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HIGH-PERFORMANCE DIFFUSERS WITH STRONG IMPELLER - DIFFUSER COUPLING

Executive Summary

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By: David Japikse and Sharon E. Wight

PREPARED FOR: ADVANCED CENTRIFUGAL PUMP AND COMPRESSOR
CONSORTIUM FOR DIFFUSER & VOLUTE DESIGN, PHASE VI

Project Director: David Japikse
Project Manager: Sharon E. Wight

With contributions by David M. Karon, Andrew R. Provo,
Jamin J. Bitter, Mark R. Anderson, and Ali Mahallati

EXECUTIVE SUMMARY

The Diffuser Consortium team has completed the two-year Phase VI investigation with major new insights into the performance of diffusers for centrifugal compressors and pumps. These insights are likely to change the future development of many industrial machines.

Historically, the consortium research of the 1990s covered a wide range of stages, as indicated in the test history overview, Figure ES1. The historical work covered a very large range of operating conditions and many styles of diffusers. Improved rules for design resulted and have been widely used. The LSA (Low Solidity Airfoil diffuser, including the flat-plate LSA) have become very popular since that time. Phase VI began with posing many fundamental questions that needed answers and the recognition that select stages should receive increased instrumentation and careful retesting. Results for both the vaneless and vaned diffusers are very insightful. Work for Phase VI has been done with the High Ns stage.

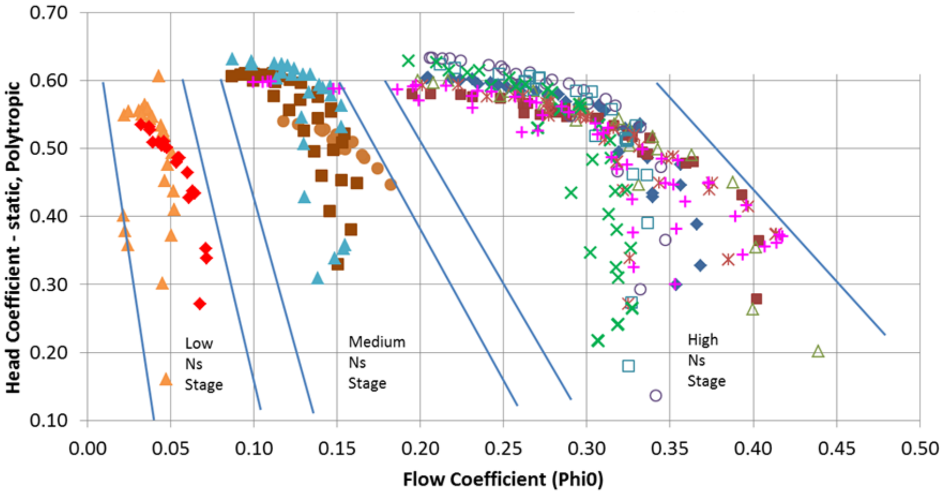
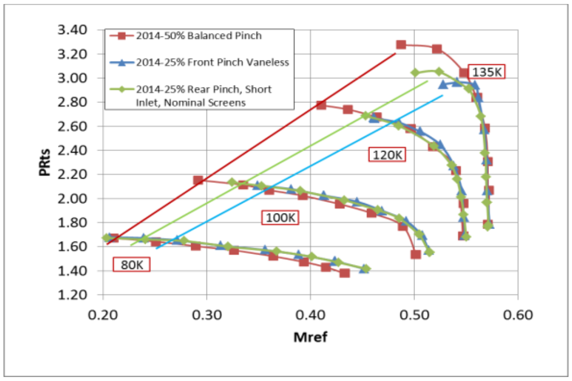


Figure ES1. Diffuser consortium investigations using *all* classes of diffusers and three different impellers and test rigs

Figures ES2 and ES3 show 2014 measured results for the three major vaneless diffusers, similar to their 1990s precedents. Superficially, they reveal very little different from common industrial know-how, but the details are very significant. First, an array of 13 pressure taps at diffuser inlet revealed a non-axisymmetric pressure profile circumferentially.



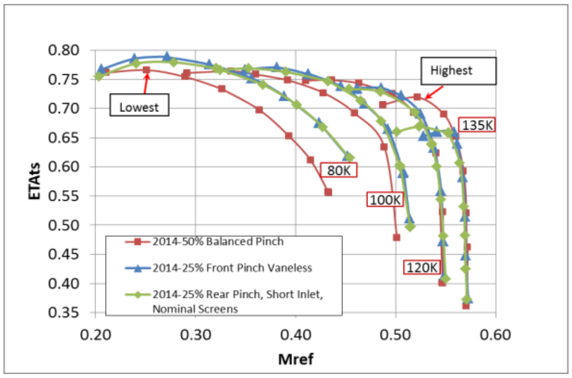


Figure ES2. Pressure rise, pinched vaneless Figure ES3. Efficiency, pinched vaneless

Strictly interpreted, the flow is nonsymmetric at the diffuser inlet, and periodicity does not rigorously apply, though it may still be a very useful approximation for some design work. The pressure variations along the diffuser walls are compared in Figures ES4 and ES5. The rear pinch vaneless diffuser shows a very smooth recovery trend, and the front pinch data show a similar variation, but the balanced pinch diffuser shows a kink in all normal operating points up to surge (Fig. ES4). For near-choke, the balanced pinch case (Fig. ES5) shows a strong reduction in pressure rise compared to the other two, even though it is with the same impeller at the same flow and speed. At this condition, there is no defect in efficiency (see Fig. ES3), and at the highest speed, it is even more pronounced (not shown here). The physics behind this comparison is not clear; there are real circumferential distortions, which are created at the diffuser inlet, and the coupling effects are strong. Ironically, at high speed, the best efficiency vaneless (50% pinch) has the worst internal flow state, and at lower speed, the best efficiency is the 25% front pinch case, even though the range is best for the balanced and then the rear pinch cases! These differences must be charged to irregular coupling of impeller and diffuser.

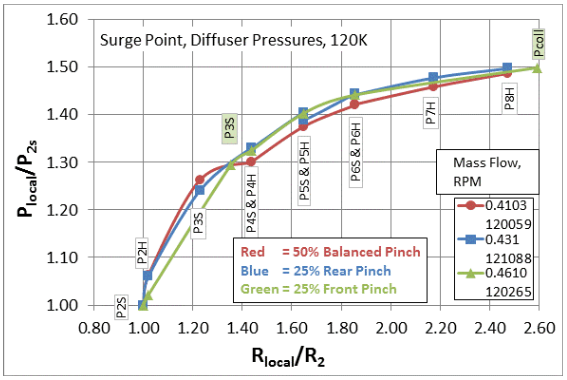


Figure ES4. Pressure traces near surge

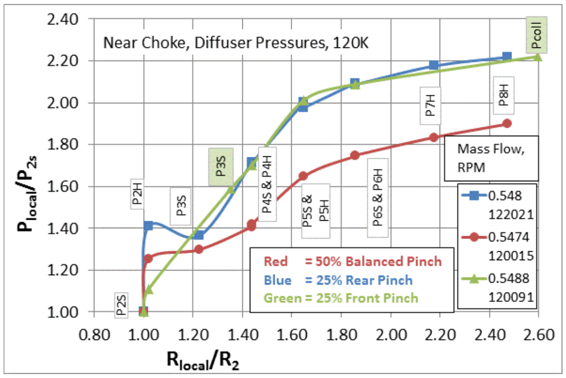
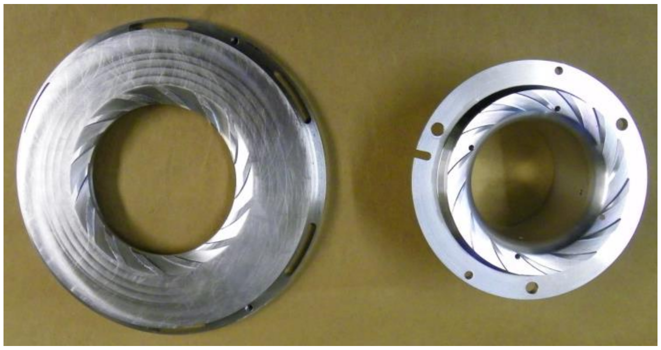


Figure ES5. Pressure traces near choke

A careful study of both CFD and L2F laser velocimetry measurements points to a cause and a solution. The development of the secondary flow in the impeller passage creates significant mixing losses and delivers a highly distorted flow field to the diffuser. Since the cause is the formation of a secondary flow with high vorticity, one can redirect this flow by using flow-wise grooves along the cover, as shown in one embodiment in Figure ES6.



Patent No. 8,926,276 B2
January 6, 2015

Figure ES6. The grooved cover – impeller cover is on the right,
which mates with the 25% pinch diffuser front cover shown on the left

The test results with this cover are interesting, as shown in Figure ES7. The surge line has been healed, and a much better map has been created. This work continues; more patents are pending.

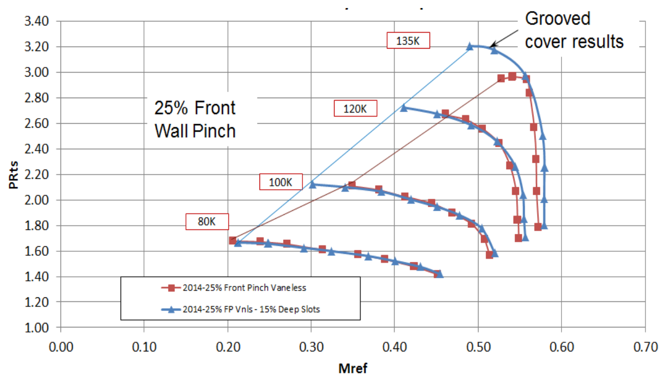


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Figure ES7. Measured performance map for the 25% front pinch vaneless diffuser

Similar progress has been made with the vaned diffusers. A set of LSA diffuser maps is given in Figures ES8 and ES9. The efficiencies achieved are very high levels for an impeller of this small size: 2.7 inch D2 or 69 mm (diameter about 2.5 times the width of a man's thumb). The levels are 81+% at low speed and 76% (ts, adiabatic) at high speed, which is transonic (M_2>1). The difference compared with the vaneless is interesting: the vaneless has better range for pr<2.5, but not above; low speed efficiencies are 2 points better for the LSA and 4 points better for the LSA at high speeds (transonic). The best channel diffuser is currently close behind this LSA by just one point; it is a double divergent diffuser. As the grooved cover is perfected, it will be interesting to see just how these differences stand in the future. The flat-plate diffuser is also excellent; it needs to be tested at higher solidity to confirm trends.

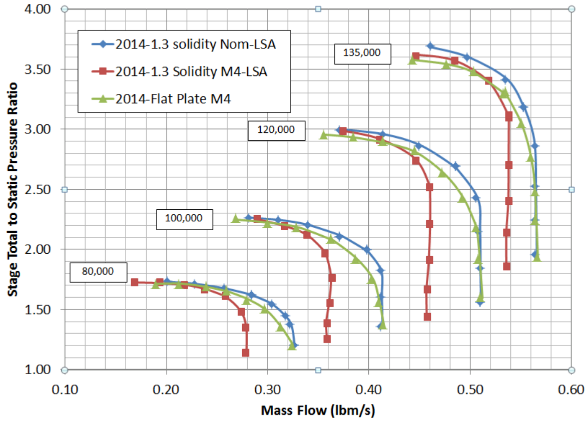

Figure ES8. Pressure rise for select LSAs

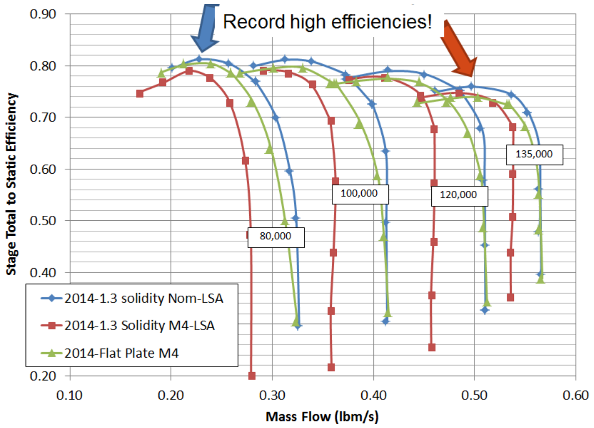

Figure ES9. Efficiency for several LSAs

The performance of the vaned diffusers is intriguing. The classical rules of diffuser layout have been revised based on many small details learned during the course of this work (see text). New limits on both LSA and channel diffuser design parameters have been set. Of greatest interest is the question of periodicity, which has been severely challenged through this work. Early p_2 studies raised alarm; a new cover with 36 p_2 taps was built, and the results are dramatic (see Figure ES10 below). Four different vaned diffusers, including LSA, flat-plate LSA, and channel diffuser types were tested with the 36 p_2 tap array. The impeller has 16 blades, whereas these diffusers had 14, 15, and 16 vanes depending on the design. All of the tests at all speeds and flows showed results similar to Figure ES10.

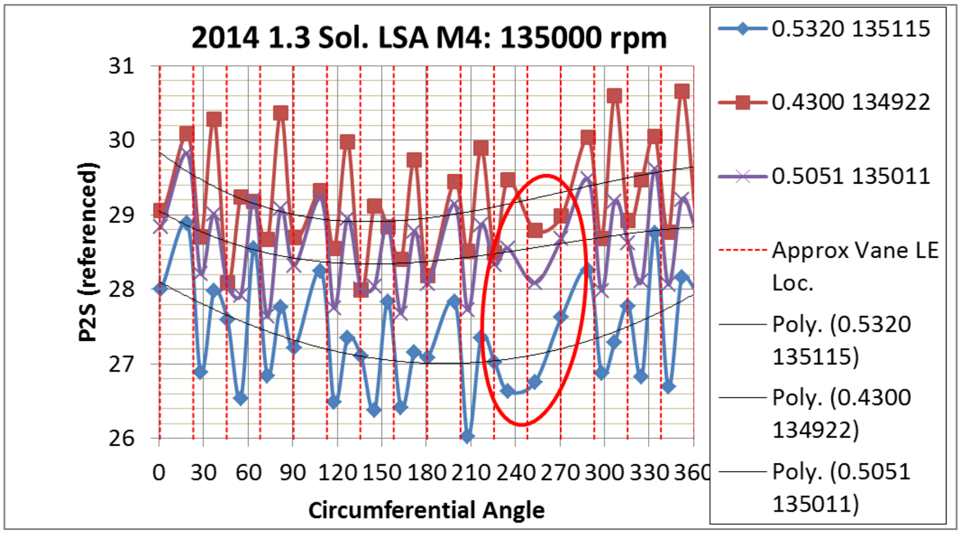

Figure ES 10. Typical example of diffuser entry static pressure measurements

Although all tested cases show the general characteristics of Figure ES10, the variances are interesting. The pseudo-cyclic mean value variation shown by black lines in Figure ES10 vary in form, with some cases showing one max and one min, whereas other cases have 2 or 3 each. The saw-tooth pressure pattern is, of course, simply the vane-to-vane pressure loading pattern from the diffuser vanes. But the saw-tooth is far from uniform; some passages show a strong max and a low minimum, whereas others have very weak ones. Hence, it is impossible for each vane to have the same incidence and equal flow per passage! The loading of each diffuser passage is not the same at diffuser inlet; hence, local flow turning is also different, giving different amounts of work input circumferentially and also giving diffuser vane incidence variations.

Of real interest is the area covered by the red ellipse. All of the dotted lines on the figure correspond to a diffuser vane location. There are 16 diffuser vanes, so this case matches the impeller vane count. In the elliptical zone, there is no saw-tooth maximum! In fact, there are only 15 such maxima! This pattern has been seen in other cases; sometimes, there are as many maxima as diffuser vanes, but many times there are not. It does not seem to vary with vane/blade count. The elliptical zone exists on other diffuser data sets, but not on all of them. Observing these patterns has led to new insights, which are the subject of a current provisional patent.

Work continues now with the grooved cover and vaned diffusers.

It is seen that much of the past diffuser design work has been based on weak or false paradigms of flow physics; indeed some of the design work has been notional at best. For example: *historically, we have all assumed, at some level, that the flow leaving an impeller, regardless of the number of blades, and then entering the diffuser, again regardless of the number of vanes, was essentially periodic and axisymmetric and completely and uniformly filled each diffuser passage, which is false*. Surely, there are also time-fluctuating characteristics, not yet studied here, that are also important, but even the quasi-steady patterns are not periodic. It is doubtful that any CFD is correctly modeling the 3D effects now evident.

New design charts for each class of diffuser, with recommendations for development, are included herein. It is now clear, at least for stages on the right-hand side and the middle of Figure ES1, that improved performance can still be eked out of many stages.