

The Design and Analysis of Low Solidity Vaned Diffusers for Increased Turbopump Throttling Capability

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Low solidity vaned diffusers (LSVD) offer the potential to increase static pressure recovery over that attainable with a vaneless diffuser and do so over a flow range larger than what is possible with a conventional vaned diffuser (CVD). Such a technology could benefit liquid rocket engine (LRE) turbopumps required to perform deep throttle operations such as those envisioned for ascent/descent operations. In this test effort 5 LSVD concepts are designed, manufactured, and tested in a water test loop at Barber-Nichols Inc. along with a CVD configuration to provide baseline comparison data. The LSVDs were successful in offering a consistent static pressure recovery over a flow coefficient range analogous to deep throttle operation in a turbopump and achieved a level of increased pump head coefficient higher than the CVD diffuser at flow coefficients below 0.09. Shaping the leading edge of the second LSVD concept based on predictions from a modified potential flow free-streamline analysis produces higher pump head coefficients over the LSVD concept with a full radius leading edge. The test results suggest that the LSVD design guidelines for low speed compressors may be successfully applied to pumps, and further that the adaptation and modification of an existing free-streamline analysis methodology to guide the contouring of diffuser vane leading edges was successful.

Nomenclature

<i>CVD</i>	=	conventional vaned diffuser
c_m	=	impeller discharge meridonal flow velocity
ΔH	=	head (ft)
<i>LRE</i>	=	liquid rocket engine
<i>LSVD</i>	=	low solidity vaned diffuser
<i>N</i>	=	shaft speed (rpm)
<i>NPSH</i>	=	net positive suction head (ft)
N_s	=	specific speed, $\frac{N\sqrt{Q}}{\Delta H^{0.75}}$
<i>Q</i>	=	volumetric flow rate (gpm)
r_3	=	diffuser inlet radius
r_4	=	diffuser discharge radius
<i>t</i>	=	vane thickness
<i>U</i>	=	impeller tip speed (ft/sec)
<i>Z</i>	=	vane number
λ	=	$\frac{D_{inlet}/hub}{D_{inlet\ tip}}$
ϕ	=	impeller discharge flow coefficient, $\frac{c_m}{U}$
ψ	=	pump head coefficient, $\frac{\Delta H}{U^2/g}$
σ	=	vane solidity

I. Introduction

DEEP throttle capability in pump-fed liquid rocket engines (LREs) places unique challenges on centrifugal turbopumps. Engine systems required to perform deep throttle operations such as those envisioned for ascent/descent missions require turbomachinery capable of operation at Q/N ratios of 0.2 to 1.1 for 10:1 engine throttle operation¹. Such operational ranges are particularly difficult for vaned radial diffusers which are prone to fluid separation and stall at extreme Q/N operation. Vaneless diffusers while capable of wide flow range operation, lack the static pressure recovery capability possessed by vaned diffusers. Low solidity vaned diffusers (LSVDs)

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offer the potential for static pressure recovery over a wider Q/N range than is possible with a conventional vaned diffuser (CVD) while attaining a static pressure recovery greater than possible with a vaneless diffuser. An increase in pump stage static pressure assists in increasing pump efficiency which in turn can reduce the amount of propellant required for a given mission allowing for an increased payload or reduction in vehicle mass.

The concept of a LSVD for centrifugal pump applications is credited to Sutton² with further development for centrifugal compressors performed by Senoo³. The design premise is that by eliminating the aerodynamic throat through the diffuser the stage flow range is controlled by the impeller allowing the stage to operate out to its choked flow limit provided, as mentioned by Holweg⁴, “the diffuser vane incidence is matched properly”.

The bulk of the published literature concerning LSVDs comes unsurprisingly from the compressor industry where the use of vaned diffusers is more common than for pumps. Although LSVDs have been applied to pumps no known work regarding the efficacy of using compressor-derived design guidelines is known to be available. This work seeks to explore the potential benefits of LSVDs as applied to pumps and add to the knowledge base of LSVDs by examining the effects of diffuser leading edge geometry and incidence angle.

II. LSVD Design Procedure

The majority of the published literature relating to the design and analysis of LSVDs concerns application in compressors flowing compressible fluids and are not specific to pumps using incompressible fluids. Wherever possible, data relating to low Mach number operation (< 0.4) has been used for creation of the LSVD pump design strategy.

Delaying the onset of flow separation is a problem common between LSVDs in pumps and compressors. In LRE pump impellers and inducers the problem of flow separation is often linked to the inception of cavitation at low inlet flow coefficients and low inlet pressures, suggesting that strategies for cavitation suppression may aid in the design of vaned diffuser leading edges. Potential flow based free-streamline theory models the steady state boundary between the core flow and the separated flow. This boundary is referred to as the free streamline. Understanding the shape of the free-streamline enables creation of an airfoil leading edge contour that minimizes or prevents flow separation⁵. The linear analysis developed by Stripling and Acosta⁶ predicts the free-streamline behavior for a linear cascade of hydrofoils, representative of high suction performance pump inducers. The premise is that there exists a free-streamline flow for low values of the cavitation number where vapor and a turbulent wake exist on one side of the free-streamline and liquid on the other. This arrangement is depicted in Fig. 1, adapted from Fig. 9 of Ref. 7. By shaping the blade leading edge to be at or below the thickness of the free-streamline contour the suction performance is improved over blades with leading edge thicknesses that exceed the free-streamline height. Modification of the free-streamline analysis for use in a LSVD cascade would provide a pump specific design guideline. This is the approach taken here.

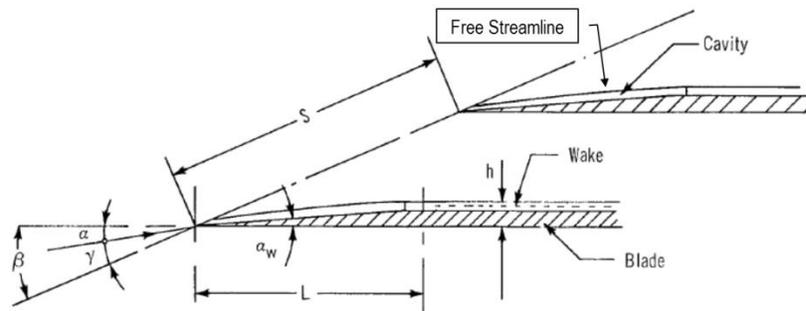


Figure 1. Depiction of the free streamline in a linear cascade, adapted from Figure 9 of Ref. 7.

The defining characteristic of the LSVD is the absence of a true aerodynamic throat. To simplify the analysis it is assumed that this lack of a throat permits the diffuser vane to be modeled as a single, isolated airfoil. The Stripling and Acosta⁶ free-streamline theory assumes a cascade of infinitely long blades (and therefore infinite solidity). The theory may be modified for LSVDs however, as the infinitely long blade assumption was made for ease of computation, eliminating the need for a non-linear potential solution that describes cavity closure and the laborious algebra that results. There is nothing fundamental in the theory that confines it exclusively to a high solidity cascade. Based on these boundary conditions, the appropriate modifications to the Stripling-Acosta methodology were made

and the theory implemented for use in designing LSVDs, with the goal of designing a separation-resistant diffuser vane leading edge.

A. Test Articles

LSVDs comprised of flat camber lines are used in this test effort. This geometry was selected based on its simplicity of design, ease of implementation, and effectiveness. Engeda^{8,9} successfully demonstrated such a design in his work. The technical approach for the design of the LSVDs described here relies heavily on data and information contained within these papers and retains the nomenclature of his work. The nomenclature and geometry description is shown in Fig. 2.

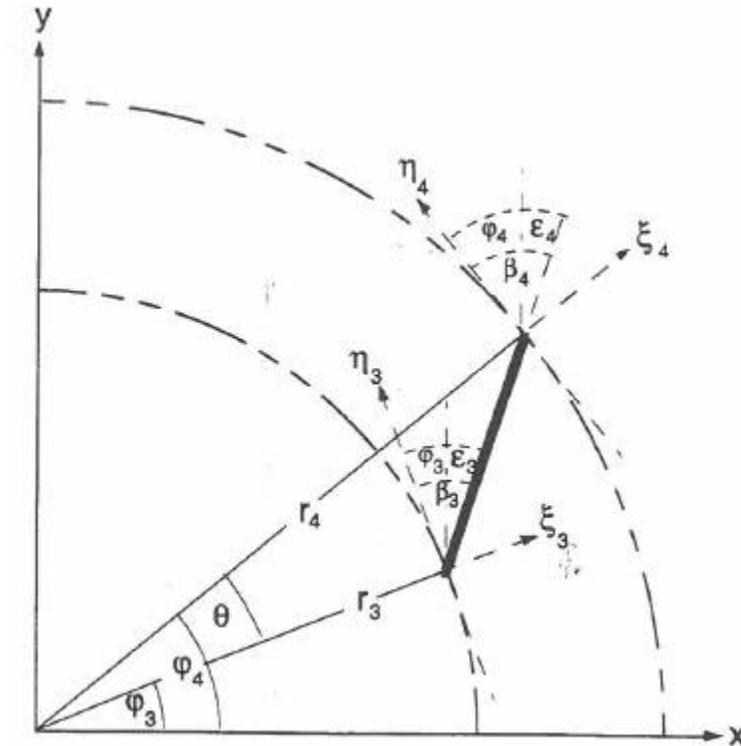


Figure 2. Nomenclature and geometry description for LSVDs from Engeda⁸.

The first step in the design of the LSVDs is the selection of the design incidence angle, i_d . Two LSVD design incidence angles were selected for testing, a positive incidence of 3 degrees and a negative angle of -0.5 degrees. Sorokes and Welch¹⁰ provide data suggesting that higher compressor efficiencies were obtained with slightly negative incidence angles. Hohlweg's⁴ data showed a maximum efficiency with an incidence angle of $i_d = -1.9$. A negative incidence angle allows for a bias toward improved low flow performance as it limits the largest positive incidence that will occur at the lowest flow coefficient.

Two distinct designs are used for the leading edge shape of the LSVD test articles. The first design is a full radius leading edge, designated the "full round" configuration while the second design uses the modified free-streamline theory to shape the leading edges. The free-streamline leading edges are referred to as the "shaped" configuration.

For a given LSVD incidence angle design 2 leading edge configurations are created for a total of 4 LSVD designs. A separate and distinct geometry was created based on a modified NACA 65 series airfoil with no camber as a comparison to the flat plate LSVD designs. The NACA 65 series geometry was selected as it has been successfully used in the past for diffuser designs. Additionally a CVD was designed and used as a control case against which to judge the performance of the LSVD configurations.

The diffuser radius ratio, the ratio between the diffuser vane leading edge radius and the impeller blade trailing edge radius (r_3/r_2) is taken from the guidelines given in Ref. 10. The LSVDs are found to be more effective when positioned at a lower radius ratio value. For this test article 2 radius ratios of 1.08 and 1.13 are used.

The remaining design parameters are chosen based on consideration of non-hydrodynamic constraints. The number of vanes Z , is chosen as a multiple of 3 to make use of the diffuser anti-rotation and orientation features present in the test article pump. For this investigation 9 vanes are used for the LSVDs. The blade thickness t_{bl} is chosen to provide adequate strength and material to allow for the insertion of anti-rotation pins.

The suction side leading edge shape for the shaped LSVD is designed for a flow rate less than the design flow rate of 180 gpm. The strategy is to accommodate the flow conditions at a much lower than design flow in an effort to increase the diffuser performance at the lower flow coefficients where high incidence angles are encountered.

With the incidence angle, radius ratio, vane number, and blade thickness chosen, the inlet blade angle β_3 can be found based on the impeller discharge flow characteristics at the design point. The diffuser discharge blade angle, β_4 and radius r_4 are then determined through the following relations given in Ref. 8.

$$\beta_4 = \tan^{-1} \left(\tan \beta_3 + \frac{2 - \sin\left(\frac{180}{Z}\right)}{\cos \beta_3} - \frac{t_{bl}}{2r_3 \sin \beta_3} \right) \quad (1)$$

$$r_4 = r_3 \frac{\cos \beta_3}{\cos \beta_4} \quad (2)$$

For the current test article a solidity of ~ 0.8 was used as it provided a good compromise between the required structural integrity and desire to use as low of a solidity as possible. Test results of Refs. 8 and 10 indicate that better stability at low flows is obtained with low solidities. Solidity is given in Ref. 8 and is defined as

$$\sigma^2 = (l/s)^2 = \frac{(r_4/r_3)^2 + 1 - 2(r_4/r_3)\cos(\beta_4 - \beta_3)}{2 - \cos(360/z)} \quad (3)$$

A summary of the diffuser test articles and their corresponding design parameters is given in Table 1.

Table 1. LSVD design parameter summary.

	b_3/b_2	r_3/r_2	r_3 (in)	β_3 (deg)	β_4 (deg)	Z	σ	t_{bl} (in)	i_d (deg)	Q_d (gpm)	N_d (rpm)
LSVD Full Round 12 deg	1.43	1.08	2.8	12	33.3	9	0.79	0.125	3.0	180	3471
LSVD Shaped 12 deg	1.43	1.08	2.8	12	32.3	9	0.76	0.125	3.0	180	3471
LSVD Full Round 9 deg	1.43	1.13	2.93	8.5	28.1	9	0.77	0.125	-0.5	180	3471
LSVD Shaped 9 deg	1.43	1.13	2.92	8.5	28.1	9	0.77	0.125	-0.5	180	3471
LSVD NACA 65 series	1.43	1.13	2.93	8.5	32.3	9	0.79	0.054	-0.5	180	3471
CVD	1.43	1.13	2.93	14	24.4	12	NA	-	5.0	180	3471

The 5 LSVD cascades created for the test program are shown in Fig. 3 through Fig. 8.

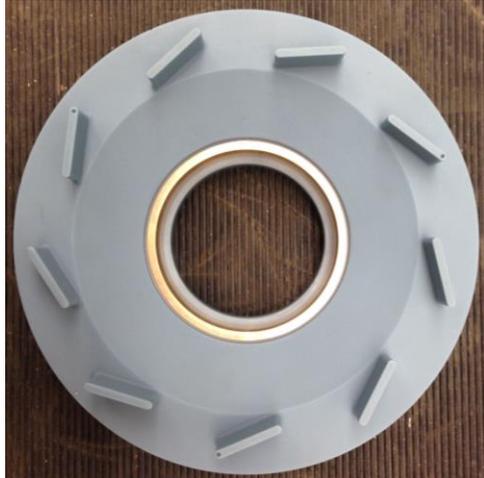


Figure 3. LSVD with a full radius leading edge and 12 degree inlet angle.

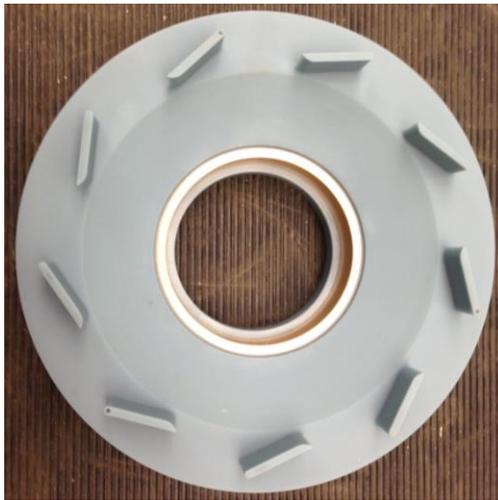


Figure 4. LSVD with a shaped leading edge suction side and 12 degree inlet angle.

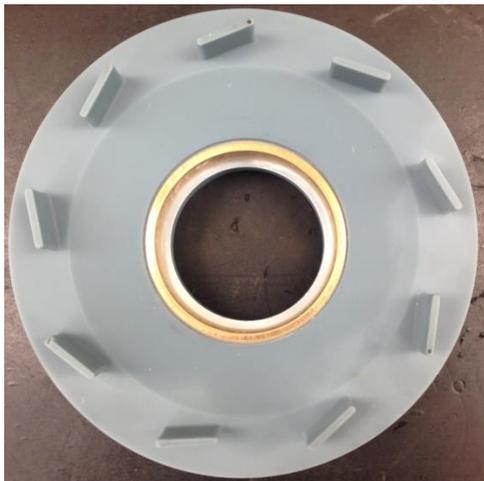


Figure 5. LSVD with a full radius leading edge and 9 degree inlet angle.



Figure 6. LSVD with a shaped leading edge suction side and 9 degree inlet angle.

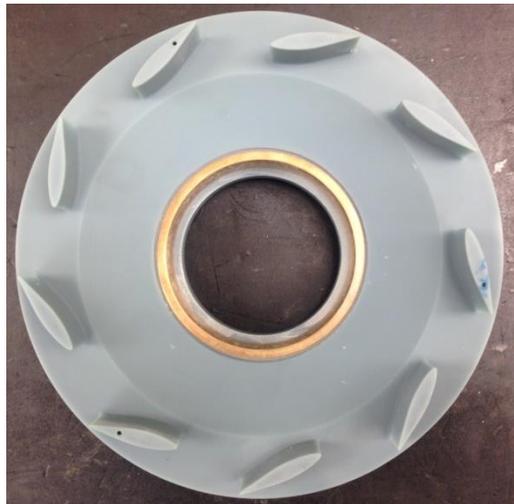


Figure 7. LSVD based on a modified NACA 65 series airfoil with 9 degree inlet angle.

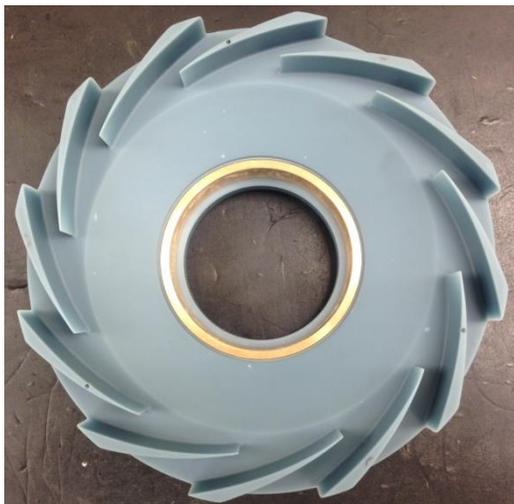


Figure 8. Conventional vaned diffuser with a 14 degree inlet angle.

The diffuser assemblies are created through the use of additive manufacturing (AM), allowing rapid manufacturing turnaround times and for a lower cost test article as opposed to machined aluminum.

III. Test Facility

The test loop for this investigation is shown schematically in Fig. 9. The test loop is constructed in the test area at Barber-Nichols Inc. (BNI) and consists of a 3000 gallon water tank connected to the test pump article via 4 inch schedule 80 PVC pipe. The water tank together with its discharge and return piping are shown in Fig. 10. The water tank is located outdoors while the rest of the loop is indoors, inside the test area. Two couplings, isolation valves and hose bibs allow the loop to be partially disassembled and drained after each diffuser configuration is tested. A sump pump controlled by a thermostat switch is placed inside the tank to re-circulate the water and prevent freezing of the lines when the temperature outside drops below freezing.

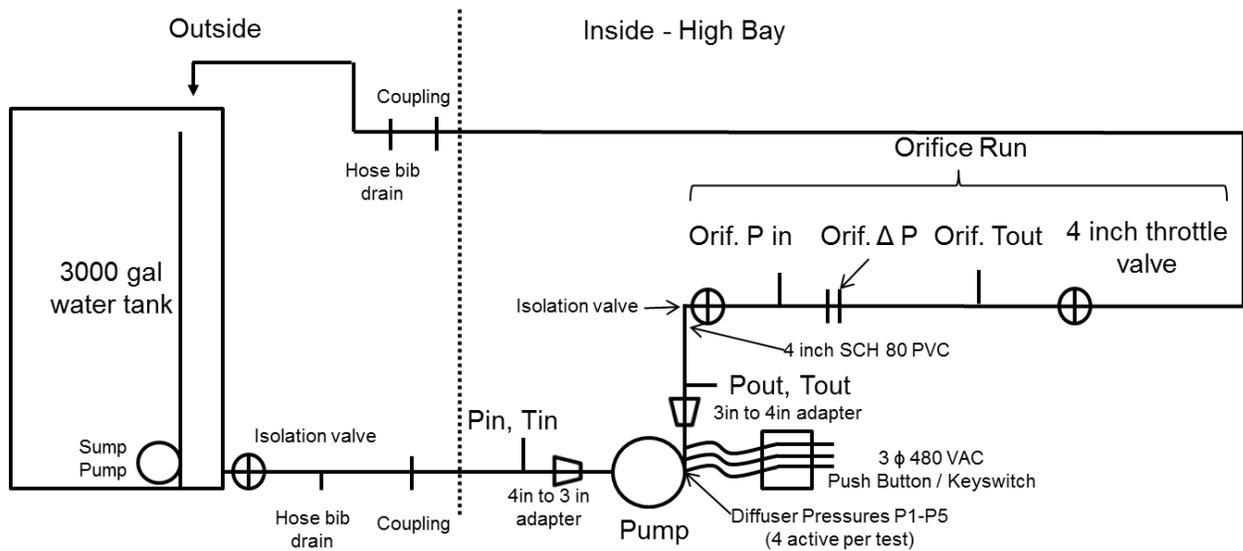


Figure 9. Water test loop schematic.



Figure 10. 3000 gallon water tank with discharge and return piping.

Mass flow measurement in the loop is via an ASME standard orifice run. Flow rate through the test loop is controlled by a 4 inch gate valve. The orifice run and flow control gate valve are shown in Fig. 11.



Figure 11. Test facility orifice run with throttle valve.

Pressure is measured in 8 locations throughout the facility. Temperature is measured via thermocouples in 4 locations in the test loop, while pressure and temperature data is recorded by means of a digital data acquisition (DAQ) system. Speed is measured by use of a strobe light using the motor cooling fan as a target.

To focus available resources on LSVD test article design and testing, the decision was made to identify and procure an existing off the shelf pump to provide the inlet conditions to the test diffusers. The test pump selection criteria consisted of finding a pump with a pre-existing vaned diffuser that could be easily modified and has a specific speed representative of that used in a rocket engine turbopump. The Pentair WhisperFloXFK-20 pool pump was selected for this task. A picture of the pump is shown in Fig. 12.



Figure 12. Pentair WhisperFloXFK-20 test pump.

The pump runs at a nominal specific speed, N_s of 1600 which is comparable to the N_s of several LRE oxidizer turbopumps. The pump uses a fixed speed 5HP 2 pole motor to provide power to the impeller and is equipped with a CVD assembly that is easily modified for purposes of the test effort.

IV. Test Results

Test data is taken at a range of flow coefficients corresponding to the Q/N range representative of 10:1 engine system throttling. Data is acquired in a double-pass procedure to control for any transient effects that could be present in the pump system.

Summary comparisons of the pump discharge head and flow characteristics for all diffuser configurations are presented in Fig. 13. For the lower range of flow coefficients (0.02 to 0.09) the LSVD with $\beta_3 = 9$, shaped leading edge configuration exhibits the highest performance. For the higher flow coefficient range (0.09 to 0.13) the CVD performs best. It is interesting to note that the $\beta_3 = 9$, shaped leading edge LSVD is only about 2% lower in head coefficient even at the highest flow coefficients recorded.

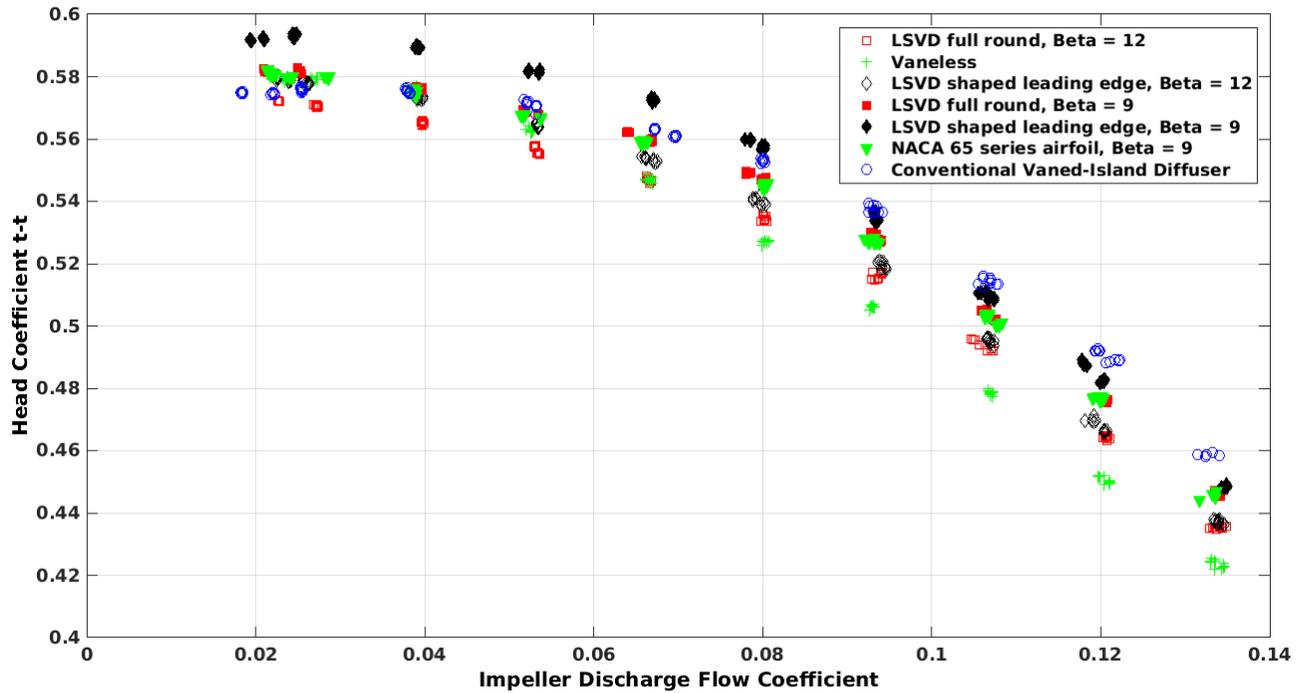


Figure 13. Flow and head coefficient comparison for all diffuser configurations.

Efficiency data, shown in Fig. 14 taken with the CVD and the $\beta_3 = 9$ diffusers display a consistent behavior with that seen in Fig. 14. The $\beta_3 = 9$, shaped leading edge LSVD is the best performer at low flow coefficients and the CVD the most efficient at the higher flow coefficients. Here again the performance differential between the CVD and the $\beta_3 = 9$, shaped leading edge LSVD is quite small.

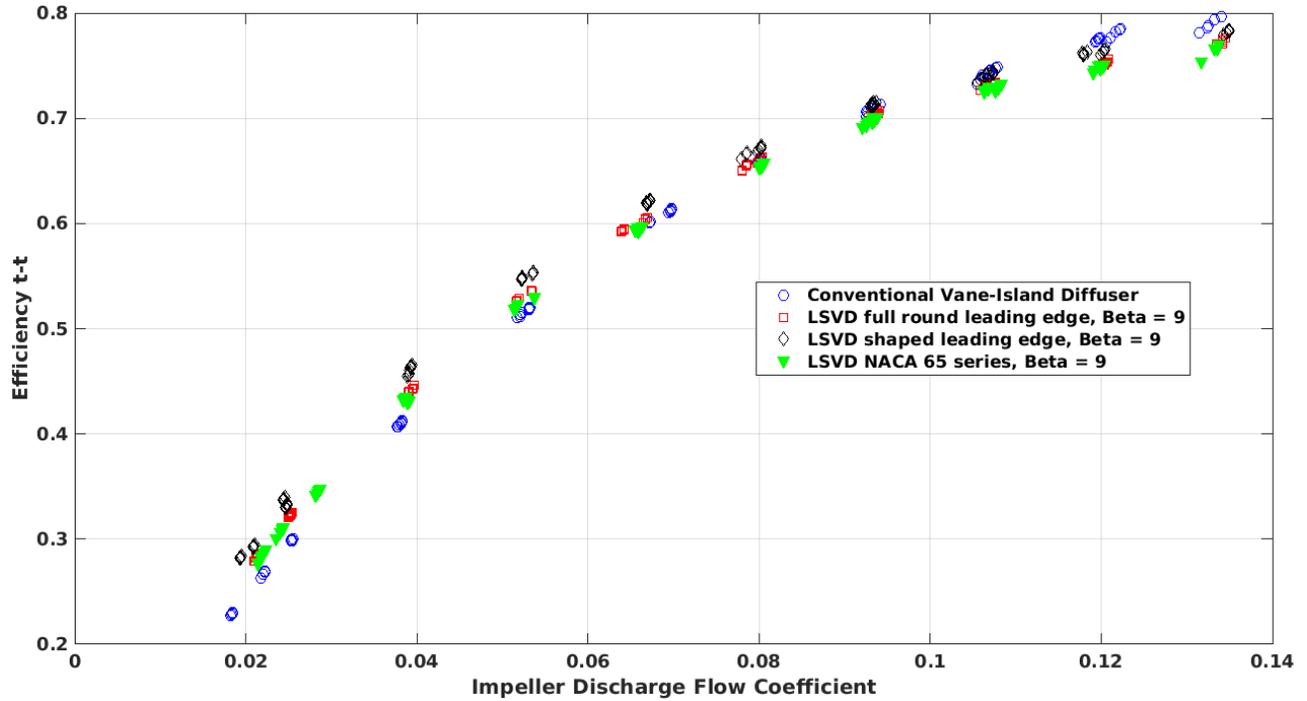


Figure 14. Efficiency comparison for the 9 degree LSVDs compared to the CVD.

A. Blade Angle Comparison

The data from the 2 full round leading edge LSVD configurations is plotted in Fig. 15. The $\beta_3 = 9$ displays better performance over the entire range of tested flow coefficients. This result is not surprising for the low flow coefficients where the incidence on the diffuser vanes is more positive. For the flow coefficient of 0.2 the incidence angle for the $\beta_3 = 9$ diffuser is 7.4 degrees while for the $\beta_3 = 12$ diffuser the incidence is 10.9 degrees. At the highest flow coefficient value of 0.135 the incidence angle for the $\beta_3 = 9$ diffuser is -2.1 degrees while for the $\beta_3 = 12$ diffuser the incidence is 1.34. At this higher flow coefficient it was expected that the $\beta_3 = 12$ with the lower absolute incidence angle would have displayed slightly better performance. It is possible that since the data is based on the pump discharge pressure, and that the difference in head coefficients between the 2 configurations is about 2% or less that the pump discharge collector is affecting the results.

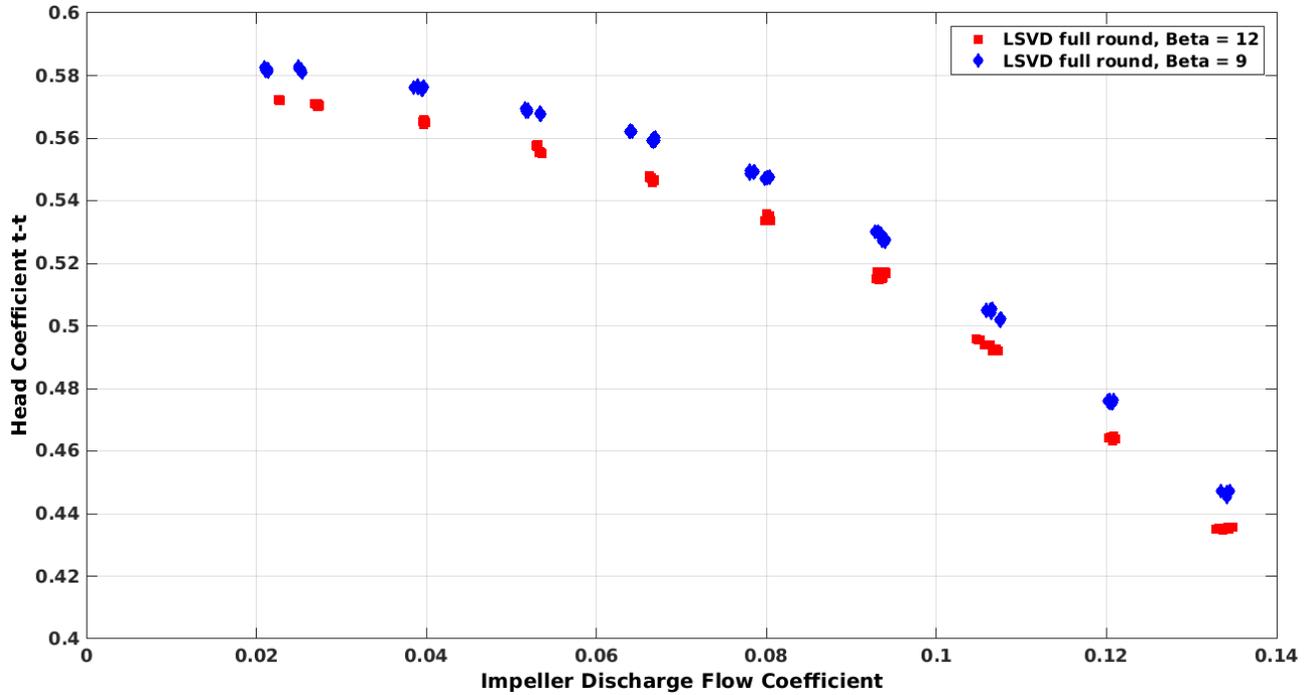


Figure 15. Effect of blade angle on pump performance for the LSVDs with the full round leading edge.

The data from the 2 shaped leading edge LSVD configurations is plotted in Fig. 16, with the data following the same overall trend as observed in Fig. 15 for the full round configuration diffusers. The incidence angle range is identical to that seen in Fig. 15. The data from Figs. 15 and 16 show that regardless of leading edge configuration, the $\beta_3 = 9$ diffusers perform better over the flow coefficients of interest.

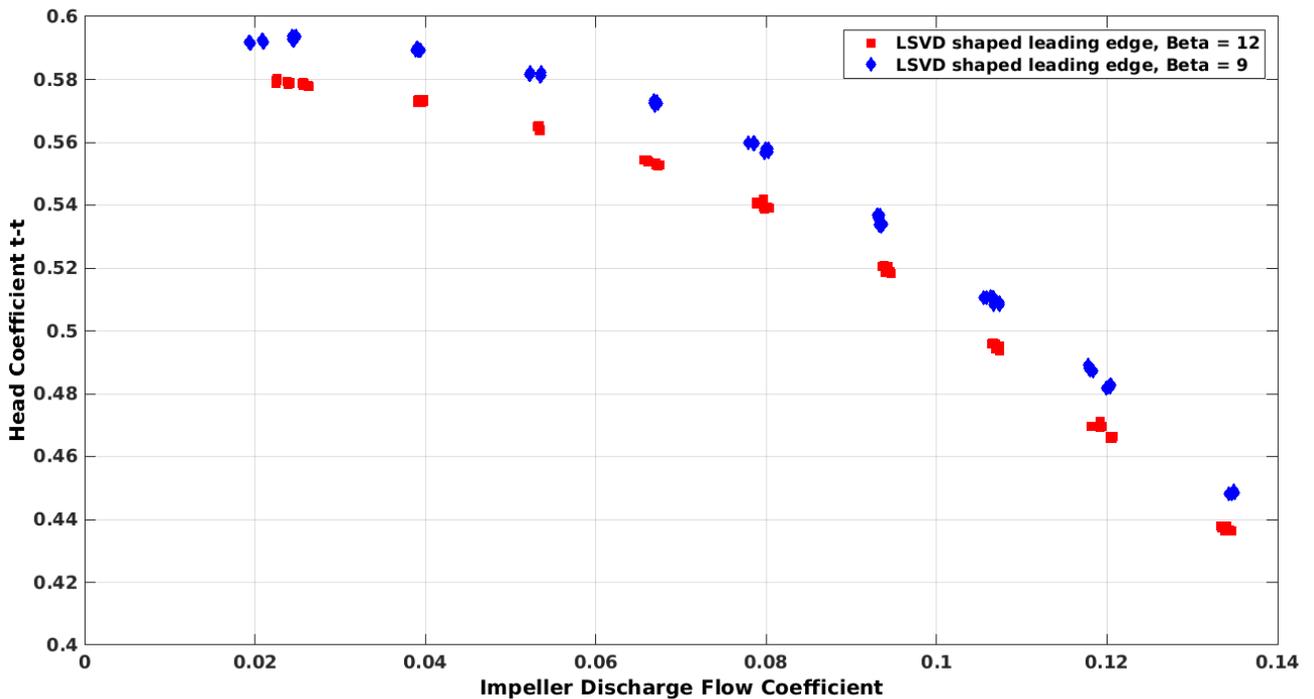


Figure 16. Effect of blade angle on pump performance for the LSVDs with the shaped leading edge.

B. Geometry Comparison

Comparison of the effect of geometry for the $\beta_3 = 9$ LSVDs is shown in Fig. 17. For the low flow coefficient range of 0.02 – 0.09, the shaped leading edge exhibits the best performance while all the LSVDs produce equivalent performance over the flow coefficient range of 0.1 to 0.135. No discernable benefit is seen between the full round configuration and the NACA 65 series airfoil configuration, indicating that in this case the performance of a flat plate LSVD is equivalent to that of an airfoil shaped vane.

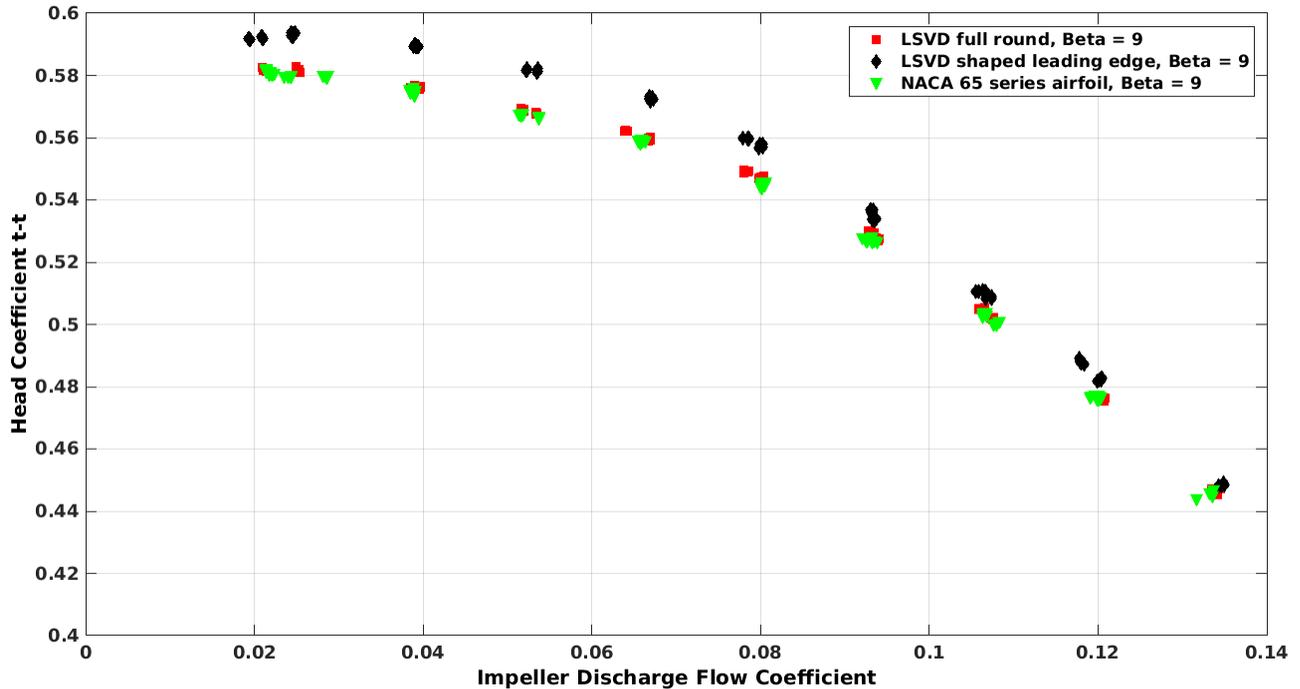


Figure 17. Effect of geometry for $\beta_3 = 9$ LSVDs.

V. Summary and Conclusions

The use of LSVDs in pump applications has been examined as an enabler for potentially increasing the pressure recovery of LRE turbopumps over a flow coefficient range anticipated for engine systems capable of a 10:1 throttle range. General design guidelines developed for centrifugal compressor LSVDs were identified and used together with a modified free-streamline analysis based on the work in Ref. 6 to design 4 LSVD test articles specifically for implementation in pumps. The LSVDs were designed at 2 different inlet angles and 2 different leading edge configurations to examine separately the effects of blade angle and geometry. The LSVD diffusers were all designed to attempt to improve head coefficient at the lower range of flow coefficients. A CVD and an additional LSVD based on geometry from a modified NACA 65 series airfoil were created and tested to provide additional comparison.

For both angle settings the shaped leading edge LSVD configuration provided the best overall pump performance based on pump head coefficient. These leading edge shapes were determined through use of the modified free-streamline theory. The airfoil shaped LSVD performed on a par with the flat plate full round leading edge configuration and displayed no performance advantage. The shaped leading edge configuration for the $\beta_3 = 9$ LSVD showed the best overall head coefficient performance across all diffusers tested for the low flow coefficient range while the CVD gave the best performance at the higher flow coefficients. The test data appears to indicate that the use of the modified free-streamline theory together with flat plate geometry is effective in designing an LSVD capable of increased head coefficient at low flow coefficient values as compared to a conventional vaned diffuser.

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