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COMPARISON OF CONVENTIONAL AND LOW SOLIDITY VANED DIFFUSERS

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ABSTRACT

Test results are presented comparing the aerodynamic performance of single stage centrifugal compressors with thin flat plate, low solidity vaned diffusers to conventional thin vaned diffusers. The test data were acquired from a low Mach number process gas compressor and a high Mach number industrial air compressor. The data are all normalized relative to baseline vaneless diffuser results. Performance parameters of stability, head rise to surge, overload flow margin, and stage efficiency are compared. The low solidity vane inlet incidence angle is shown to be an important design parameter that influences both compressor operating range and efficiency.

NOMENCLATURE

A - diffuser area ratio, $(r_4 \sin\beta_4) / (r_3 \sin\beta_3)$
a - sonic velocity
b - passage hub-to-shroud width
C - absolute velocity
c - vane chord length
ΔC - average blade-to-blade velocity difference $= 2\pi(r_3 Cu_3 - r_4 Cu_4) / (ZL_B)$
E - Vaned diffuser effectiveness, $(1 - 1 / A^2) / (1 - 1 / R^2)$
H - head
i - vane incidence angle, $\beta_3 - \alpha_3$
M_U - rotational Mach number, U_2 / a_0
L_B - vane mean camberline length
L - diffuser vane loading parameter, $\Delta C / (C_3 - C_4)$
N_s - dimensional specific speed
$2\theta_c$ - $2\tan^{-1}[\pi(r_4 \sin\beta_4 - r_3 \sin\beta_3) / (ZL_B)]$
R - diffuser radius ratio, r_4 / r_3
r - radius
t - vane pitch, $2r_3 \sin(\pi / Z)$
U_2 - tip speed
Z - number of diffuser vanes
α - flow angle with respect to tangent
β - vane angle with respect to tangent
δ - deviation angle
η - stage efficiency
σ - vane solidity, c / t
ϕ - inlet flow coefficient
% stability $= 100(1 - \phi_{SURGE} / \phi_{DESIGN})$
% OVLD $= 100(\phi_{MAX} / \phi_{DESIGN} - 1)$
% HRTS $= 100(H_{PEAK} / H_{DESIGN} - 1)$
% $\eta = 100(\eta / \eta_{VLD} - 1)$

Subscripts

A - adiabatic
P - polytropic
0 - impeller inlet
2 - impeller tip parameter
3 - diffuser vane inlet parameter
4 - diffuser vane exit parameter

INTRODUCTION

The concept of low solidity vane diffusers (LSVD), first introduced by Senoo (1981) and later reported by Kaneki and Ohashi (1982) and Senoo, et al (1983), has been shown to offer impressive efficiency gains over vaneless diffusers (VLD) with apparently little or no loss in flow range. The primary feature of this design is a low vane solidity such that the geometric throat is eliminated. Senoo's work demonstrated efficiency gains for both single and tandem airfoil vane cascades with flow range approaching that of a vaneless diffuser stage. The lack of a vane geometric throat has the understandable effect of allowing the stage to operate out to its impeller choke flow limit (provided the diffuser vane incidence is matched properly). However, the

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influence of this "absent throat" on surge flow extension is not readily apparent. Surge flow with conventional vaned diffusers (CVD) is highly dependent on vane stall due to flow incidence. The gains in diffuser efficiency with the LSVD are quite good for such short highly loaded vanes. They seem to follow the same reasons CVD's increase diffuser pressure recovery by means of vane loading and a larger effective passage area. How well the LSVD performs relative to a CVD has been addressed only once previously in the literature by Kano, et al (1982). Further experimental studies were reported by Osborne and Sorokes (1988) using design procedures derived from Senoo, but with simple flat plate vane construction. They also demonstrated significant gains above a vaneless diffuser for designs covering a wider range of specific speed. Sorokes and Welch (1991) provided a comprehensive set of LSVD data showing the effects of various setting angles on both diffuser performance and overall stage performance. This gives very useful design information regarding this important design parameter. Further test results on a rotatable LSVD were reported by Sorokes and Welch (1992).

Vaned diffusers are applied in a wide variety of compressor applications. Their impact on the operating range of a single stage compressor depends upon such parameters as diffuser inlet Mach number, inlet flow angle, impeller performance and component matching. It is often possible to design a CVD to choke at the same flow as the impeller and still achieve an adequate surge flow. Thus only range to surge will be reduced relative to a vaneless diffuser stage. Also, this difference in range may be small if impeller inducer stall is controlling the surge flow. It is therefore necessary to evaluate the relative merits of both the LSVD and the CVD before choosing one or the other if optimum performance based on several design requirements is desired.

The intent of this paper is to present the results of experimental studies that compare the overall stage performance of the LSVD, CVD and VLD. Relative changes in the efficiency, head and surge margin are discussed. These data offer further insight into the design and application of the LSVD.

LSVD DESIGN PROCEDURE

All of the low solidity vaned diffusers (LSVD) in this paper were designed with a solidity equal to 0.7. This is essentially the same as Senoo's original design. Although values of solidity up to 0.9 could be employed in this type of design, 0.7 was chosen based on the apparent success at this level in the published literature. Similar to the approach taken by Osborne/Sorokes, simple flat plate vanes were used throughout (Figure 1). These were chosen based on their reported success and inexpensive design. The vane thickness, leading edge taper, vane height, and vane inlet radius were designed to the same dimensions as the corresponding conventional vaned diffuser (CVD). With the solidity and vane shape fixed, only the number of vanes and the vane inlet angle were needed.

The number of vanes was, in part, restricted by frequency

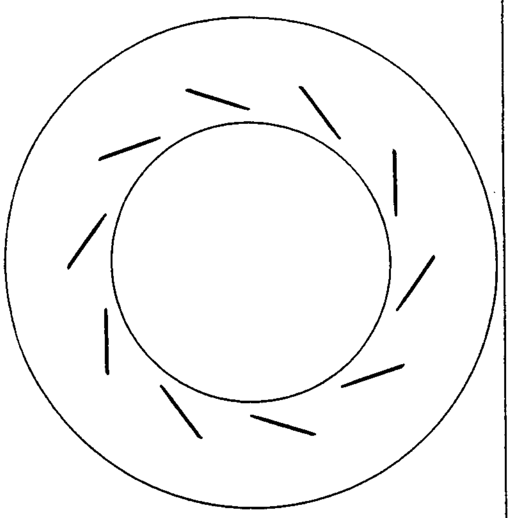

FIGURE 1: LOW SOLIDITY VANE DIFFUSER
SOLIDITY = 0.7

considerations based upon the impeller blade to diffuser vane interaction. Also, based upon consideration of the downstream component matching, it was decided to design toward vane discharge angles that would result in flow angles approaching that of the conventional vane diffuser. Because of the high vane loading for these low solidity designs, large flow deviation angles (up to 8 degrees) were estimated at the vane trailing edge. An inviscid blade-to-blade flow analysis with a trailing edge Kutta condition imposed was used for this purpose. For constant solidity, designing toward higher discharge vane angles resulted in a lower number of vanes. Despite the resultant increase in deviation angle, this approach appeared to offer some increase in the discharge flow angle to allow better matching with the volute or return channel. The LSVD vane number was therefore selected as 16 for the air compressor and 10 for the process compressor. However, there was concern regarding the level of vane loading since no guidelines were available for LSVD's. Table 1 lists the tested diffuser design parameters. Further work is planned that will better define the influence of vane number on overall stage performance.

The LSVD inlet angle or setting angle was initially designed based on previous results from the CVD. Three vane inlet angles were selected for the air compressor at an impeller design M_u = 1.38. One was set to the same inlet vane angle as the CVD and two with +/- 2.1 degree variation from the nominal. The process compressor LSVD was designed for M_u = 0.7 with 1 degree lower inlet angle than its corresponding CVD. The goal of both sets of designs was to evaluate the potential of the LSVD from an efficiency and range extension point of view relative to the CVD performance.

TABLE 1: LOW SOLIDITY VANED DIFFUSER DESIGNS

PARAMETER	PROCESS COMPRESSOR	AIR COMPRESSOR LSVD1	LSVD2	LSVD3
σ	0.7	0.7	0.7	0.7
i_{DESIGN}	-3.1°	-4.1°	-1.9°	+0.3°
β_3	17.0°	18.3°	20.4°	22.5°
β_4	36.8°	31.3°	33.2°	35.1°
Z	10	16	16	16
b_3/b_2	1.0	0.85	0.85	0.85
r_3/r_2	1.11	1.10	1.10	1.10
r_4/r_3	1.19	1.11	1.12	1.13
r_{EXIT}/r_2	1.61	1.60	1.60	1.60
A	2.45	1.84	1.76	1.70
L	1.39	1.36	1.35	1.33
$2\theta_C$	34.2°	21.4°	21.6°	21.7°
E	2.84	3.74	3.39	3.02
δ	8.2°	5.7°	6.0°	6.3°

TABLE 2: CONVENTIONAL VANED DIFFUSER DESIGNS

PARAMETER	PROCESS COMPRESSOR	AIR COMPRESSOR	RECOMMENDED VALUES
i_{DESIGN}	-2.3°	-2.1°	--
β_3	18.0°	20.4°	16° - 20°
β_4	31.5°	36.8°	--
Z	14	19	--
b_3/b_2	1.0	0.85	--
r_3/r_2	1.11	1.10	1.06 - 1.10
r_4/r_3	1.45	1.40	--
r_{EXIT}/r_2	1.61	1.60	--
A	2.45	2.40	2.2 - 2.4
L	0.31	0.32	0.30 - 0.33
$2\theta_C$	10.5°	10.9°	10° - 11°
E	1.60	1.70	1.5 - 1.7
i_{STALL}	8.3°	2.7°	--
δ	3.7°	4.0°	--

The conventional vaned diffuser parameters of L, A, $2\theta_C$, and E are tabulated for the LSVD designs for comparison only. Their relevance to LSVD design may be minimal since parameters such as L and $2\theta_C$ fall well outside the normal range of good diffuser design practice. The deviation angle is an estimate from an inviscid blade-to-blade flow analysis with a trailing edge Kutta condition imposed. It must be viewed as simply an estimate, since the validity of this approach for the LSVD has not been confirmed.

CVD DESIGN PROCEDURE

Both conventional vaned diffusers were designed to replace deficient existing vaned diffusers. The air compressor's vaned diffuser was a direct retrofit. This imposed significant restrictions upon the design, due to the need to match the existing impeller and volute. The process compressor's vaned diffuser design emphasized optimization of the vaned diffuser. Both the impeller and return system of this stage were redesigned to support this objective.

Both CVD designs are based upon the design and performance analysis procedure of Aungier (1988) and Aungier (1990). Table 2 shows the key design parameters used, along with recommended values from Aungier (1988).

The primary compromise imposed upon the air compressor's vaned diffuser is evident from the stall incidence angle predicted. This low value of stall incidence limits the stage surge margin. The combination of a higher inlet vane angle and larger number of vanes than would have been preferred is the primary cause. These values were imposed by impeller matching and resonance considerations.

The predicted stall incidence angle for the air compressor has been shown to be very accurate (Aungier, 1990, therein, designated as compressor "A", V.D. #2). Test confirmation of the predicted stall incidence for the process compressor's vaned diffuser was not obtained, since the impeller stall occurred at higher flows than the vaned diffuser stall.

TEST FACILITY

Experiments were conducted on two separate compressor test arrangements. The process compressor was run on a permanent, closed loop with a radial inlet and return channel discharge shown in Figure 2. The air compressor used a standard production compressor with axial inlet and volute discharge shown in Figure 3. Both are steam turbine driven and capacity controlled by discharge throttling. Total pressures and temperatures were measured at the inlet and discharge using 1/16 and 1/8 inch diameter kiel probes and 1/8 inch diameter

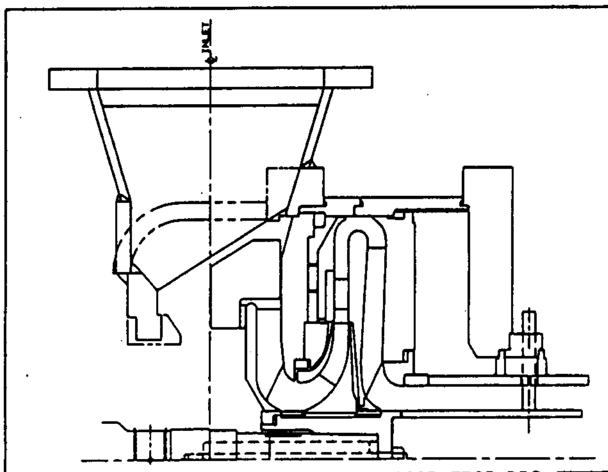

FIGURE 2: PROCESS COMPRESSOR TEST RIG

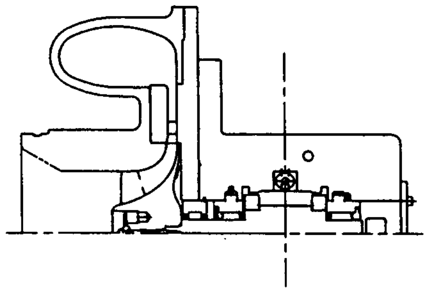

FIGURE 3: AIR COMPRESSOR TEST RIG

stagnation type thermocouples (CU - CN extra precision wire). These were installed at 4 locations, 90 degrees apart circumferentially. Corresponding static pressures were also recorded using 1/16 inch diameter tubing. Mass flow was calculated based on ASME orifice plate differential pressure measurements. The compressor casing on both test configurations was insulated to minimize external heat transfer. Data acquisition employed a Scanivalve transducer and digital voltmeters linked to a local computer system. Normally three scans of data were acquired for each flow point to insure thermal stability had been achieved and no fluctuation in inlet pressure. Table 3 lists the nominal test conditions.

TABLE 3: TEST CONDITIONS

COMPRESSOR	M_U	TEST GAS	INLET PRESSURE PSIA	INLET TEMP. °F
Process	0.53	N_2	16.0	75 - 85
Process	0.70	N_2	16.0	75 - 85
Air	1.38	Air	14.2	75 - 85

PERFORMANCE RESULTS

Test head and efficiency (based on overall stage total-to-total conditions) were calculated as polytropic for the process compressor and as adiabatic for the air compressor. All performance curves are dimensionless, using the rated performance of the VLD stage as the reference values for each curve.

PROCESS COMPRESSOR

The LSVD and CVD stages were designed (matched) and tested with the same diffuser width and the same return channel width. The VLD stage was designed and tested with a 30% narrower diffuser width and 25% narrower return channel. The return channel vane design was the same for all 3 configurations. The impeller is a semi-inducer, two dimensional blade design with 48 degrees backward lean and 18 full blades. Figures 4 and 5 compare the CVD, LSVD and VLD at tip rotational Mach numbers of 0.53 and 0.70 for the process compressor. The peak

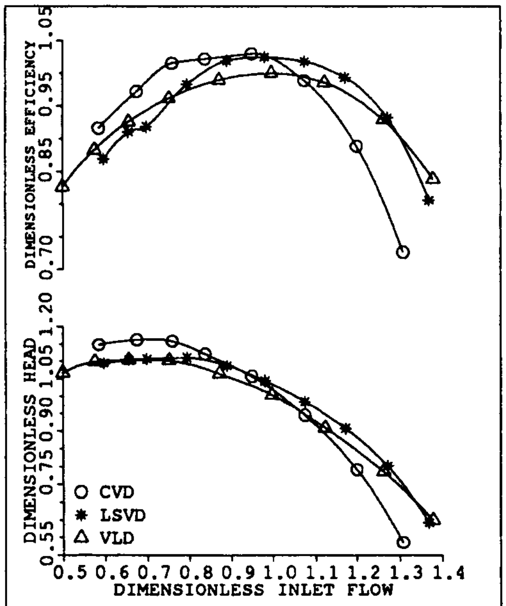

FIGURE 4: PROCESS COMPRESSOR PERFORMANCE Mu = 0.53

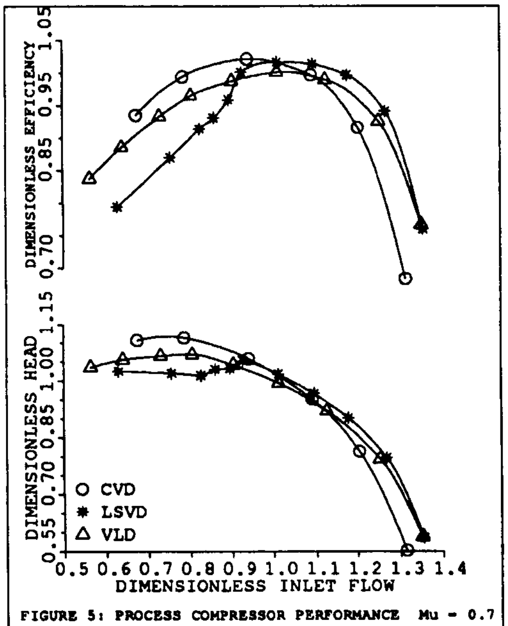

FIGURE 5: PROCESS COMPRESSOR PERFORMANCE Mu = 0.7

efficiency of the LSVD held up quite well compared to the CVD and at rated flow was essentially equal to the % efficiency gain of the CVD (ref. Table 4). The LSVD produced the expected capacity similar to the VLD and was not affected by the higher negative incidence angles in the overload range as was the CVD. Excellent efficiency gains were achieved in this range over both the CVD and VLD. However, in spite of its lower inlet vane angle, the LSVD showed an early stall, especially at 0.7 Mach number. Stability at this speed was only 8% compared to 25% for the CVD. Overall range is 12% less than the CVD. Narrowing the diffuser or decreasing the vane inlet angle may help the stability, but it would reduce the pressure recovery and efficiency. Also, overload margin may be reduced due to higher negative incidence losses, as seen in the Sorokes/Welch investigation with variable inlet vane angle. From the 0.53 speed curve, one can see the signs of an incidence limitation for the LSVD by the steeper sloped curve and its crossing of the VLD curve at max flow. Thus, overall range of the LSVD may not improve with adjustment of the diffuser width or vane angle.

Process compressors often require minimum levels of stability and overload range to be an acceptable design. The LSVD at the 0.7 Mach number is clearly unacceptable from the stability standpoint. Based on these trends, it was determined higher speed testing would only aggravate the stability problem. Thus, no further testing was performed. One other noticeable aspect of the LSVD performance was its reduced head rise to surge (ref. Table 4). At Mach number = 0.53, the LSVD was 6.5% less than the CVD. It appears for this relatively low speed range, the simple flat plate LSVD design can achieve diffuser pressure recovery equivalent to the CVD as long as incidence is in the negative region. As the flow rate decreased the incidence angle became more positive causing the vane to stall (abruptly for the 0.7 Mach number test) with an accompanying increase in loss. It may be the small number of vanes (10) combined with the thin vane leading edge allow large stall cells to develop in the diffuser. This might be alleviated if an airfoil shaped vane or larger vane number was employed. Certainly the goal of further development would be to try to regain the lost head and stability at low flow, while preserving the LSVD performance gains out to maximum flow rate.

TABLE 4: PERFORMANCE AT FLOW RATIO = 1.0

PROCESS COMPRESSOR: $\phi_{DESIGN} = 0.052$, $N_S = 84$

DIFFUSER	M_U	$\%\eta_P$	% STABILITY	% OVLD	% HRTS
CVD	0.53	2.2	29.5	30.0	13.9
LSVD	0.53	2.3	23.0	39.0	7.4
VLD	0.53	0	29.5	41.5	10.4
CVD	0.70	1.8	25.0	30.0	9.0
LSVD	0.70	1.8	8.0	35.0	2.7
VLD	0.70	0	24.0	35.0	7.0

AIR COMPRESSOR: $\phi_{DESIGN} = 0.055$, $N_S = 80$

DIFFUSER	M_U	$\%\eta_A$	% STABILITY	% OVLD	% HRTS
CVD	1.38	7.6	8.5	9.4	12.5
LSVD#1	1.38	4.9	13.2	10.5	11.1
LSVD#2	1.38	5.0	8.1	10.5	9.4
LSVD#3	1.38	2.2	5.7	10.5	4.6
VLD	1.38	0	14.1	10.5	4.7

Notes: $\%\eta$ relative to VLD
% Stability and HRTS based upon peak head
% OVLD based upon flow at 60% design head

AIR COMPRESSOR

All test configurations used the same discharge volute which was designed and matched originally to the CVD stage. Thus for the vaneless diffuser test, the volute area was 30% oversized. The impeller was a three-dimensional, full-inducer blade design with 42 degrees backward lean and 15 full, 15 splitter blades. Results of the air compressor testing at design speed are shown in Figures 6, 7 and 8. Each LSVD is compared with the CVD and VLD. From Table 4 it can be seen the CVD surpassed all of the LSVD stages by at least 2.6% in efficiency at design flow. LSVD's 1 and 2 have quite good efficiency gains of 5% above the VLD stage. Overload or choke margins are essentially equal for all of the configurations. The CVD is just 1% lower than the VLD choke flow. LSVD1 with the vane inlet angle equal to 18.3 degrees (2.1 less than the CVD) exhibited the best overall performance of all the LSVD's. Although, the design could not achieve the same level of pressure recovery as the CVD at this high Mach number, it did increase the compressor stability range by 5%. This represents a 30% gain in overall operating range.

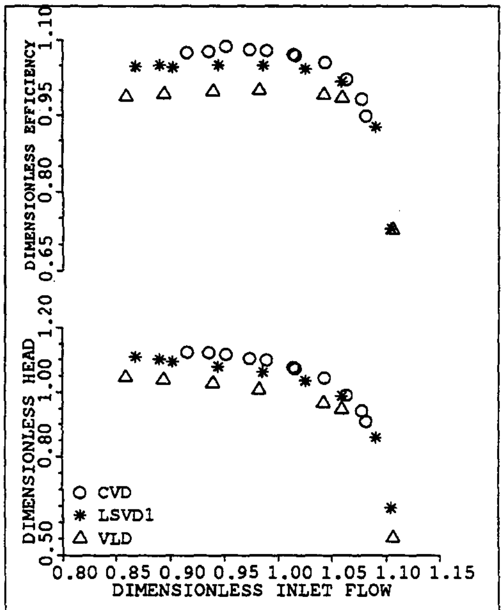

FIGURE 6: AIR COMPRESSOR PERFORMANCE Mu = 1.38

The LSVD2, with design incidence slightly more positive than the CVD, had slightly less stability range than the CVD. As the design incidence became even more positive with LSVD3, stability range deteriorated to less than 6%. Also, the efficiency declined significantly for the LSVD3 (over 5% lower than the CVD) while head rise to surge was no better than the VLD. It should be mentioned that stability on the air compressor was very well defined by its violent and very audible surge.

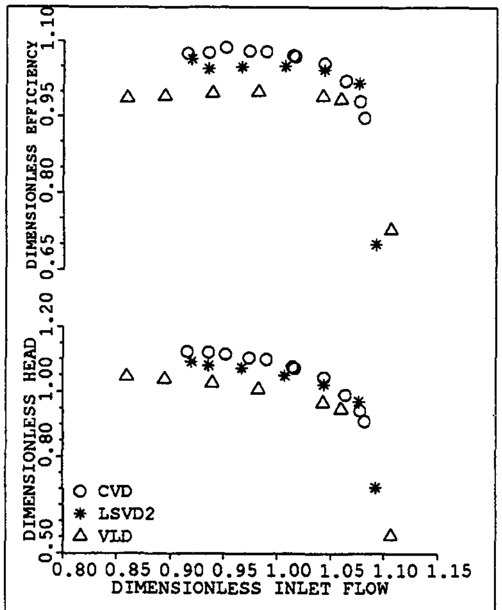

FIGURE 7: AIR COMPRESSOR PERFORMANCE Mu = 1.38

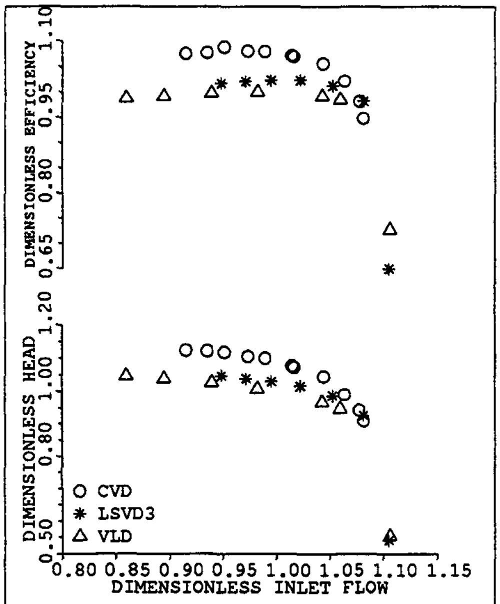

FIGURE 8: AIR COMPRESSOR PERFORMANCE Mu = 1.38

It is clear the vane incidence angle is a critical design parameter. Performance of the air compressor shows significant change in both efficiency and surge margin for a total LSVD design incidence angle variation of 4.4 degrees. A positive design incidence appears to be undesirable and should be avoided. The fact that the LSVD1 achieved within 1% the same overall range as the VLD with good efficiency gains compares well with previous results in the literature. Comparisons with the CVD indicate there is a trade off relative to efficiency and stability. Both are viable choices over a vaneless diffuser depending on the specific application. For example, in a 2 or 3 stage air compressor, the 1st stage might be the CVD where the operating flow envelope may be shorter and attaining the highest possible efficiency is appropriate. In the downstream staging, wider flow range is desirable due to the cascade/volume ratio effects. Thus using an LSVD offers a good compromise between the VLD and CVD. As stated earlier, a more complex LSVD vane design may offer the best of both worlds (CVD efficiency and VLD stability), but that remains to be seen. These results indicate there is an optimum design incidence for an LSVD just as there is with a CVD for a given set of conditions.

In spite of the LSVD's lack of a geometric throat, it behaved more like a CVD than the VLD primarily due to flow separation and incidence loss effects from the vanes. The process compressor at the lower tip speeds show a somewhat different result than the air compressor relative to stability range. Even though it had more negative incidence than the CVD, the LSVD surge margin was greatly reduced. This limited test data was not able to provide a good explanation of this result.

Off design speed data taken at M_u = 1.18 on the air compressor test clearly indicate the effect of higher negative incidence on overload margin as seen on Figure 9. The "maximum" flow,

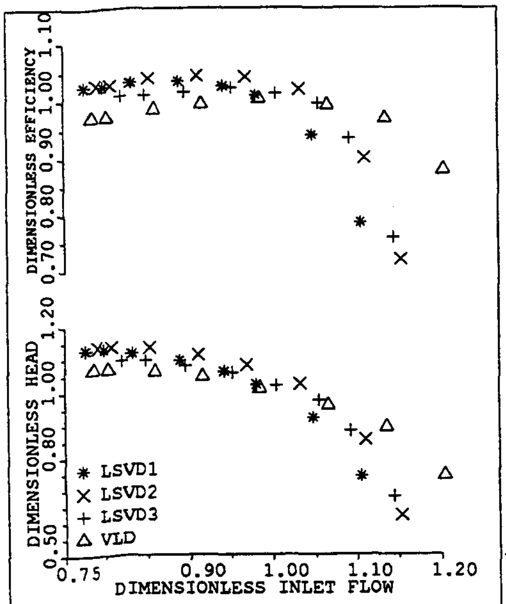

FIGURE 9: AIR COMPRESSOR PERFORMANCE Mu = 1.18

occurring at a vane incidence near -11 degrees, is significantly reduced from the VLD. Also an optimum incidence angle relative to stage efficiency is apparent. The best efficiency at flow ratio = 1.0 occurred at -6.9° degree incidence for LSVD2. Of course where the stage optimizes at off design speed is also influenced by the impeller performance. Stability range for the LSVD1 and LSVD2 were equivalent to the VLD, but with less overload range due to the higher negative incidence. No data was available for the CVD at this speed.

CONCLUSIONS

High Mach Number Industrial Air Compressor

1. The CVD, in all cases, achieved a minimum of 2.6% efficiency higher at design flow than the closest LSVD. The LSVD1, with -4.1 degree vane incidence, had the best all around performance at design speed. It surpassed the CVD flow range by 30% (nearly same as the VLD) while attaining a very respectable 4.9% efficiency gain over the VLD.

2. The LSVD3, with a +0.3 degree design incidence angle, decreased in efficiency and stability significantly below the CVD. This indicates positive incidence should be avoided for LSVD design.

3. Designing for even higher negative incidence may improve the LSVD stability range, but it is expected design efficiency will decline. This is evident from the off design performance comparisons of Figure 9. Stability increased a small amount for the LSVD1 but at a large expense of efficiency.

4. Vane incidence angle had a direct effect on both range and efficiency of the LSVD. There is an optimum design incidence angle that achieves the best range/efficiency combination. It appears that setting it to a negative incidence that just meets the VLD choke flow will maximize stability while achieving good efficiency gain. Going to higher negative incidence will cause the LSVD to lose choke flow capacity and design point efficiency.

Low Mach Number Process Compressor

1. The LSVD achieved essentially the same design point efficiency level as the CVD.

2. At design speed of 0.7 Mach number, the LSVD stability range was significantly less than the CVD (8% versus 25%). This was a much different result than seen with the air compressor tests. Incidence angle appears not to be the controlling parameter since in spite of more negative incidence the stability decreased. It is speculated that vane number (10 vanes for LSVD) may be too low which allowed large stall cells to develop due to low flow angles and excessive divergence angles. Future testing will address the issue of optimum vane number for an LSVD. A more complex airfoil vane shape may help this stability problem. Also, design guidelines are needed with respect to vane loading and equivalent divergence angle limits.

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