

Experimental Results on a Rotatable Low Solidity Vaned Diffuser

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ABSTRACT

This paper reviews test results from a rotatable low solidity vaned diffuser (RLSD). The device was installed in a single stage test vehicle consisting of a pseudo-return channel inlet, a subsonic centrifugal impeller (approx. 2:1 pressure ratio), the rotatable diffuser, a return channel and a dump collector. Static taps, total pressure probes, and thermocouples were located in critical areas throughout the stage. Manual traverse probes measured the pressure and angle profiles at RLSD leading and trailing edges. Results for various stagger angles, leading edge radius ratios, etc. are presented in terms of pressure recovery (C_p) and loss coefficient (LC). Comments are made regarding the applicability of the RLSD in production units.

NOMENCLATURE & DEFINITIONS

Nomenclature

- A_0 - Sonic velocity of gas
- BEP - Best efficiency point
- C_p - Static pressure recovery =
 $(P_{sex} - P_{sin}) / (P_{tin} - P_{sin})$
- g - Gravitational constant
- LC - Total pressure loss coefficient =
 $(P_{tin} - P_{tout}) / (P_{tin} - P_{sin})$
- LE - Leading edge
- L/F - Long and few vanes configuration
- LSD - Low solidity vaned diffuser
- μ - Head coefficient = Head * g / U_2^2
- $N_s(us)$ - Dimensional specific speed =
 $Q^{.5} N / \text{Head}^{.75}$ with:
 Q in ACFS; N in RPM; Head in ft.
- OD - Outside diameter (i.e., impeller)
- Φ - Flow coefficient ($700Q / ND^3$)
- P_s - Static pressure
- P_t - Total pressure
- r_3 / r_2 - Radius ratio diffuser LE to impeller exit

- S/M - Short and many vanes configuration
 SSTR - Single stage test rig
 U_2 - Impeller tip speed
 w_5' - Diffuser vane separation from trailing edge of one vane to leading edge of adjacent vane

Subscripts

- 2 - Impeller exit
 3 - Diffuser leading edge
 $5'$ - Diffuser trailing edge
 5 - Overall diffuser exit
 6 - Return channel leading edge
 8 - Stage exit

Definitions

Choke margin - Percent increase in capacity from stage design to choke condition

Rise to surge- Percent increase in head level from design point to surge

Stability - Percent decrease in capacity from design point to surge

INTRODUCTION

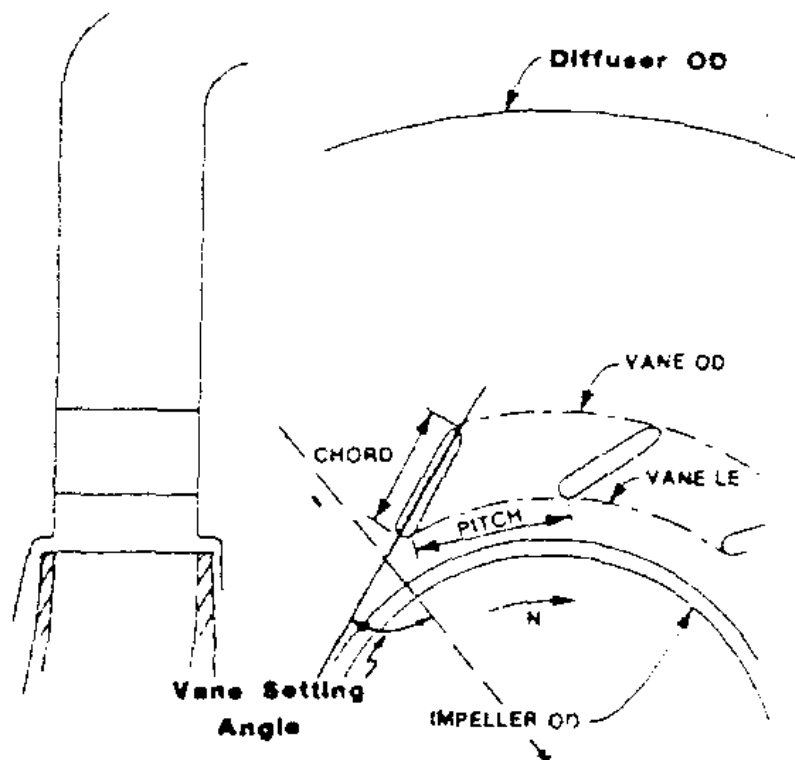
Recently, interest has increased in the use of low solidity vaned diffusers in industrial centrifugal compressor stages. Such diffusers exhibit many of the benefits of full vaned designs; i.e., improved pressure recovery enhanced efficiency; while eliminating the most critical drawback, limited flow range. Given the advantages, it is not surprising that much effort is being expended to improve our understanding of these unconventional diffusers. This paper traces recent testing done on an adjustable LSD apparatus. The tests were completed to discern some of the critical parameters in low solidity diffuser design. The paper also briefly describes the history of the LSD concept and suggests further work to be done.

BACKGROUND

The earlier work of Osborne/Sorokes (ref. 1) gives a concise history of the low solidity diffuser concept. For convenience, highlights follow.

Most of the earliest available literature on the low solidity vaned diffuser concept was published by Senoo (ref. 3 - 5) . In his writings, Senoo postulated that if one removed the restriction caused by the throat of a conventional full vaned design, flow range would improve. The throat is defined as the minimum channel area produced by two adjacent diffuser vanes. If the vanes were of appropriate chord length and pitch (separation) such that no channel was formed, no true diffuser throat would exist. Therefore, choke margin should increase over that of a full vaned diffuser.

Figure 1 shows the basic low solidity vaned diffuser (LSD) geometry. Senoo suggests certain design guidelines such as: a) diffuser vanes closely coupled to the impeller; b) a low number of vanes; c) relatively flat stagger angles; etc. He also cites some application limitations; i.e., LSD's are most effective in low flow coefficient or low specific speed stages.



Senoo Suggestions

- **Low Solidity (Chord/Pitch Ratio = .7 - .8)**
- **No Conventional Diffuser Throat**
- **Limited Radial Extent**
(10% - 20% of diffuser length)
- **Little Or No Vane Camber**
- **Full Passage Height**
- **Vane Setting (Stagger) Angle Fairly Flat**
- **Can Be Multiple Row (Tandem Cascade)**

Figure 1 - Definition Of Low Solidity Vaned Diffuser

Using the Senoo's works as a guide, Osborne/Sorokes conducted further tests of the LSD concept; including the application of meridional contraction through the diffuser passage. In addition, Osborne/Sorokes showed the low solidity diffuser to be effective even at high specific speeds and over a variety of LSD geometric parameters; i.e., radius ratios, chord lengths, setting angles, etc.

In their concluding remarks, Osborne /Sorokes pointed to the need for further work to: a) firmly establish LSD geometric design guidelines; and b) determine the effective application range. The program reported herein was undertaken to address the former. By comparing the performance of various diffuser configurations, decisions regarding design guidelines were permitted.

As noted in reference 1, a significant number of low solidity vaned diffusers (now in excess of 300 stages) have been installed and tested in production compressors. Performance trends suggested that certain LSD geometries were more advantageous than others. However, there had been no opportunity to do a systematic comparison of the various designs. Still, with the large database available, it was possible to isolate a few key variables that warranted further investigation. Those included:

1. optimum leading edge radius ratio
2. optimum number of blades
3. optimum incidence level
4. the effect of any or all of the above on performance curve shape
5. the level of performance enhancement at varying specific speeds

An extensive test program was undertaken to discern the effects of each variable noted.

Obviously, minimizing the time spent disassembling and re-assembling the test vehicle would be critical. Therefore, an adjustable diffuser vane apparatus was deemed necessary. After reviewing the variables in question, a decision was made to facilitate the adjustment of vane setting angle and to require a re-build to change the leading edge radius ratio, vane length, number of vanes, etc. Further, the design must allow vane adjustment from outside the test rig.

THE ADJUSTABLE LSD APPARATUS

Figure 2 shows the angle variation possible with the adjustable LSD apparatus. The vanes pivot about the leading edge nose radius; allowing setting angle adjustments with no change in the leading edge radius ratio. The vanes are affixed to pins which project through the shroud wall. Linkage at the opposite end of the pins meshes with a ring which rotates to set the desired vane angles. The ring is actuated by means of a rod which projects to the outside of the rig.

As can be seen, the apparatus has a vane setting angle range of 20° . Vanes can be set to an accuracy of $\pm .25^\circ$ and locked into position to insure no movement during operation.

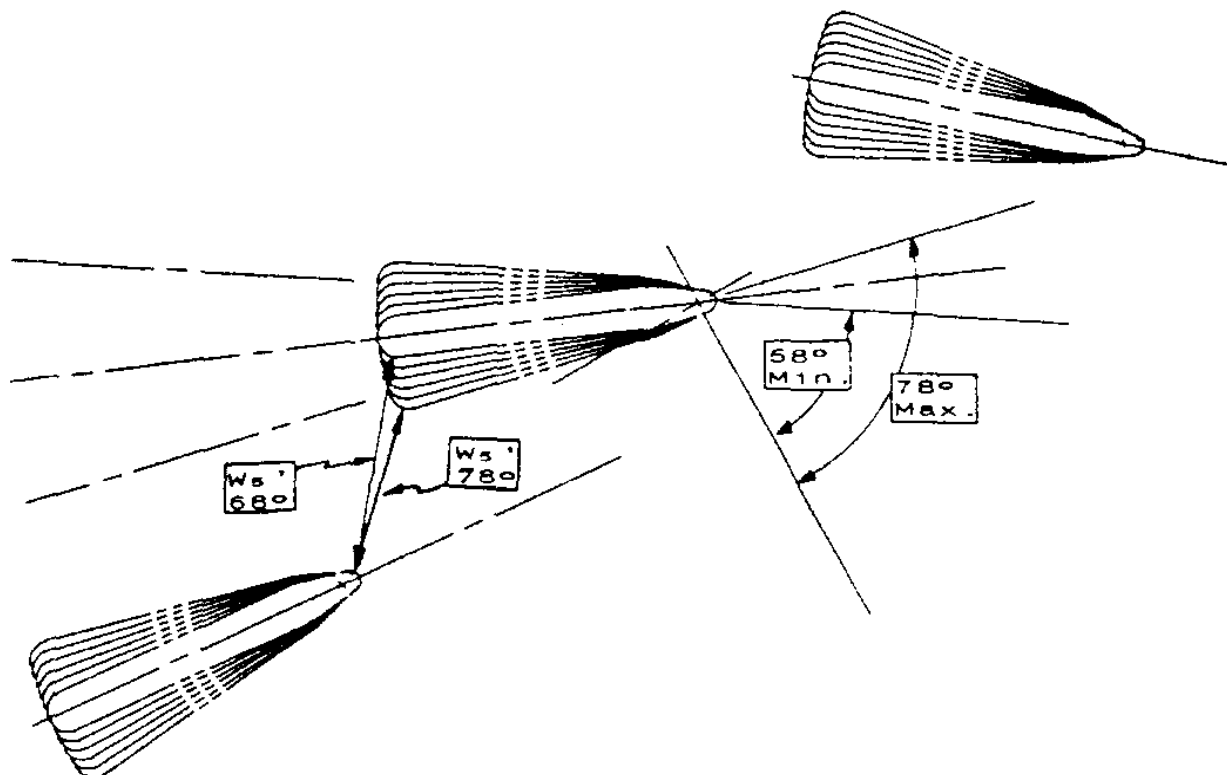


Figure 2 - Adjustable LSD Setting Angle Range

Two shroud walls were built, allowing two separate leading edge radius ratios ($r_3 / r_2 = 1.08$ and 1.15). Two sets of diffuser vanes were available; one set of 20 short (designated S/M for short and many) and one set of 10 long (designated L/F for long and few). With the combination of walls and vanes, four distinct builds were possible (see table 1). The four configurations were tested at several vane setting angles, generating a matrix of results for comparison.

	1.08 R3/R2	1.15 R3/R2
2.5" chord	Build 1	Build 3
5.0" chord	Build 2	Build 4

Table 1 - Build Definitions

Before discussing the data, brief descriptions of the test rig and instrumentation are offered.

THE SINGLE STAGE TEST RIG

As noted, data was collected in a single stage test rig (SSTR). The rig duplicates a typical centrifugal stage in both geometry and flow conditions while allowing easy access to stage components.

SSTR Internal Components

The SSTR was designed for cost effectiveness and ease of assembly. Concentric rings, fastened by tie bolts, allow assemblers to unstack internals without entirely disassembling the rig. That is, an impeller or diffuser change-out may be completed without disturbing the remainder of the rig assembly (see figure 3).

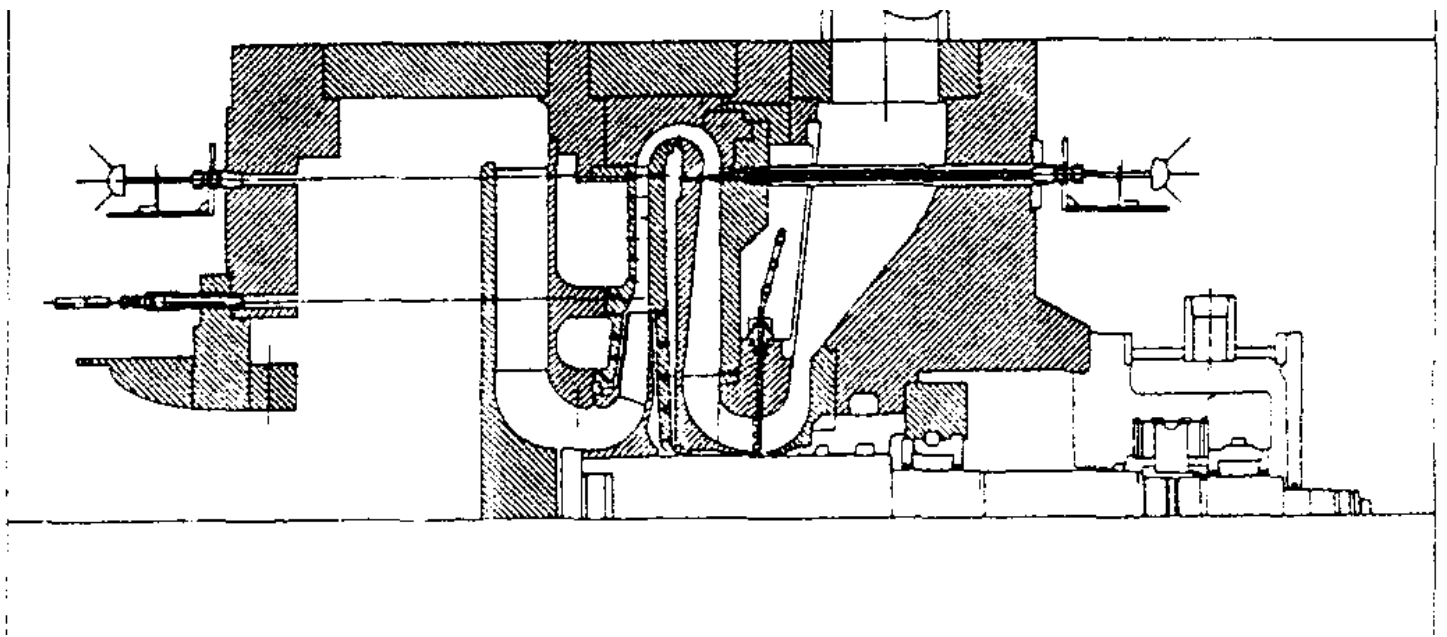


Figure 3 - Single Stage Test Rig Cross-Section

The compressor inlet consists of a plenum chamber followed by a pseudo-return channel. The false return channel was used to simulate the inlet conditions seen by a multistage centrifugal impeller.

The impeller used has a design flow coefficient, ϕ , of .09 and a dimensional specific speed $N_s(us)$ of 115. Other basic impeller information is provided in Table 2.

U_2/A_0	Inlet Rel. Mach Number	W_{s1}/W_2	Abs. Exit Flow Angle	Inlet Pressure	Inlet Temperature	Test Gas
0.80	0.43	1.58	65.5 Deg.	30 psia	100 Deg. F	Nitrogen
0.78	0.56	1.69	68.0 Deg.	30 psia	100 Deg. F	Nitrogen
0.96	0.70	1.80	69.8 Deg.	20 psia	100 Deg. F	Carbon Dioxide
1.06	0.78	1.93	71.5 Deg.	20 psia	100 Deg. F	Carbon Dioxide

Table 2 - Select Impeller Aero Parameters and Rig Operating Conditions

The return channel downstream of the adjustable LSD apparatus was designed for earlier vaneless diffuser tests but was judged to be adequate for the LSD testing.

Downstream of the return channel, the flow passes through a 180° bend (approximating a guidevane) and dumps into a collector. The flow then exits the rig and returns to the process loop.

Test Rig Control Facility and Instrumentation

The rig has its own dedicated control center. All rig functions, including speed control, valve adjustments, cooling water flow, as well as all data acquisition are regulated from the center.

Test instrumentation includes over 120 and 40 fixed pressure and temperature probes, respectively. In addition, traverse probes are located in critical areas (impeller exit, diffuser exit, etc.) to measure flow profiles.

A multiple scanivalve system is used to read all fixed pressure probes while thermocouples are used for all temperature measurements. Traverse probes are read using manometers.

An on-line real time monitoring routine allows the test engineer to examine compressor performance while adjusting the operating conditions (inlet pressure, temperature, flow, or compressor speed). The routine samples key pressure and temperature probes and uses this data to calculate flow, efficiency, and head coefficient. These parameters are then displayed; allowing the test engineer to verify that a performance point has settled prior to data acquisition.

Several data scans are read for each performance point. After all readings are stored, the data are scanned for faulty information (i.e., failed probes, transient response in the scanivalve system, etc.). The filtered data is then run through a performance routine. Summary sheets, compiling various aerodynamic parameters, are reviewed by the test and aerodynamic engineers. Once the point is approved, the operator moves to the next point. After completing a speed line, the desired performance maps are generated (efficiency versus flow, diffuser pressure recovery versus flow, etc.).

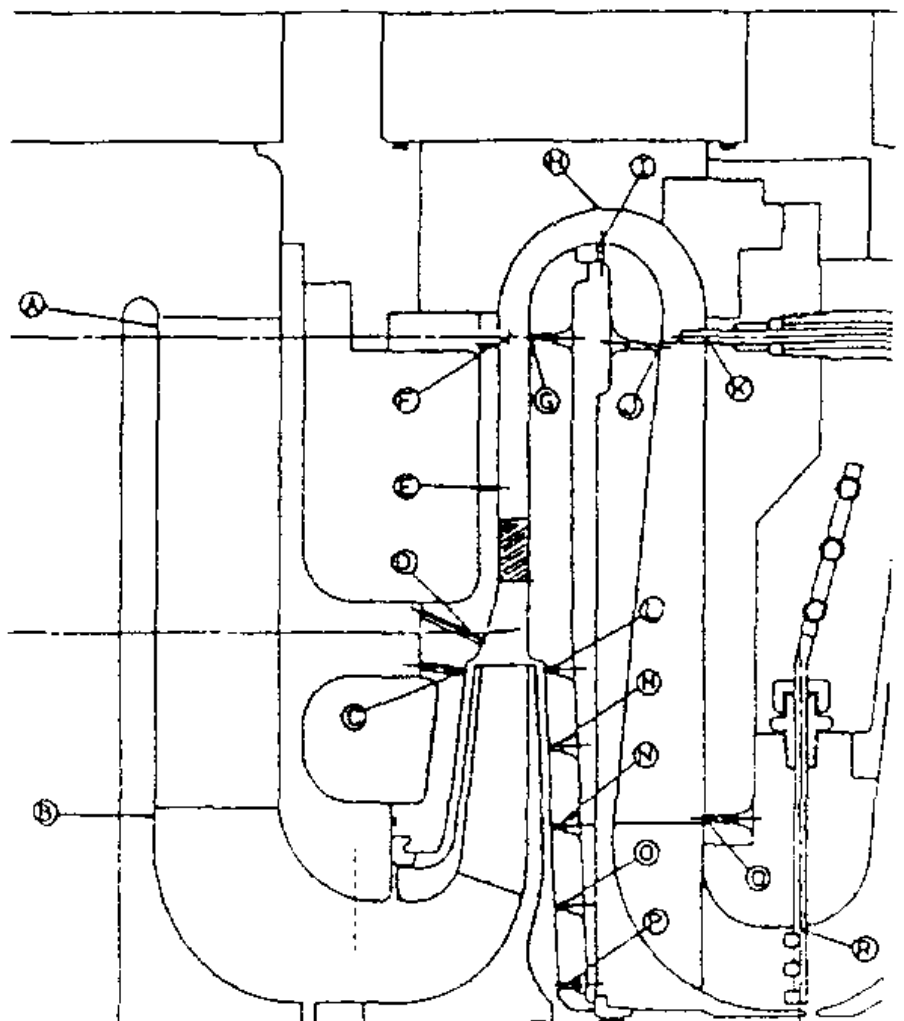


Figure 4(a) - Instrumentation Stations

INLET	-	A-E
IMPELLER	-	B-C
DIFFUSER	-	D-F
RETURN BEND	-	F-K
RETURN CHANNEL	-	K-R
OVERALL STAGE	-	B-R

STATION	Static Press. Probes	Total Press. Probes	Temp. Probes	Total Press. Ranges	Temp. Ranges	Press. Trav. Probes
A	2			2	2	
B	2			2	2	
C	1					
D	2	2	2			1
E	1	1				1
F	2	2	2			1
G	2					
H	2					
I	2					
J	1					
K	2					1
L	2					
M	2					
N	2					
O	2					
P	2					
Q	2					
R	2		1	1		1

Figure 4(b) - Number Of Probes At Each Station & Probes Used For Each Component

Parameter	Value (Range)
Leading Edge Radius Ratio	1.08, 1.15
Inlet Setting Angle	58 to 78 deg.
Exit Angle	43 to 65 deg.
W5'(minimum)	1.3°, 3.2°
Maximum Vane Thickness	.32°
Chord	2.5°, 5.0°
Pitch	3.4°, 6.8°

Table 3 - Select LSD Geometric Parameters

Figure 4a and 4b illustrate the various measurement locations and the number of probes at each station. Figure 4b also shows which stations are used to determine component performance. For example, overall performance is calculated using stations "B" and "R".

Tests were conducted using different speeds and gases to obtain varying impeller tip mach numbers; and, therefore, varying impeller exit flow angles. Table 2 (referenced earlier) reflects the operating conditions and the resulting U_2 / A_o 's and exit flow angles.

Table 3 exhibits information about the matrix of LSD geometries tested. Note that the stagger angle range encompasses all anticipated impeller exit flow angles seen in table 2.

Testing on each build began with the LSD vanes set at nominal incidence for the impeller best efficiency point (B.E.P.) exit flow conditions. A full line (choke to surge flow at constant speed, typically 5-7 points) was taken at this setting angle. The vanes were then rotated and another full line of data was read. To establish trends, a minimum of five setting angles were tested at each speed.

After completing four speed lines, the rig was disassembled and a new configuration was installed.

TEST RESULTS FOR INDIVIDUAL BUILDS

Test results presented herein will fall into three general forms: efficiency and head

coefficient versus flow diffuser pressure recovery ($C_{p_{2-5}}$) versus flow; and diffuser loss coefficient (LC_{2-5}) versus flow. Though data was taken at four U_2 / A_o 's (.61, .78, .96, and 1.06), only the .78 line will be presented.

Note: on efficiency and head coefficient plots, the performance at BEP flow and nominal setting angle was used to normalize the data. Since non-dimensional, pressure recovery and loss coefficient were not normalized.

General Observations

One can see in figures 5 through 8 that the variation in curve shape with setting angle is quite dramatic regardless of build. BEP flow, rise to surge, stability, and choke margin all exhibit strong sensitivity to stagger angle.

Despite the stated absence of a true diffuser throat in an LSD, overload capacity displays a marked decrease as the stagger angle is increased from nominal. Two factors contributed to this effect. First, traverse data indicated a flow separation from the pressure surface of the vanes. The separation cells blocked a significant portion of the diffuser passage; reducing the effective area and limiting capacity. Second, figure 2 shows that, though the LSD vanes do not overlap, the dimension w_5 does decrease significantly as the setting angle becomes more tangential.

One can also observe that as setting angle was decreased from nominal, the LSD vanes were stalling. This is evidenced by the droop to surge in both the pressure coefficient and efficiency curves seen in figures 5 -8 (note, for example, the data labeled with circles). Note that the surge margin is reduced even for a small decrease (5°) from nominal incidence.

Of particular interest is the improved rise to surge and stability as the setting angle

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