very high at the vane and low solidity vane diffusers leading edge, indicating that incidence losses at the leading edge are very high. At the leading edge of the partial vane diffuser, a small drop in total pressure occurred due to the same reason. However the partial vane diffusers have reduced diffuser vane height. Hence the drop in total pressure is not significant. At ϕ = 0.23, static pressure coefficient increases for all diffusers. As expected the vane diffuser shows highest static pressure rise and the vaneless diffuser shows lowest static pressure rise. The partial vane diffuser shows higher pressure rise than vaneless diffuser and lower than that of low solidity vane diffuser. Inside the vane passage of VD, low solidity vane diffuser and partial vane diffuser, the rate of increases of static pressure coefficient is high, compared with the vaneless part. The partial vane diffuser shows slightly higher pressure rise than VLD. Absolute velocity decrease indicates the order of pressure rise at all flow coefficients. At $\phi = 0.23$, as radius increases, absolute velocity decreases faster for the vane diffuser followed by LSVD, PVD and VLD. The drop in absolute velocity is higher from radius ratio 1.1 to 1.25, indicating that due to the presence of vane, conversion of kinetic energy in to pressure energy is high in the vane passage. The mass averaged flow angle of vaneless and partial vane diffusers remains nearly constant as radius increases. This indicates that flow through these diffusers is nearly free vortex flow and the path of the absolute stream line is nearly logarithmic spiral. Also both radial and tangential velocities decrease nearly in the same proportion with radius.

Variation of Mass Averaged Flow Parameters with Flow Coefficient : Variation of mass averaged flow parameters with flow coefficient is presented in Fig.8. The flow properties are mass averaged at radius ratios, R=1.071 and 1.379; R=1.071, corresponds to the inlet of the vane, low solidity vane and partial vane diffusers, R=1.379, corresponds to the exit of these diffusers.

Mass averaged total pressure decreases with increase of flow coefficient. For a turbulent flow, the frictional losses are proportional to square of the volume flow rate, hence dynamic losses increase with higher flow rate. The rate of decrease of mass averaged total pressure is nearly equal for the vane, vaneless, low solidity vane and partial vane diffusers at diffuser inlet (R=1.071) for all flow coefficients. Total pressure at diffuser outlet (R=1.379) is lower than diffuser inlet. In case of the vane and low solidity vane diffusers, total pressure decreases abruptly at $\phi = 0.60$, indicating that losses are very high for the vane and low solidity vane diffusers at this flow coefficient. At $\phi = 0.60$, the incidence loss and flow separation from diffuser wall are very high in case of the vane and low solidity vane diffusers. In case of partial vane diffuser, the loss of total pressure is nearly equal to that of the vaneless diffuser, indicating that the incidence and flow separation loss are less.

Mass averaged static pressure is lower at the diffuser inlet compared with that of the diffuser outlet. At the diffuser inlet static pressure is nearly same for the vane, vaneless, low solidity vane and partial vane diffusers. But at the diffuser outlet, mass averaged static pressure variation is different for all diffusers. At flow coefficient, $\phi = 0.23$, the vane diffuser shows high static pressure when compared with that of the vaneless, low solidity vane and partial vane diffusers. Performance characteristics curves of the compressor also show similar variation. At flow coefficient, $\phi = 0.60$, the vane and low solidity vane diffusers suffer a large drop of static pressure, indicating that the incidence and flow separation losses are high. In case of the partial vane diffuser, static pressure loss is nearly equal to the vaneless diffuser. However, at flow coefficient, $\phi = 0.60$, static pressure rise of the partial vane diffuser is slightly lower than that of the vaneless diffuser.

Mass averaged flow angle increases with flow coefficient. At the diffuser inlet, flow angle is nearly equal for all diffusers. At the diffuser inlet, the flow angle is nearly equal to the design value (vane angle = 75 degrees) for all diffuser vane configurations tested at design flow coefficient, $\phi = 0.34$. At flow coefficient, $\phi = 0.23$, the flow angle is less than the vane angle, the angle of incidence is positive and at $\phi = 0.60$, the flow angle is greater than the vane angle; the angle of incidence is negative. At diffuser outlet, large variation of flow angle is visible for the vane, vaneless, low solidity vane and partial vane diffusers at different flow coefficients.

Mass averaged velocity increases with flow coefficient for the vane, vaneless, low solidity vane and partial vane diffusers. The difference of velocity between inlet and outlet indicates the amount of kinetic energy transformation. At flow coefficient, $\phi = 0.23$, the vane and low solidity vane diffuser show larger difference in velocity. The partial vane diffuser shows slightly larger difference than the vaneless diffuser, but lower than the vane and low solidity vane diffusers at $\phi = 0.23$ and $\phi = 0.34$. At flow coefficient, $\phi = 0.60$, difference in velocity between inlet and outlet decreases. In case of the vane diffuser, velocity does not decrease, indicates that conversion of kinetic energy to pressure energy is very small. Mass averaged tangential velocity at the diffuser inlet and outlet for the vane, vaneless low solidity vane and partial vane diffusers with flow coefficient also shows similar pattern as that of mass averaged velocity. Mass averaged meridional velocity increases with flow coefficient. The meridional velocity at the diffuser outlet is lower than that at the diffuser inlet due to conservation of mass flow.

Conclusions

The following major conclusions are drawn from the present investigation.

- The partial vane diffuser (11PVD3HS) shows 4 percent higher maximum energy coefficient than that of vaneless diffuser.
- The vane diffuser gives a higher maximum energy coefficient (12 percent higher than VLD) but it occurs very close to surge. However the operating range is reduced. The low solidity vane diffuser shows a higher operating range than the vane diffuser and the maximum energy coefficient is higher than that of the partial vane and vaneless diffusers.
- Probe traverse results in the diffusers show incidence loss is higher for the vane and low solidity vane diffusers, particularly at the above design flow coefficient of 0.60. This causes large drop in static pressure and velocity and its circumferential component are very high.

Acknowledgement

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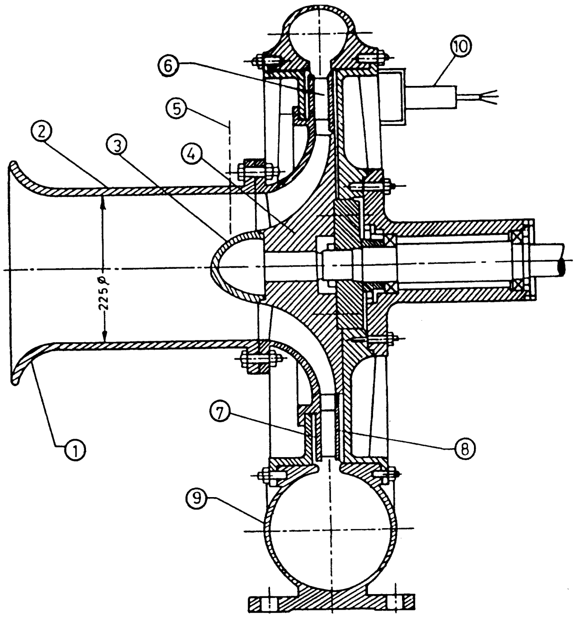
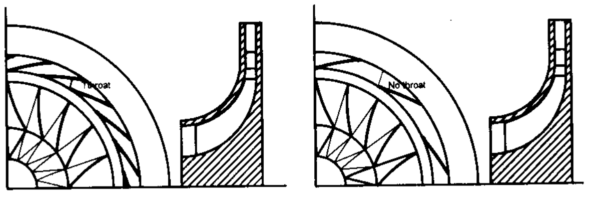
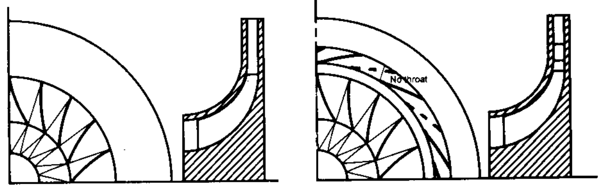


1 Inlet Nozzle **2** Inlet Duct **3** Hub **4** Impeller **5** Inlet Traverse Station **6** Vane Diffuser
7 Diffuser Shroud **8** Diffuser Hub **9** Scroll Casing **10** Exit Traverse Mechanism

Fig.1 Meridional View of the Centrifugal Compressor

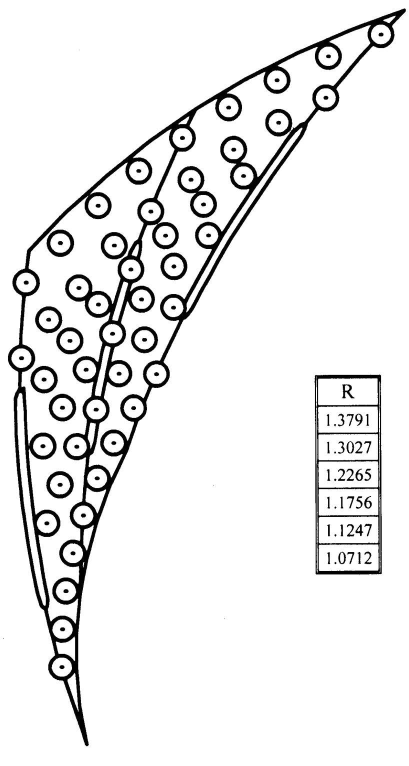


Vane Diffuser (VD) Low Solidity Vane Diffuser (VD)



Vaneless Diffuser (VLD) Partial Vane Diffuser (11PVD3HS)

Fig.2 Schematic View of Vane Vaneless, Low Solidity Vane and Partial Vane Diffusers



R
1.3791
1.3027
1.2265
1.1756
1.1247
1.0712

Fig.3 Probe Transverse Locations in Two Diffuser Vane Passages

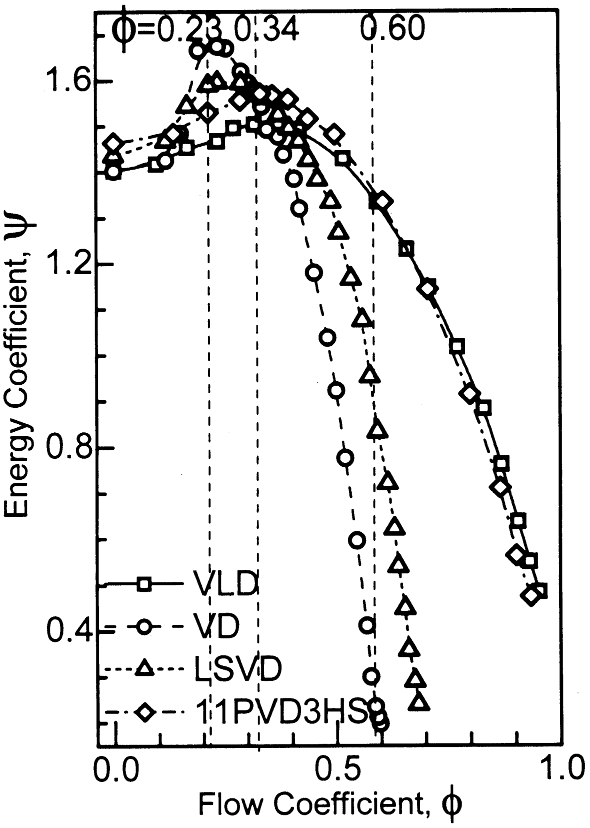


Fig.4 Performance of the Compressor with Different Diffusers

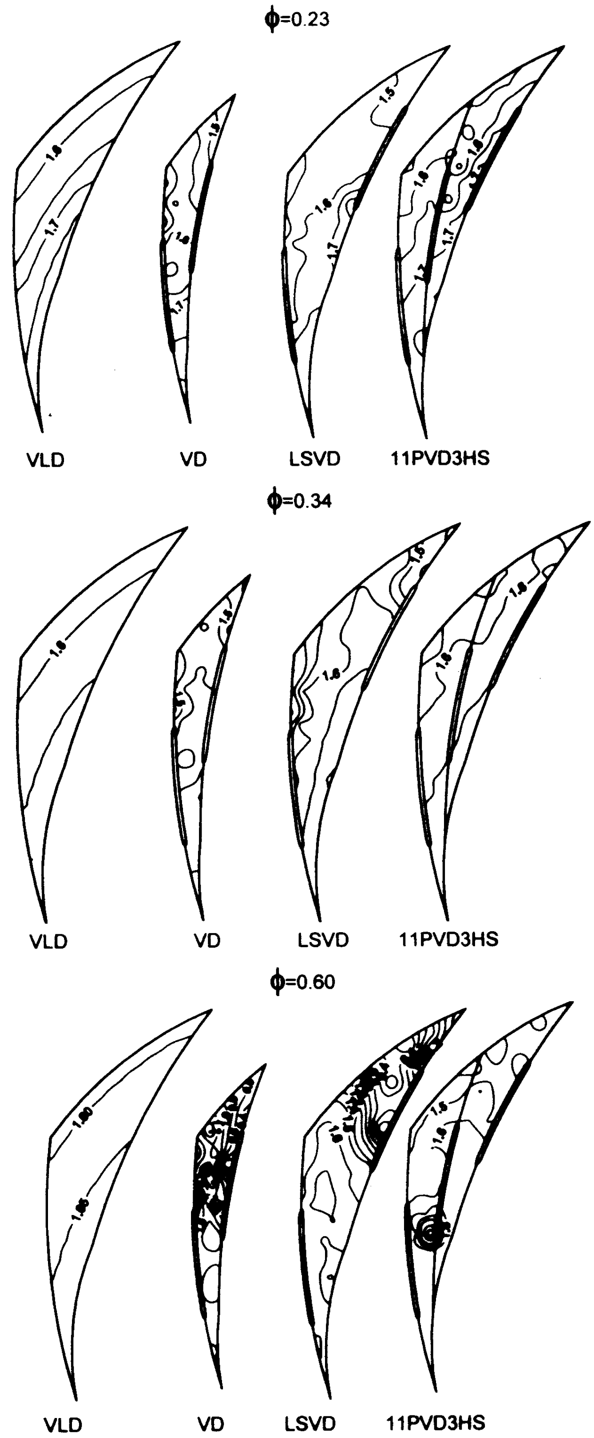


Fig.5 Distribution of Axially Averaged Total Pressure in Different Diffusers

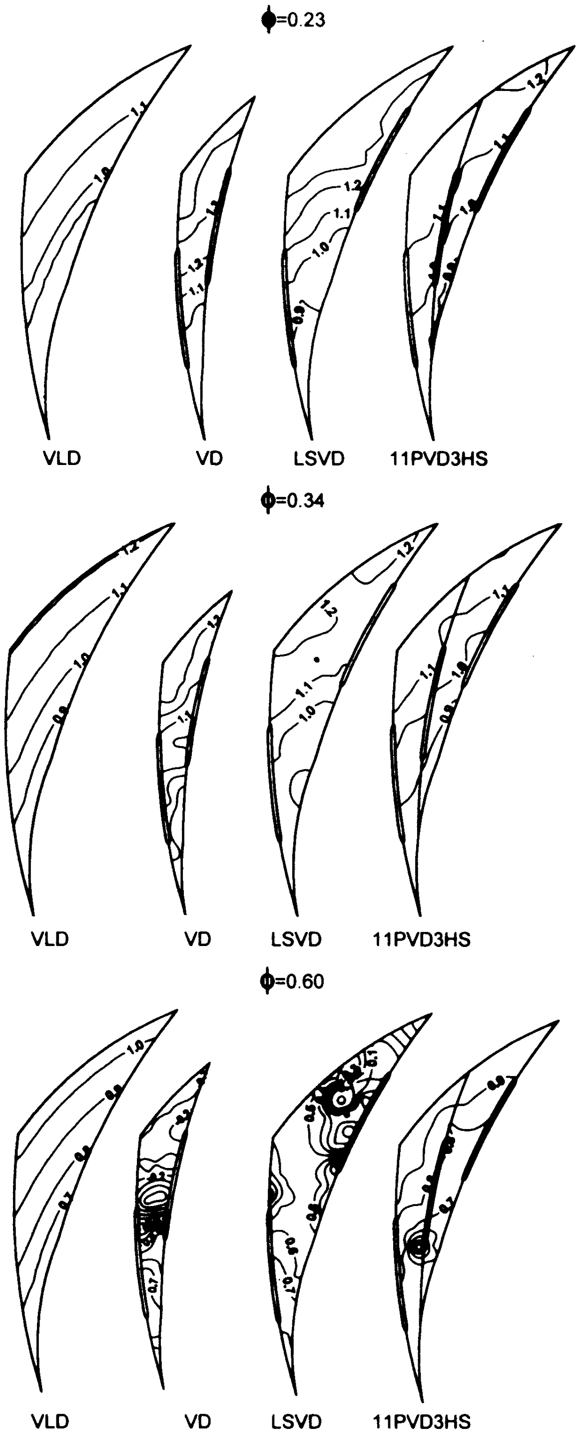


Fig.6 Distribution of Axially Averaged Static Pressure in Different Diffusers

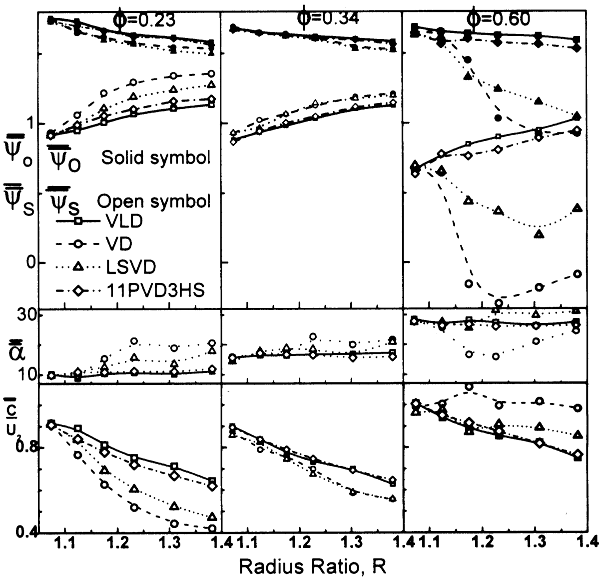


Fig.7 Radial Variation of Mass Averaged Flow Parameters

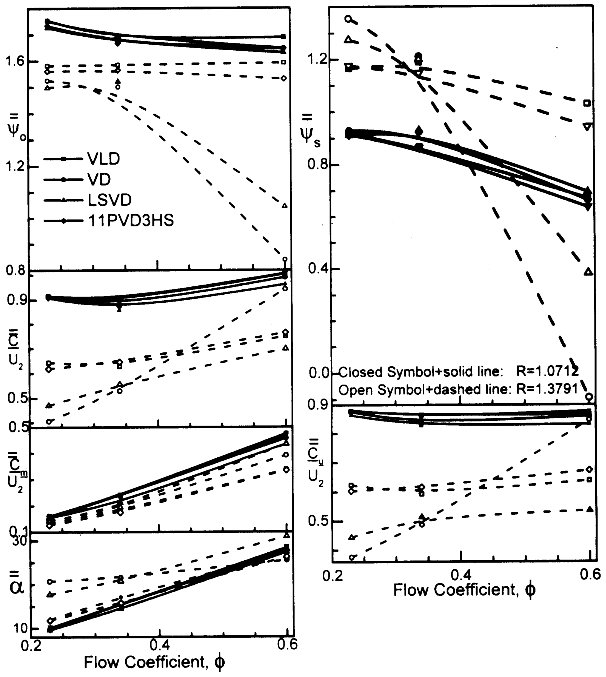


Fig.8 Variation of Mass Averaged Flow Parameters with Flow Coefficient