# THE DIFFUSER CONSORTIUM

## Phases I – VII

## +

## Phase I, II Stability Consortium

## Presented at: Friedrichshafen; Seoul; USA

## May – July, 2016

**David Japikse & Sharon E. Wight**

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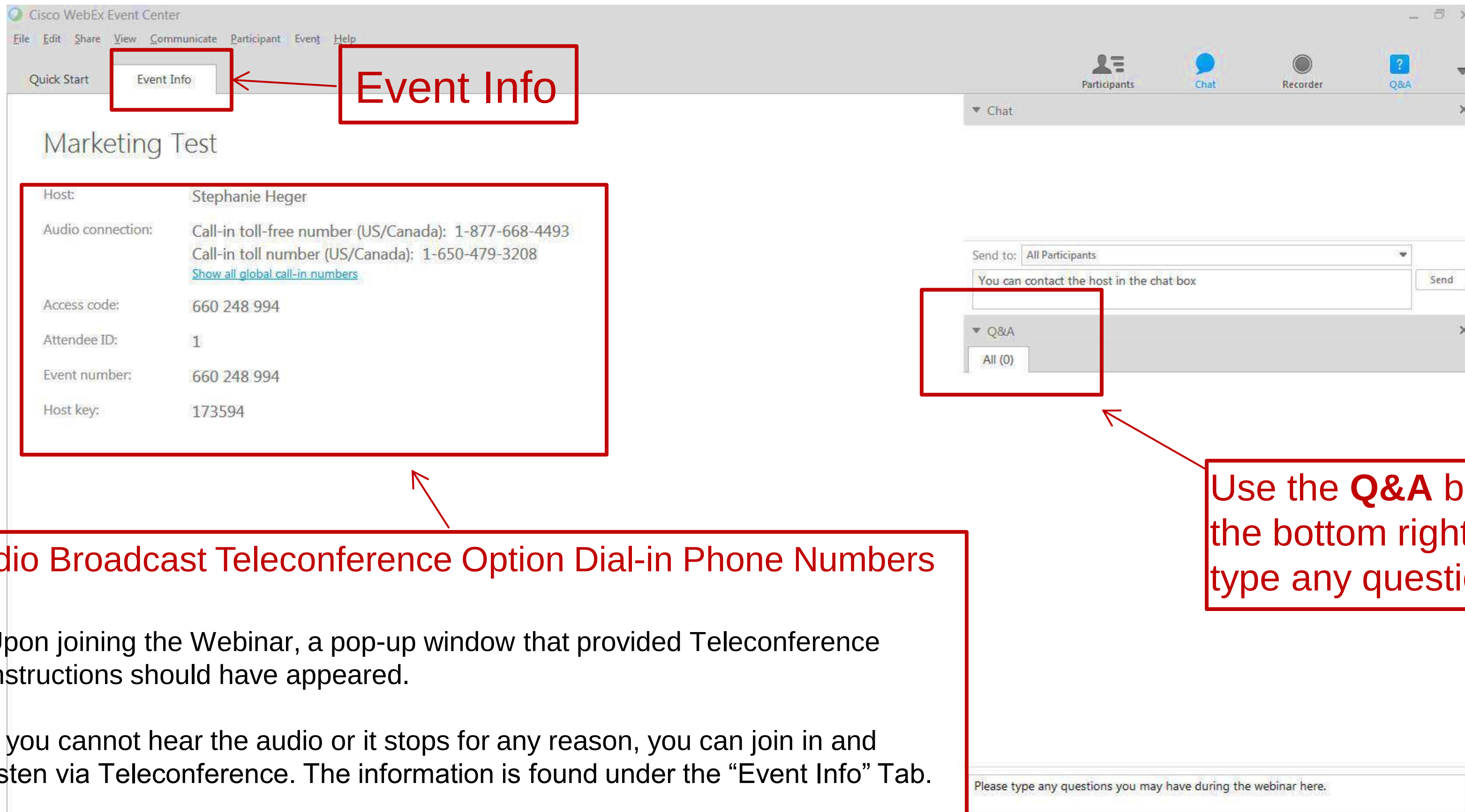


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# Historical Background
# Parts I - V

- Created Firm Foundation
- Popularization of LSA
- Re-Introduction of Flat-plate (FP) Diffuser
- Observed serious coupling

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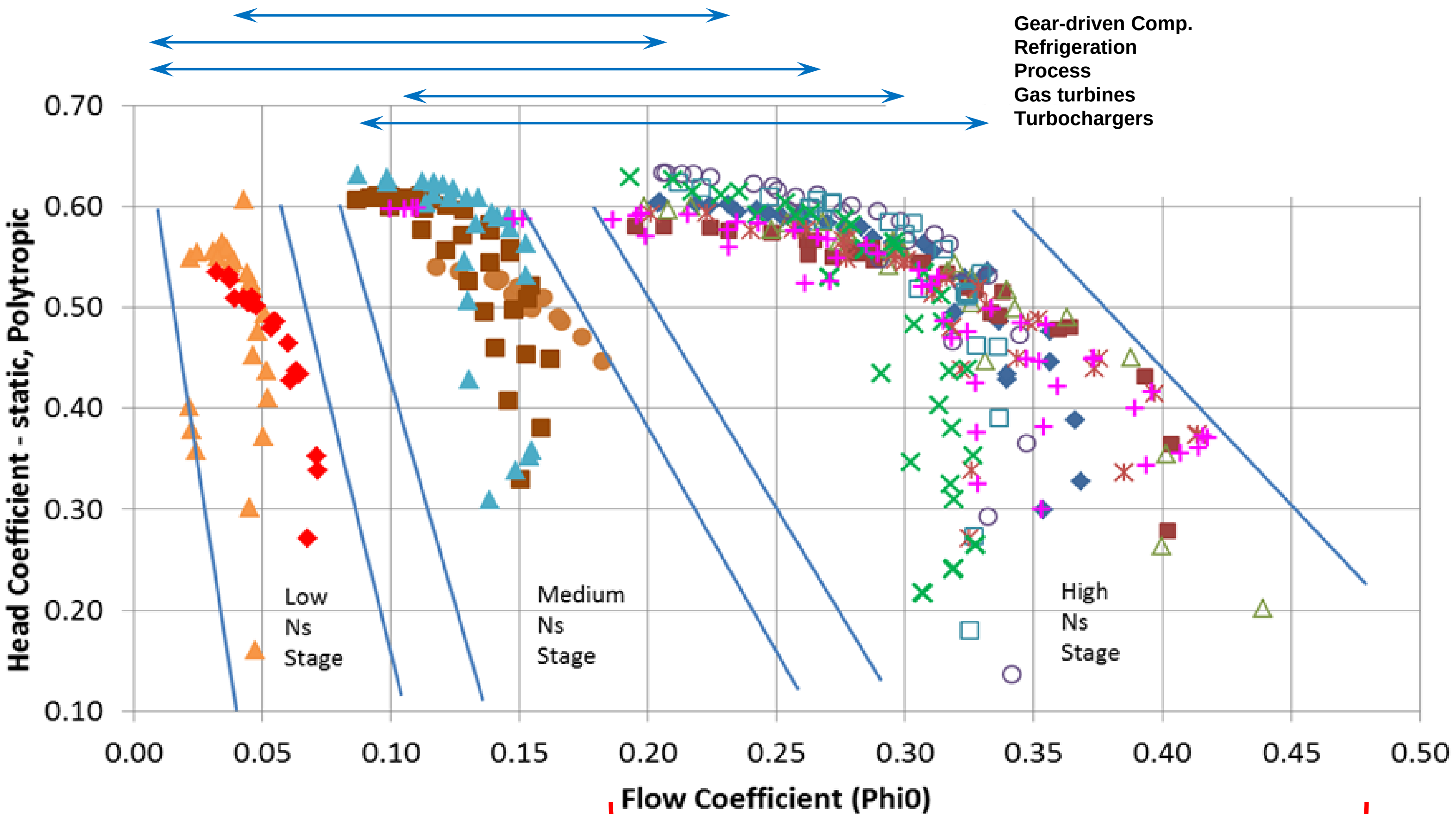
# Flow Regimes Covered by Diffuser Consortium




Phases IV – V; VII; also Stability Consortia

Phases I – III; VI, VII

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# Is 80% Cp Achievable?

- Yes if:
  - Flow is given adequate area ratio per streamtube
  - Given healthy inlet conditions
  - Given an optimum flow path and minimum skin friction
  - And it must be stable
- We have reached:
  - Cp = 0.75 for good configurations, and
  - Occasionally hit levels of 0.77 or 0.78, but not reliably
- How much area ratio?
  - Diffuser *effectiveness* of 0.85 to 0.92 is realistic based on diffuser research
  - $C_p$ of 0.8 is achievable with an AR of about 2.8 to 4.1, which is well within a practical range

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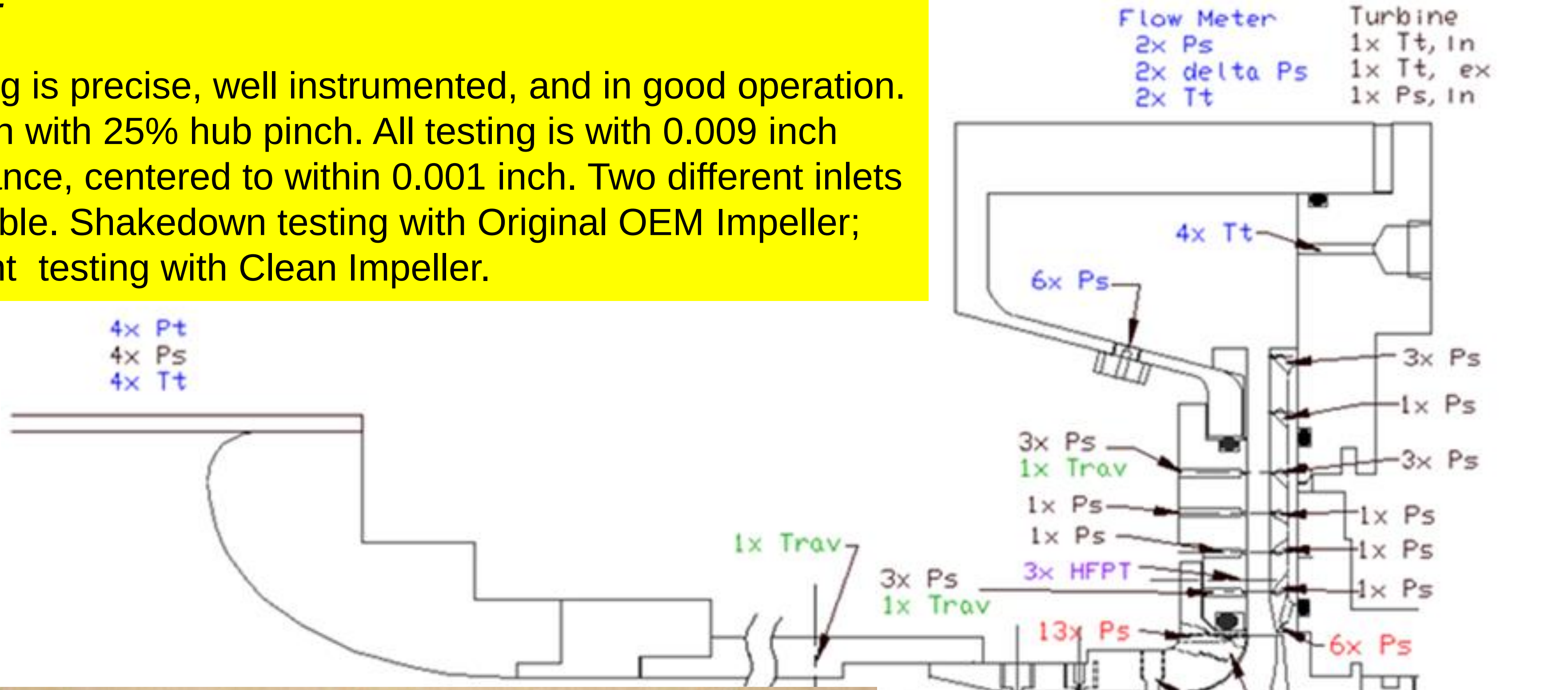
# Fully Instrumented 60 mm Test Stage (S1, etc.)

*Notes*:

Test rig is precise, well instrumented, and in good operation. Shown with 25% hub pinch. All testing is with 0.009 inch clearance, centered to within 0.001 inch. Two different inlets available. Shakedown testing with Original OEM Impeller; current testing with Clean Impeller.

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# L2F Data

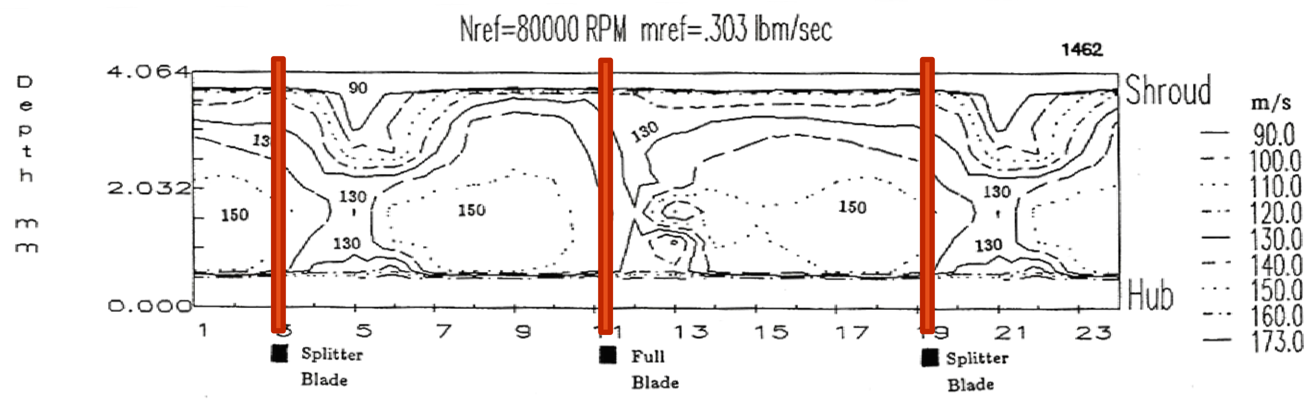


Figure 26. Distribution of Meridional Velocity at Impeller Exit ($r = 1.1r_2$)

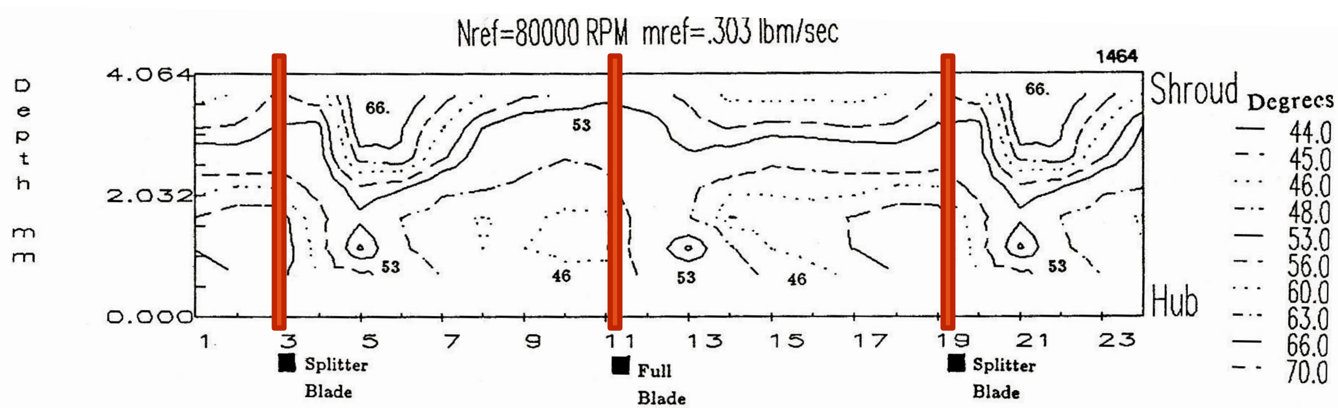


Figure 28. Distributions of Absolute Flow Angle ($r = 1.1r_2$)

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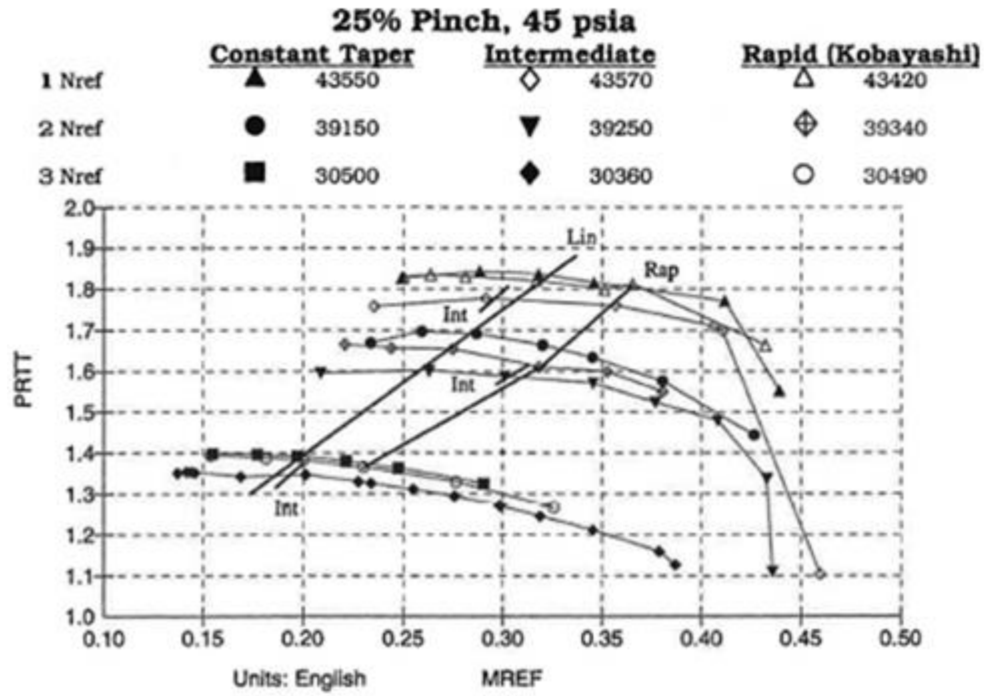
# Sample Vaneless Diffuser Tests, 120 mm Rig Low Ns Stage




The <u>linear taper vaneless diffuser</u> gave the best performance; rapid pinch diffusers stalled earlier.

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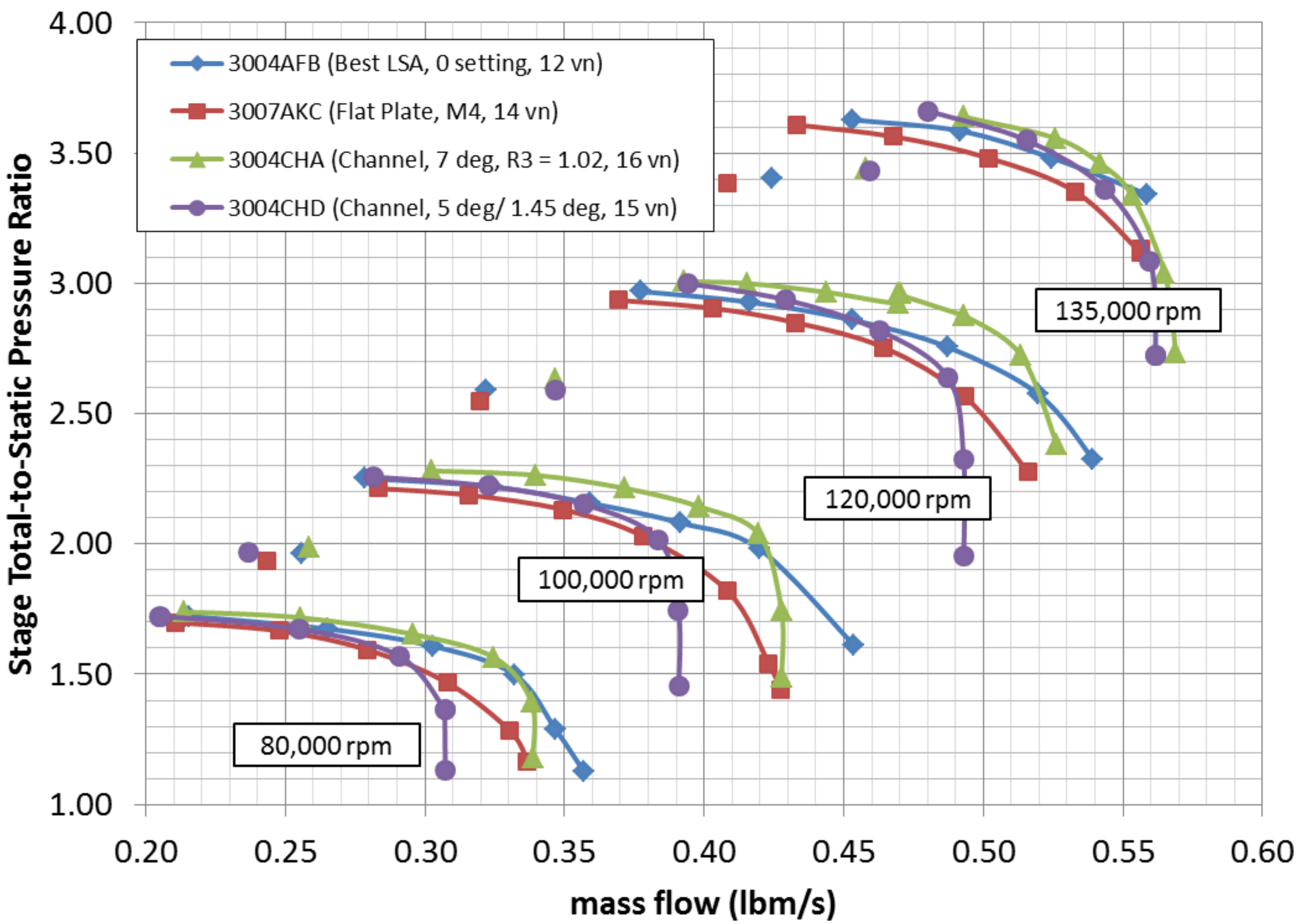
# LSA, Flat-plate, and Channel Comparison (1)

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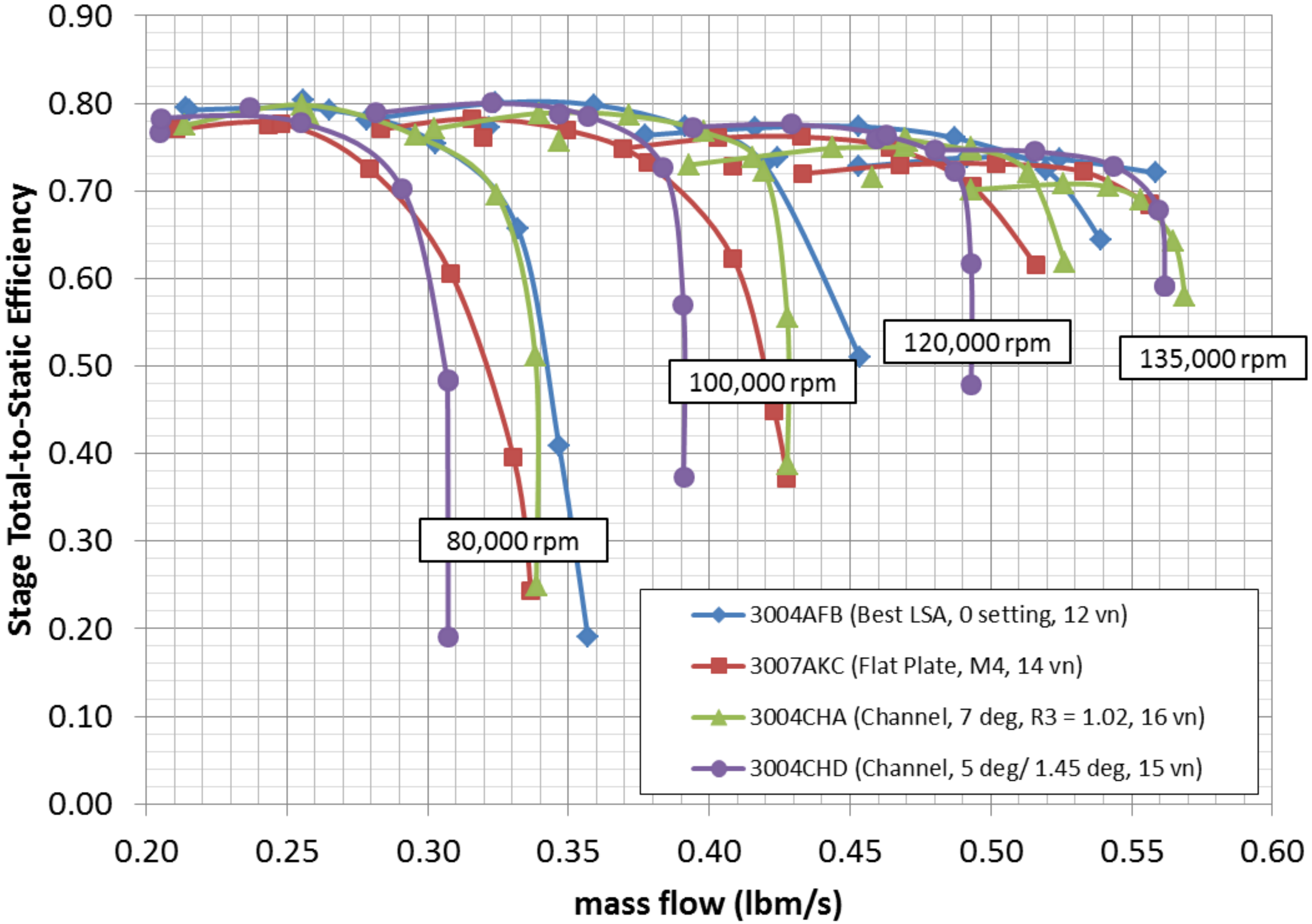
# LSA, Flat-plate, and Channel Comparison (2)

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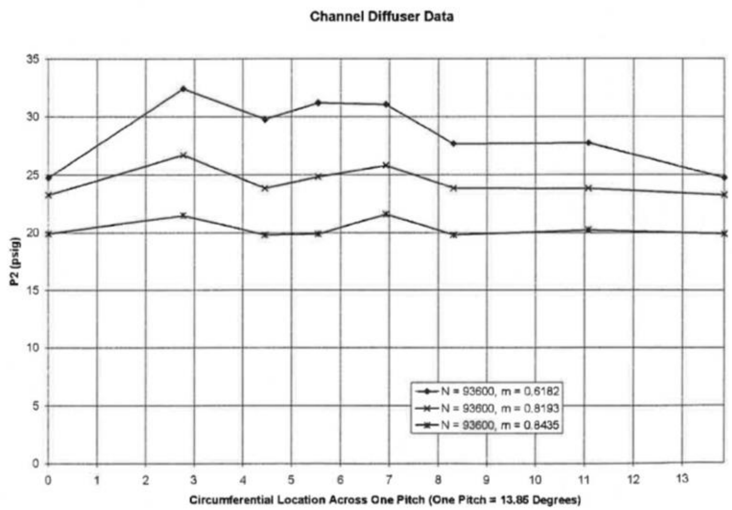
# 1997 P2 Study: Channel Diffuser

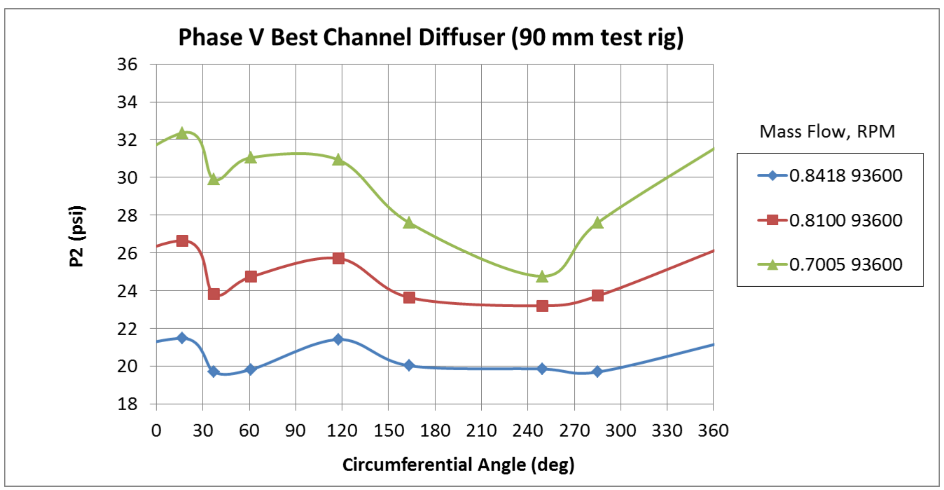



Phase V Test Data

Best channel diffuser

90 mm test rig

Replotted in 2014 vs. circumferential angle




1. Which came first?
2. Chicken or …
3. Lack sufficient redundant measurements

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# New Vaneless Diffuser Test Results (Parts VI & VII)

- Clarified pinch anomalies
- Observed strong distortions

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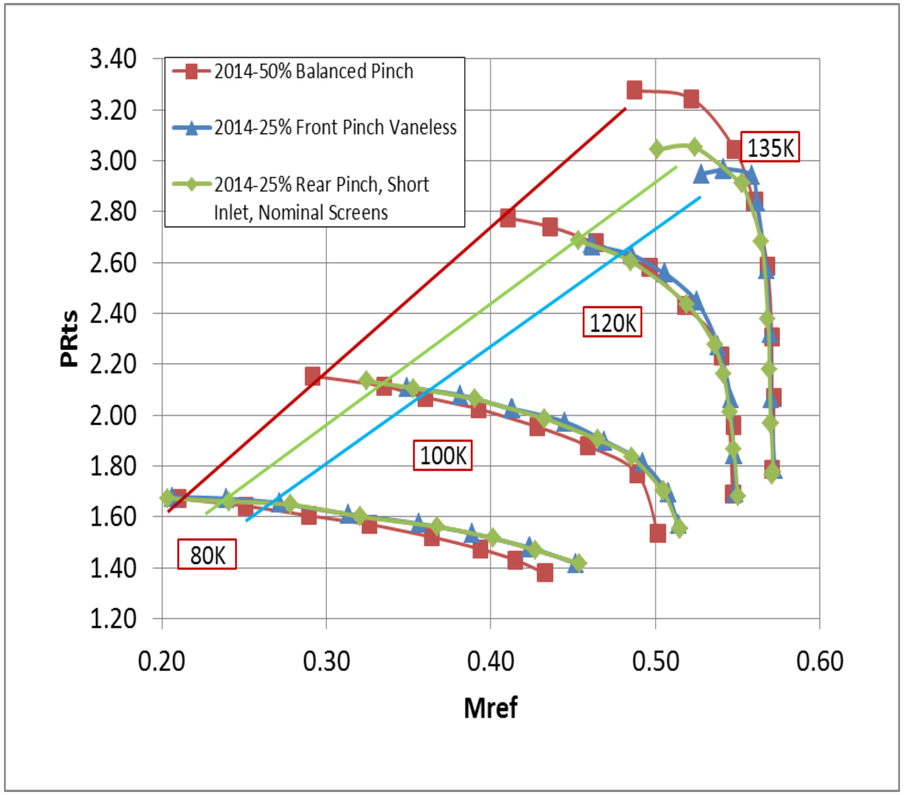
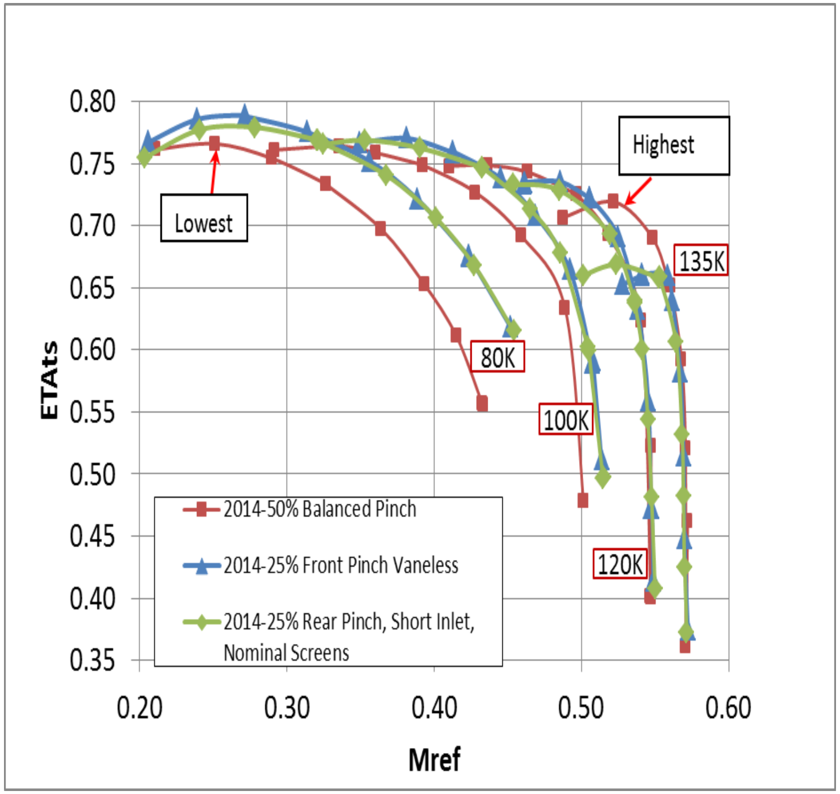
# Representative Vaneless Diffuser Results




Performance of three vaneless diffusers with various pinch schedules,
69 mm impeller; for impellers of 2x diameter, add 5 to 7 points of efficiency

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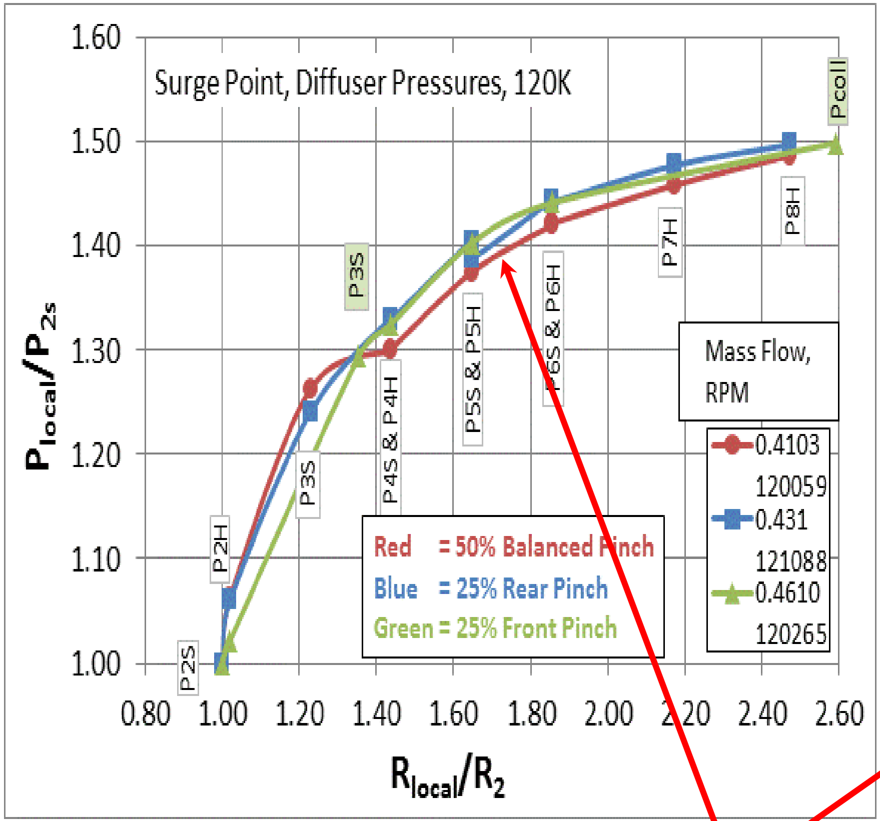
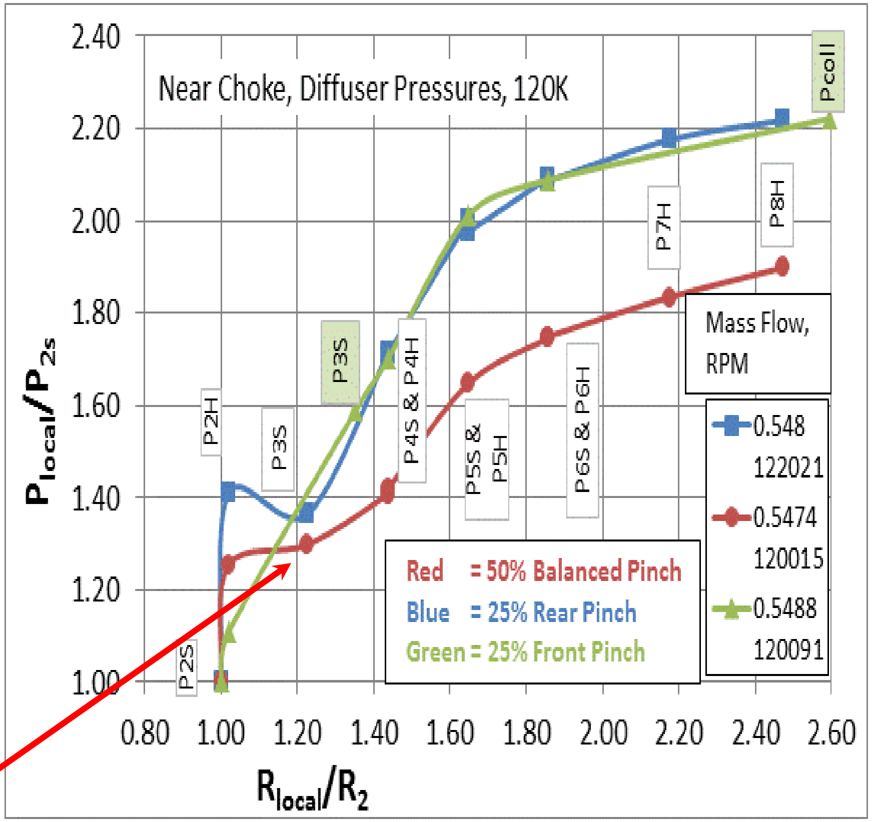
# Vaneless Diffuser Pressure Rise




50% pinch diffuser shows clear penalties, in spite of some good overall characteristics

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# 25% Rear Pinch Vaneless Diffuser

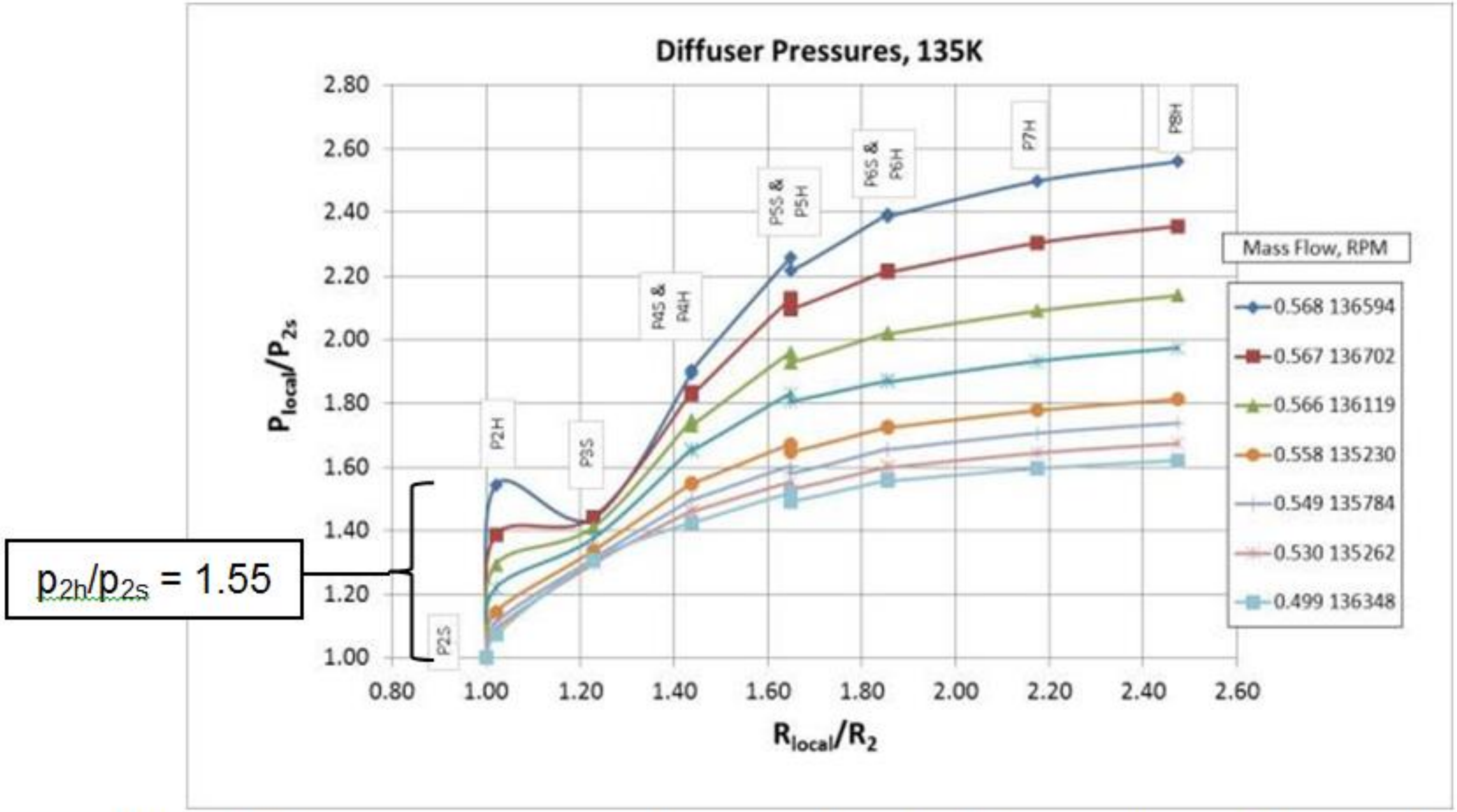


Figure 28a. Static pressure rise along each side of a vaneless diffuser; the pressures are nearly the same on each side except near the inlet, where gradients may be found across the impeller exit / diffuser inlet of 55% of the impeller static pressure rise

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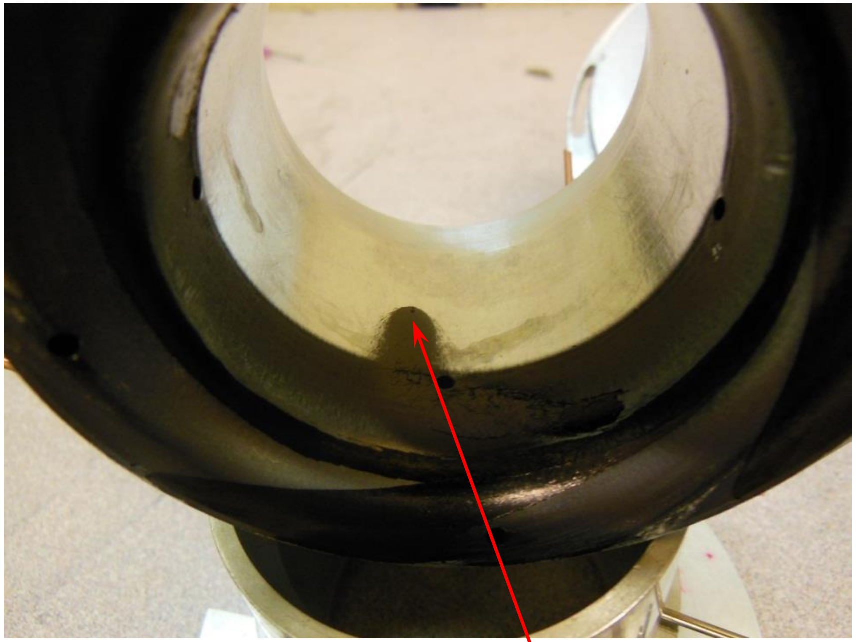
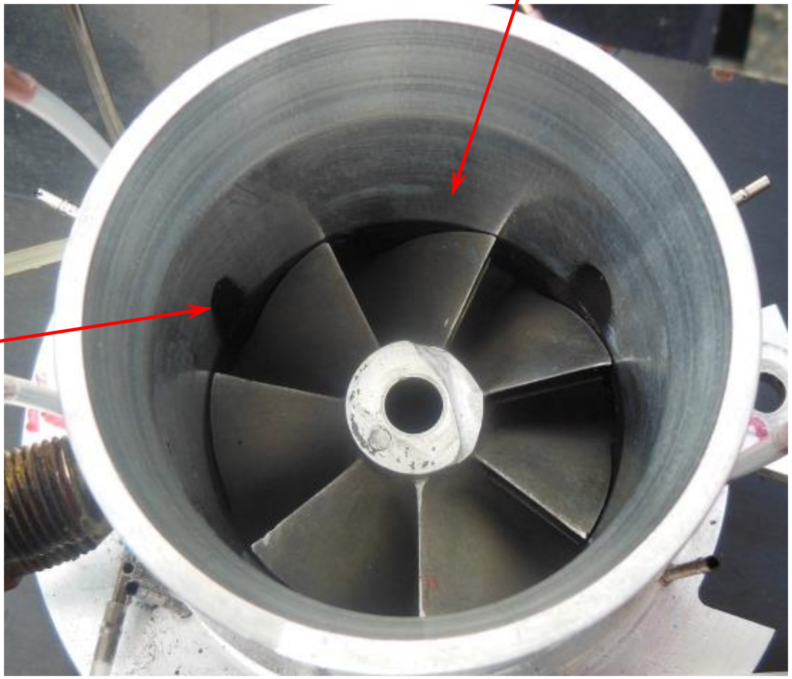
# Flow Visualization: 25% Rear Pinch, Near Surge 100 krpm



Flow visualization shows cover tip leakage in full backflow, but not into the inlet



Shroud inlet flow goes straight into the impeller

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# New Vaned Diffuser Test Results (Parts VI & VII)

- Repeats
- Improvements
- Core Insights
- Inventions

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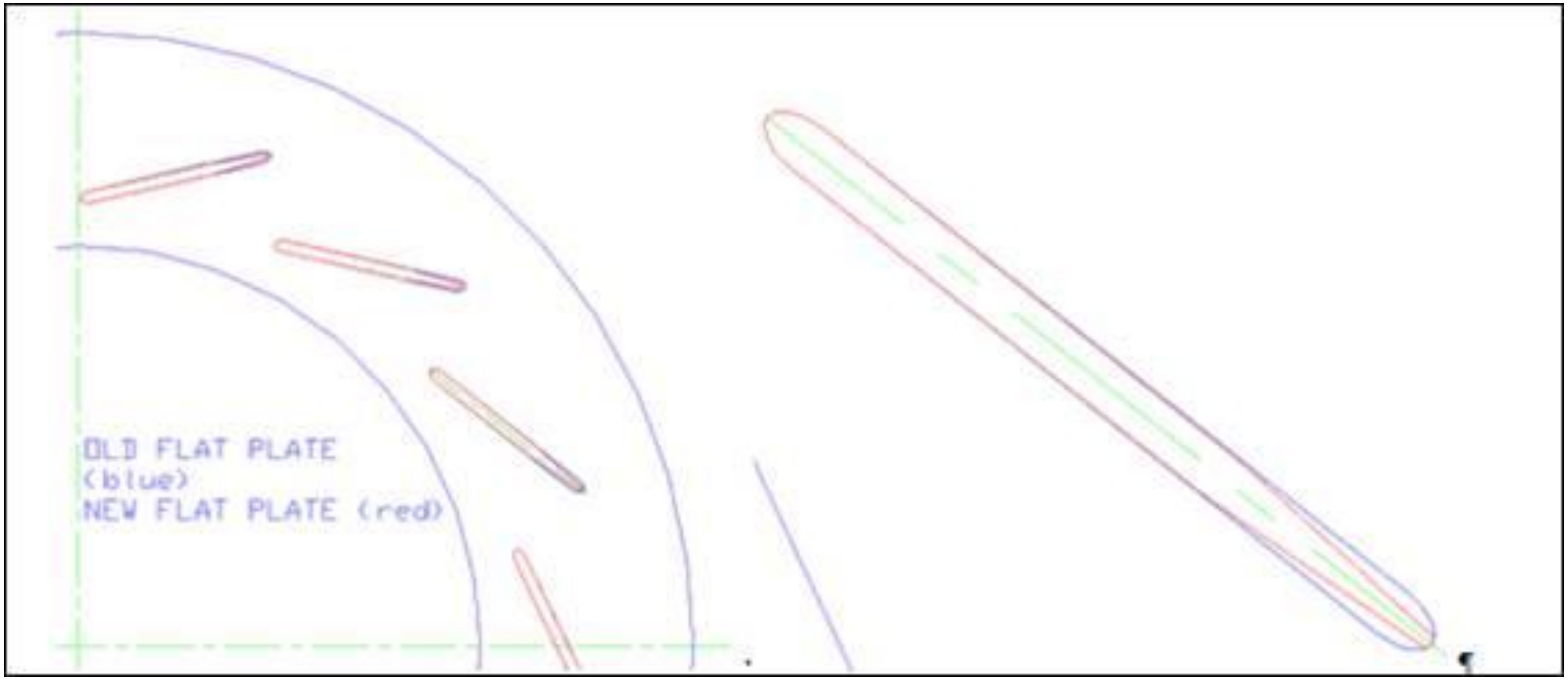
# Flat-plate Overlay

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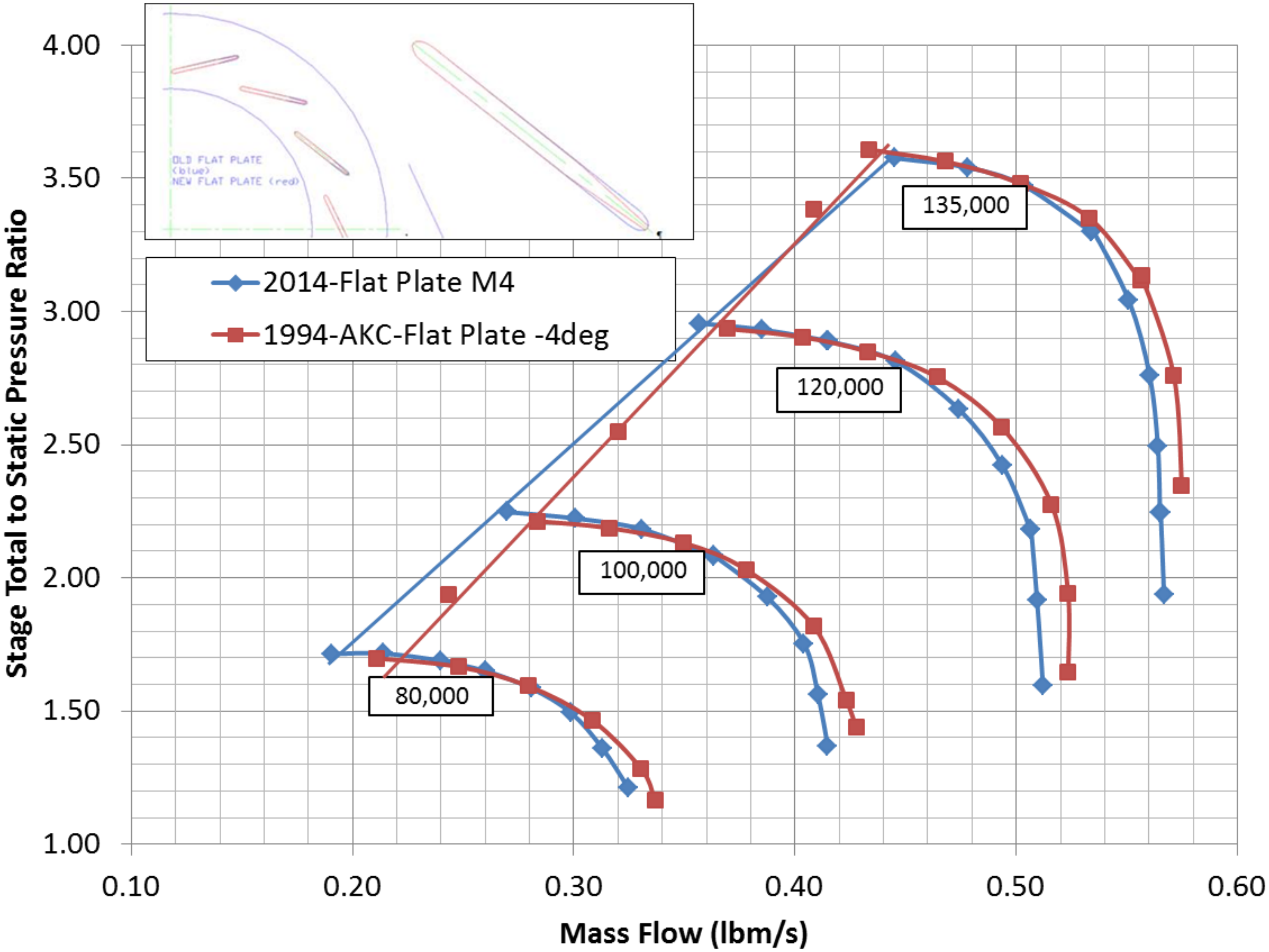
# Flat-plate Diffuser, 2014 & 1990s (1)

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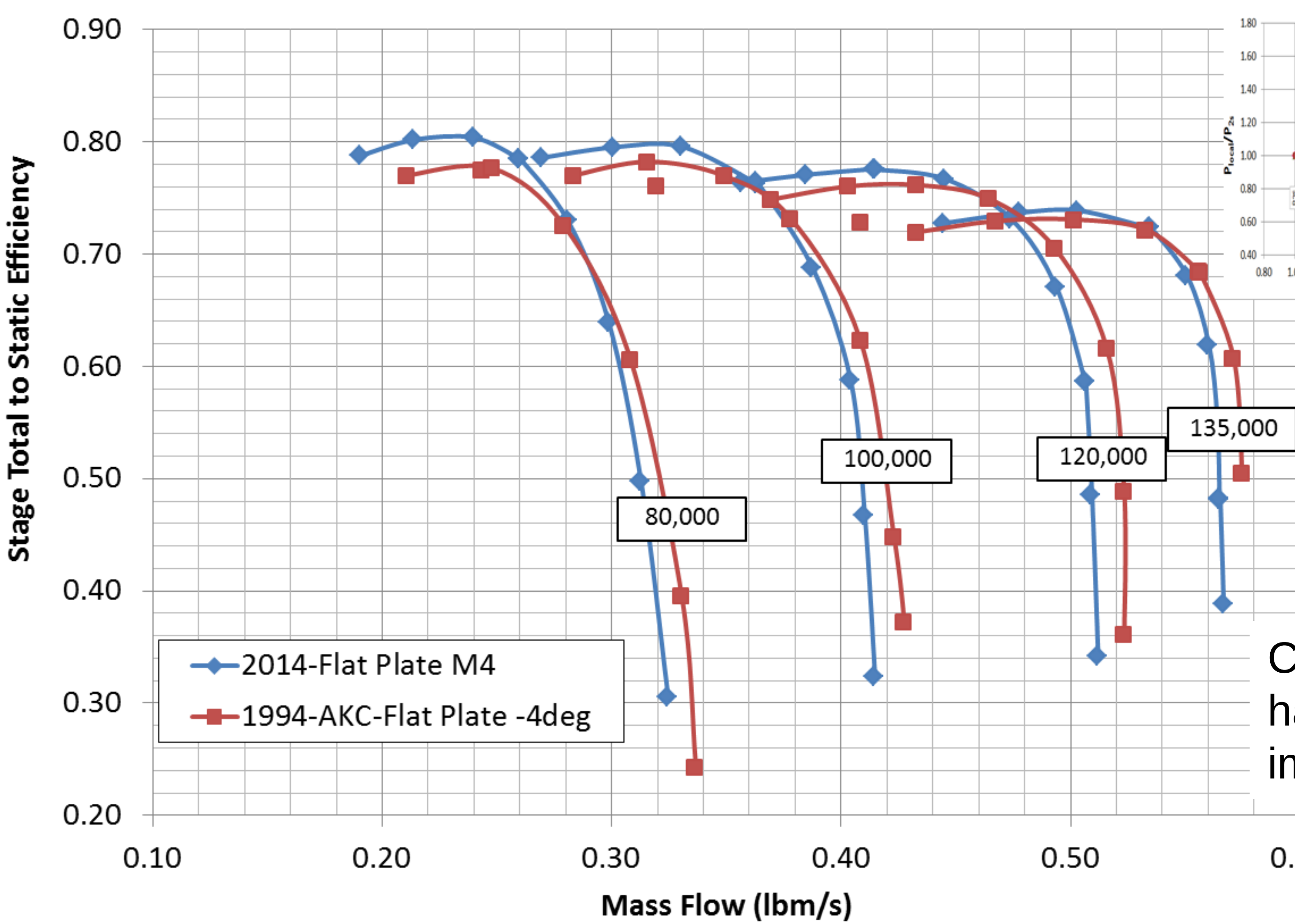
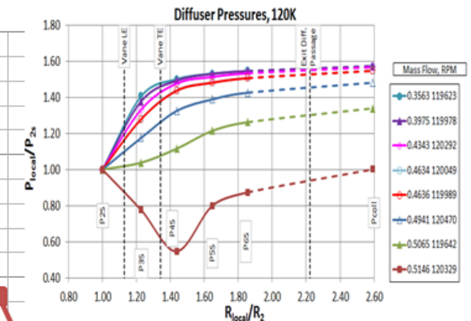
# Flat-plate Diffuser, 2014 & 1990s (2)




Clamping may have been improved!

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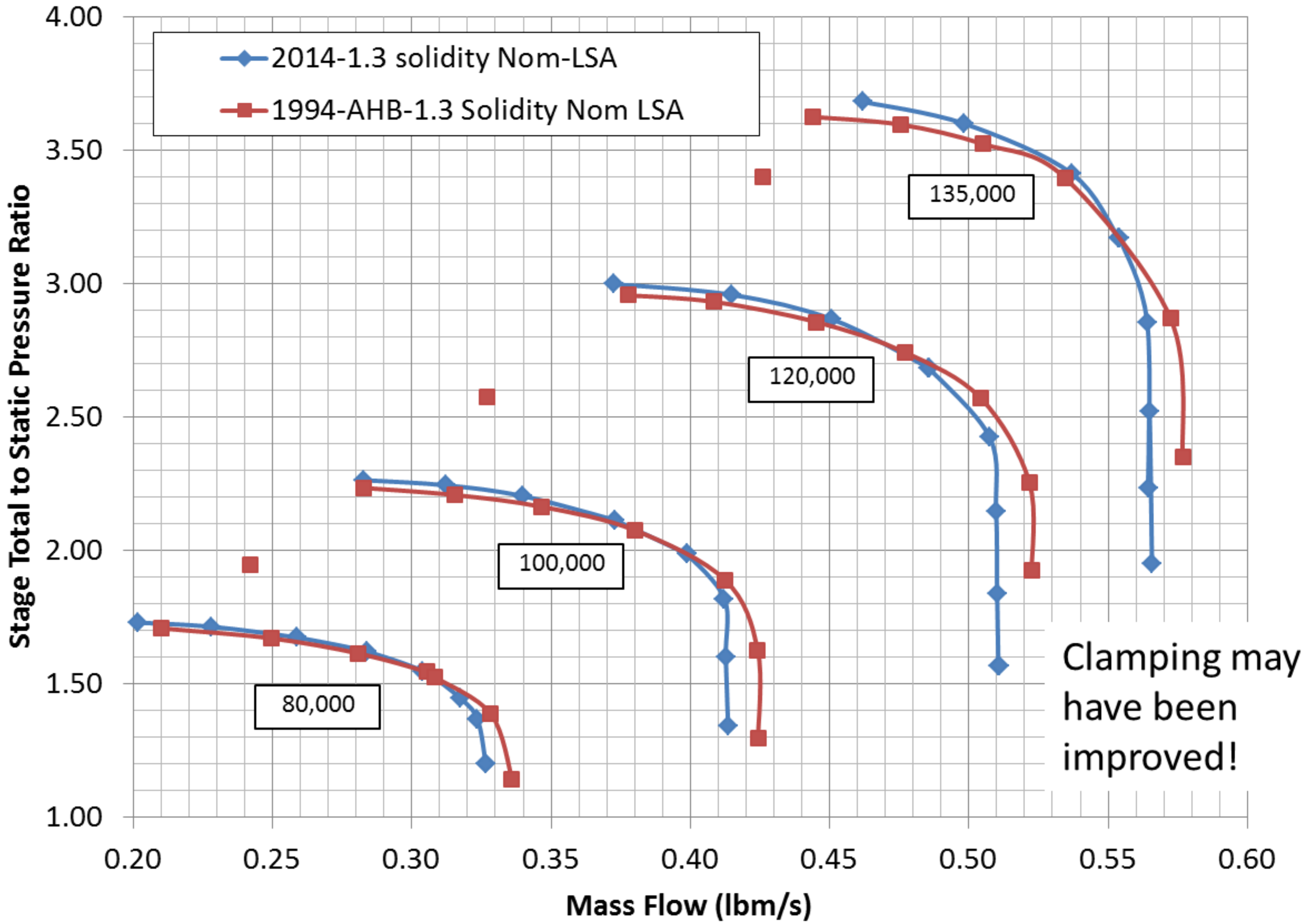
# Nom. LSA Diffuser, 2014 & 1990s (1)




Clamping may have been improved!

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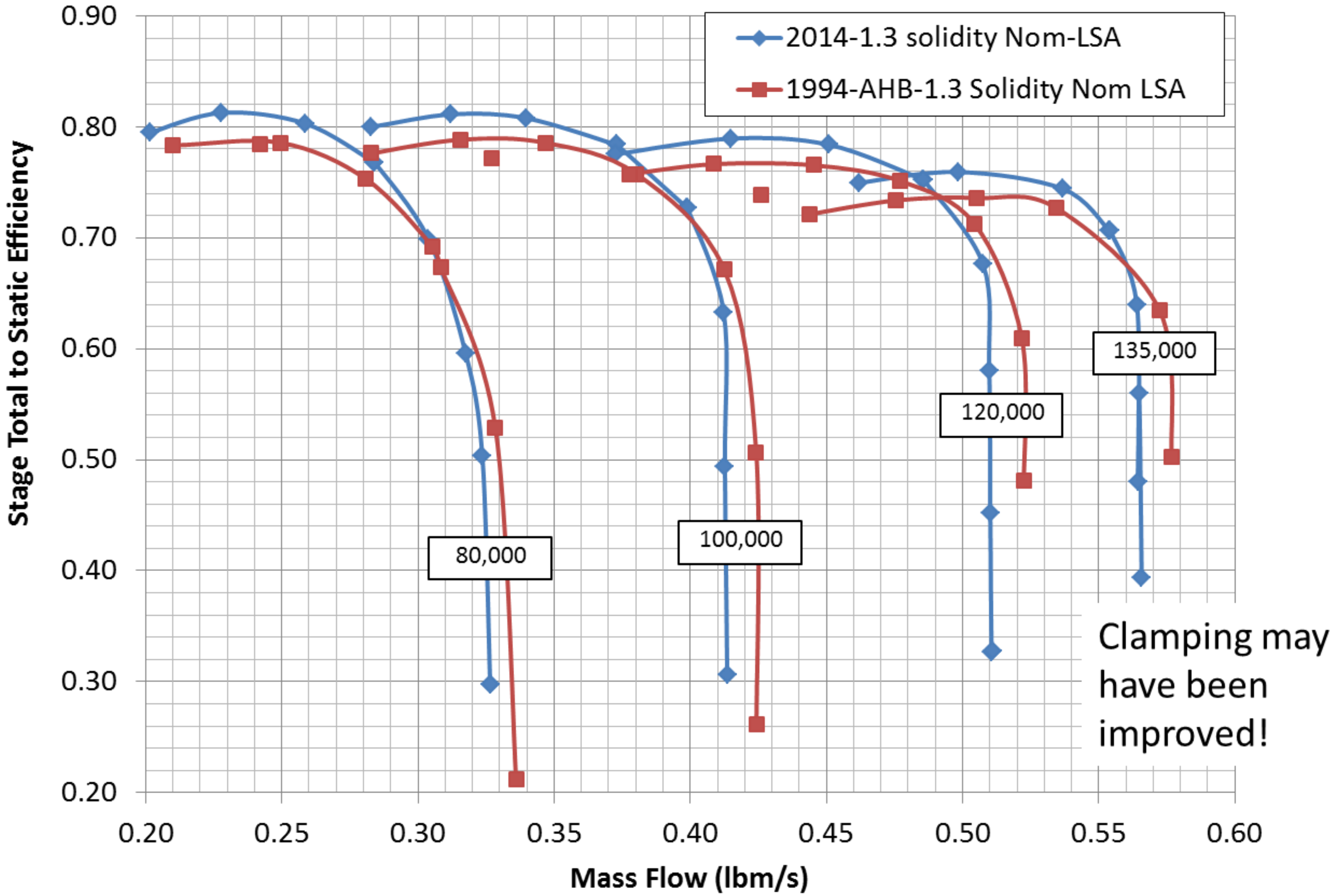
# Nom. LSA Diffuser, 2014 & 1990s (2)

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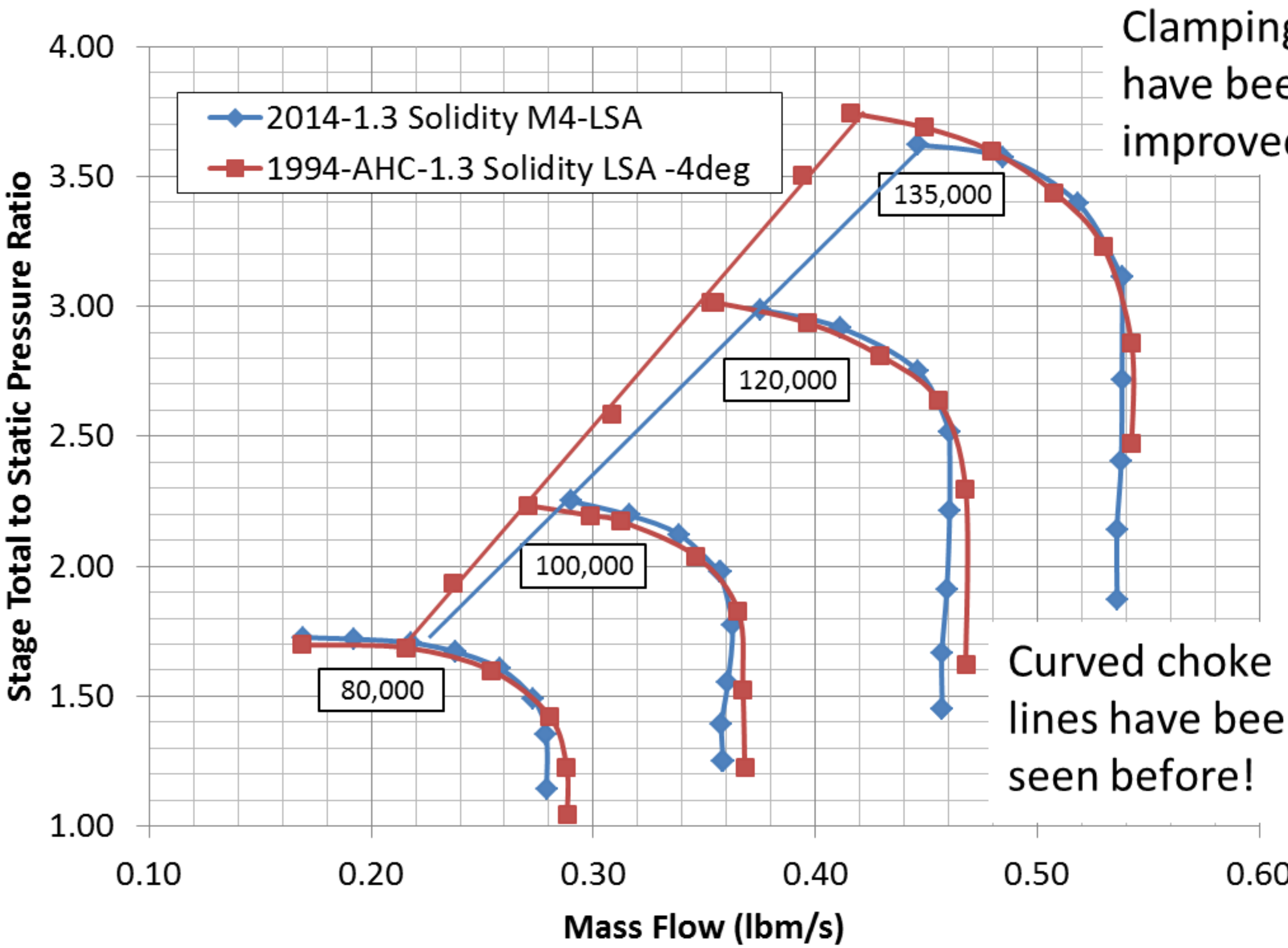
# M4 LSA Diffuser, 2014 & 1990s (1)




Clamping may have been improved!

Curved choke lines have been seen before!

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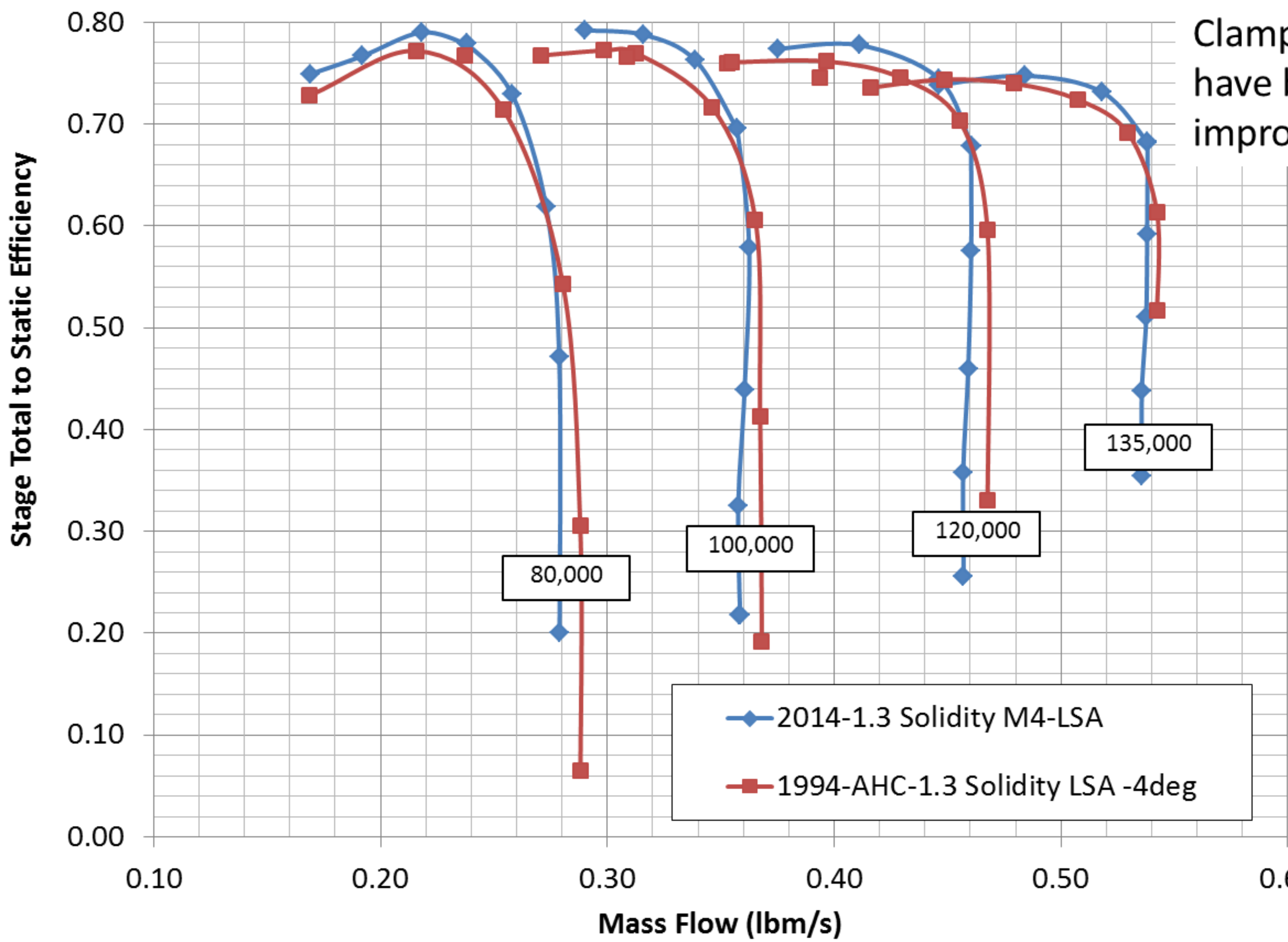
# M4 LSA Diffuser, 2014 & 1990s (2)




Clamping may have been improved!

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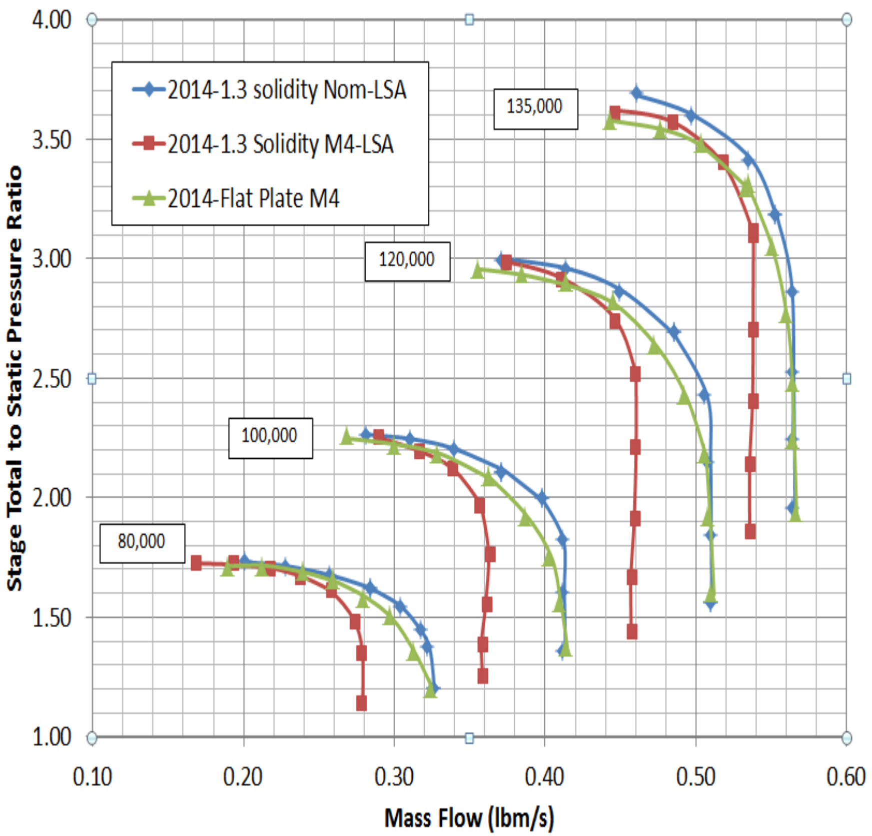
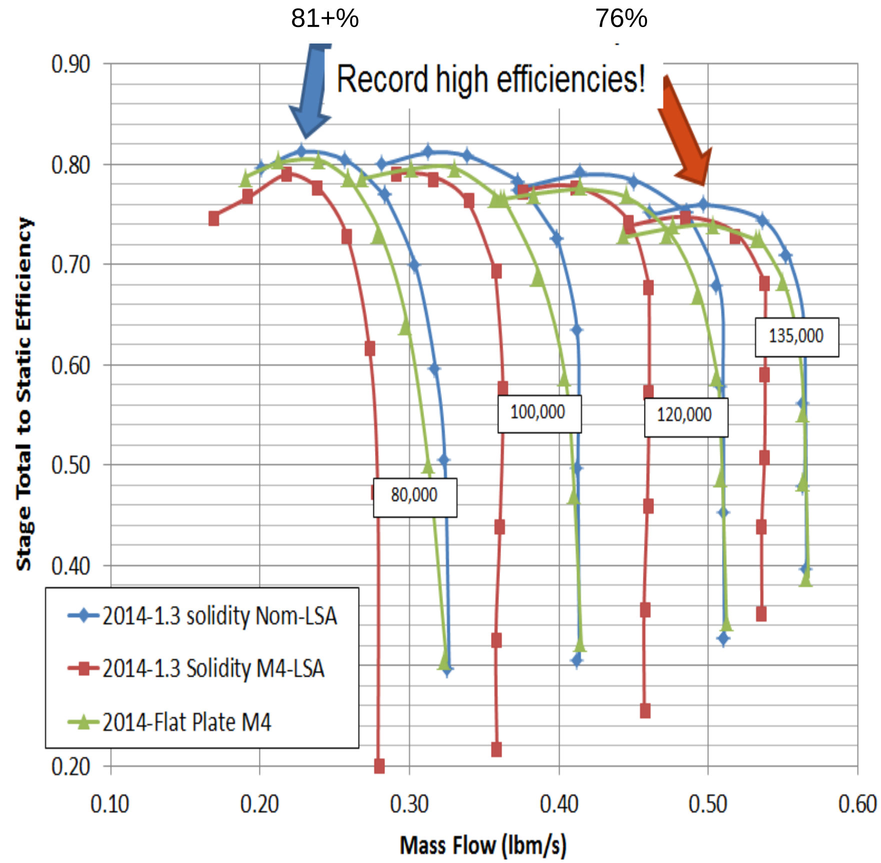
# Status: Several LSA and Flat-plate LSA Diffusers




Example performance of three diffusers; add one point of efficiency for a nominal inlet; plus for 2x impeller diameters, add 5 to 7 points of efficiency

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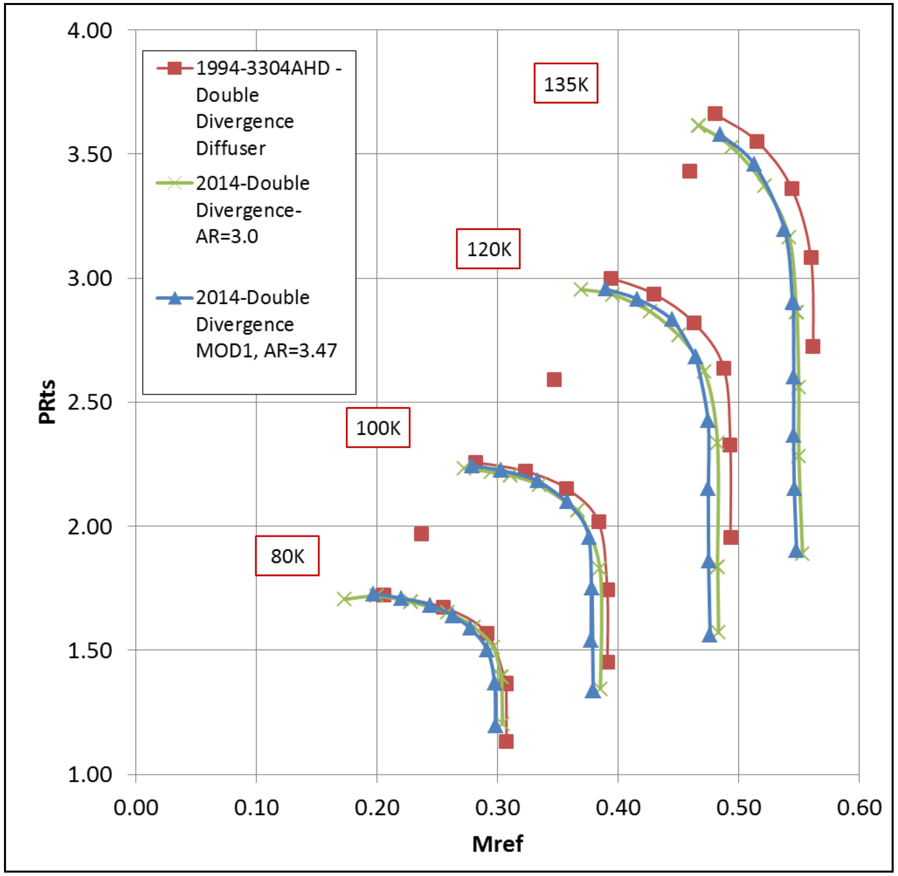
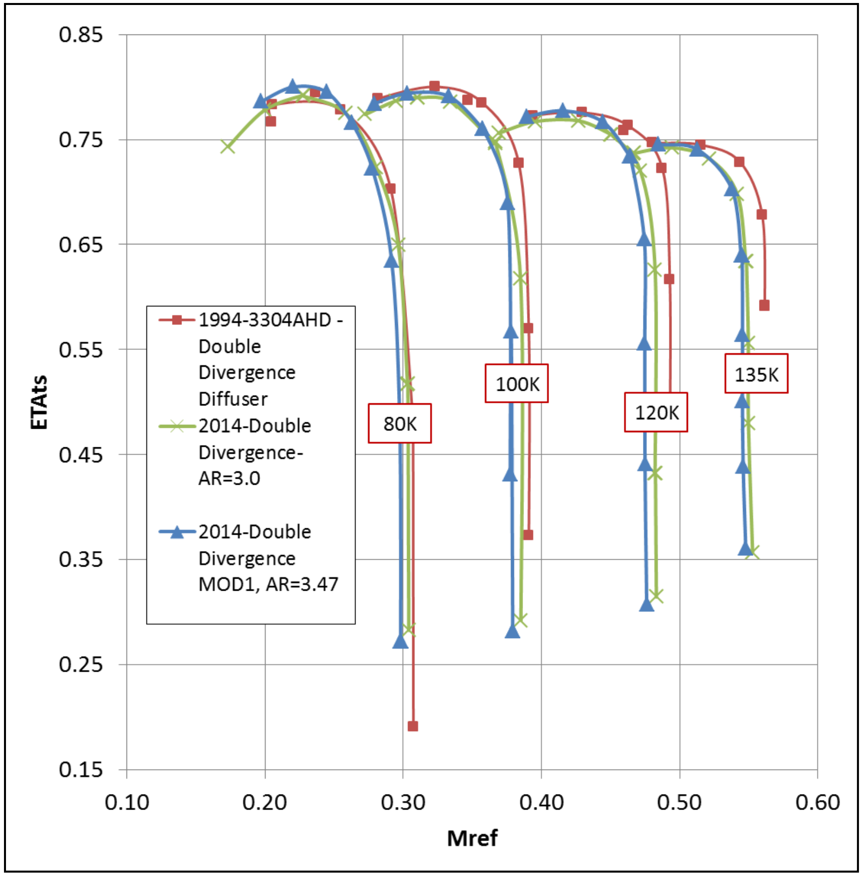
# Double Divergent Channel Diffuser Tests

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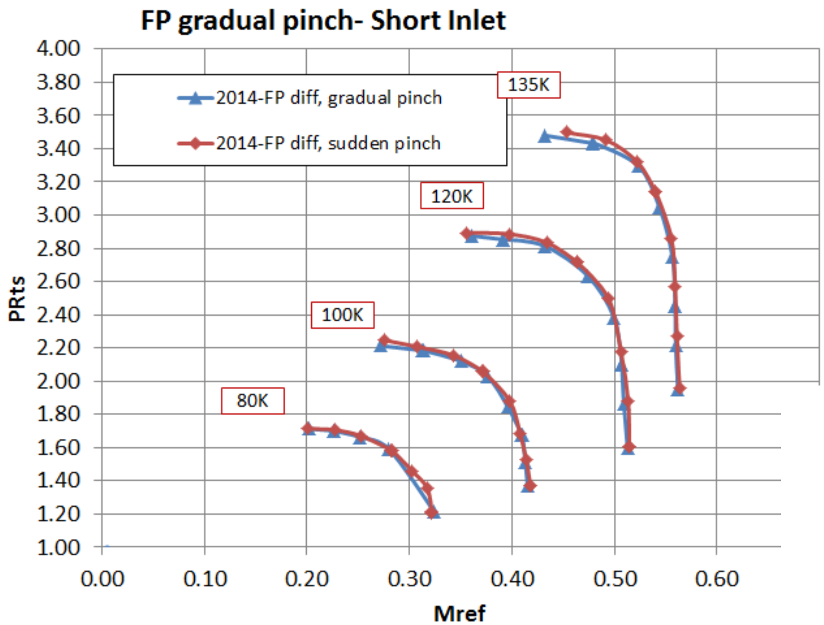
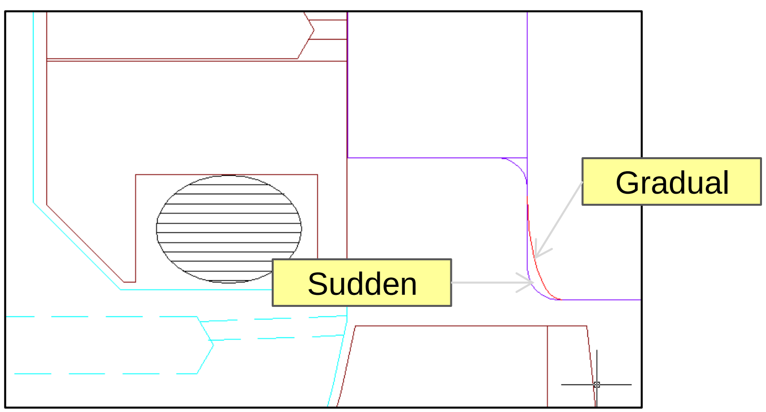
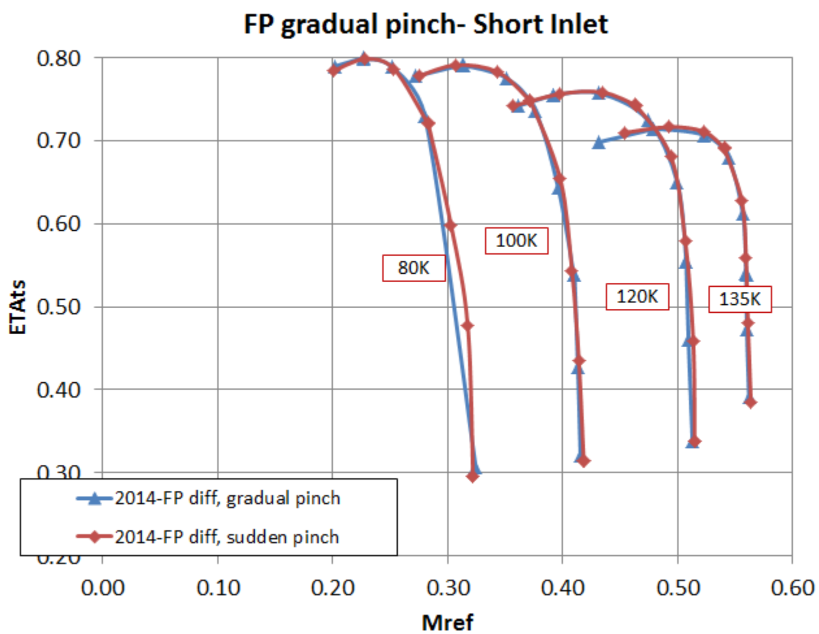
# Flat-plate Diffuser: Effect of Pinch Schedule




*Notes:*

1. Effect is nil
2. Highly repeatable data

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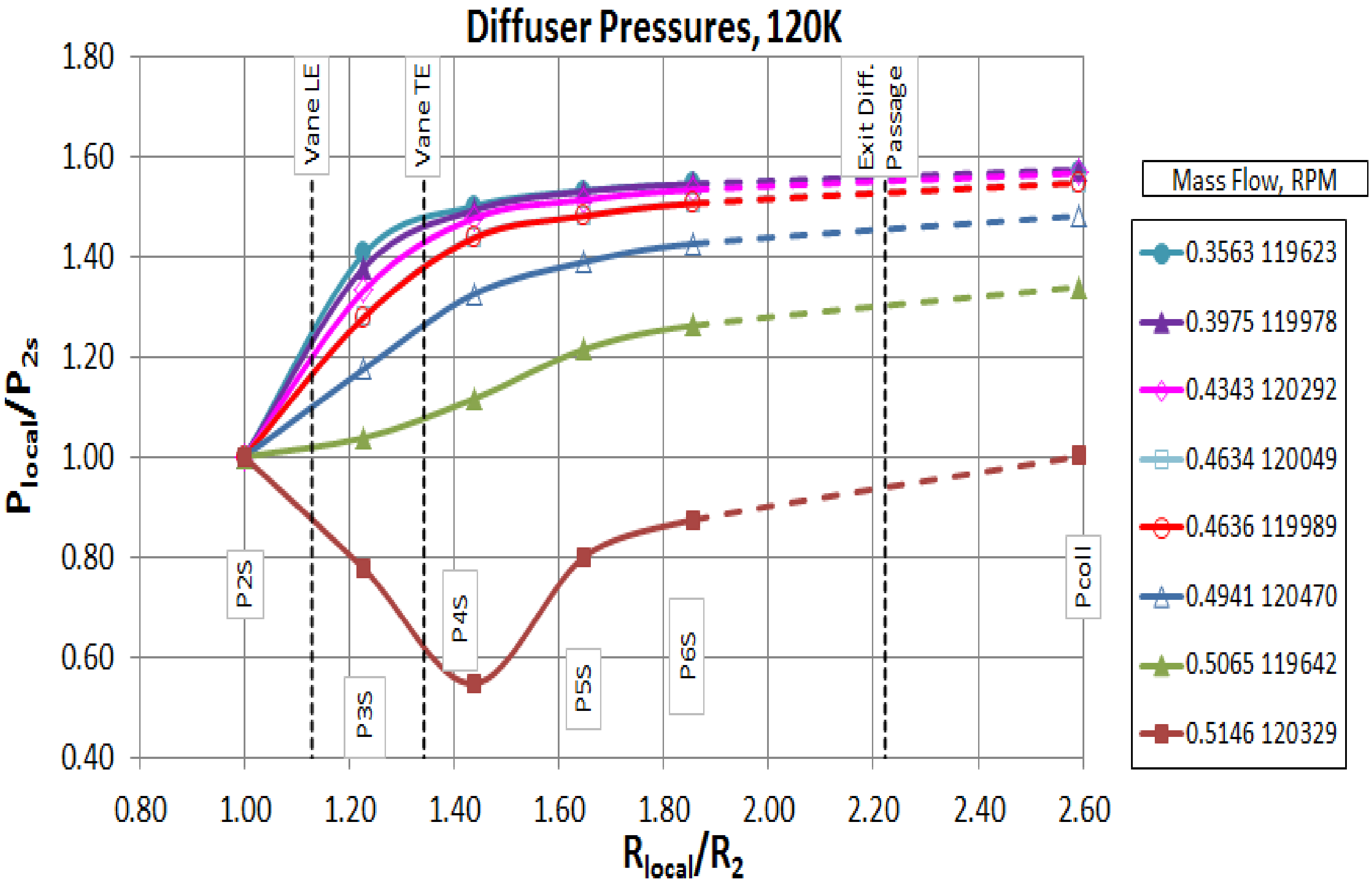
# Flat-plate Diffuser Pressure Profiles

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# Flow-wise Grooved Cover

**Patent No. 8,926,276 B2**

**January 6, 2015**

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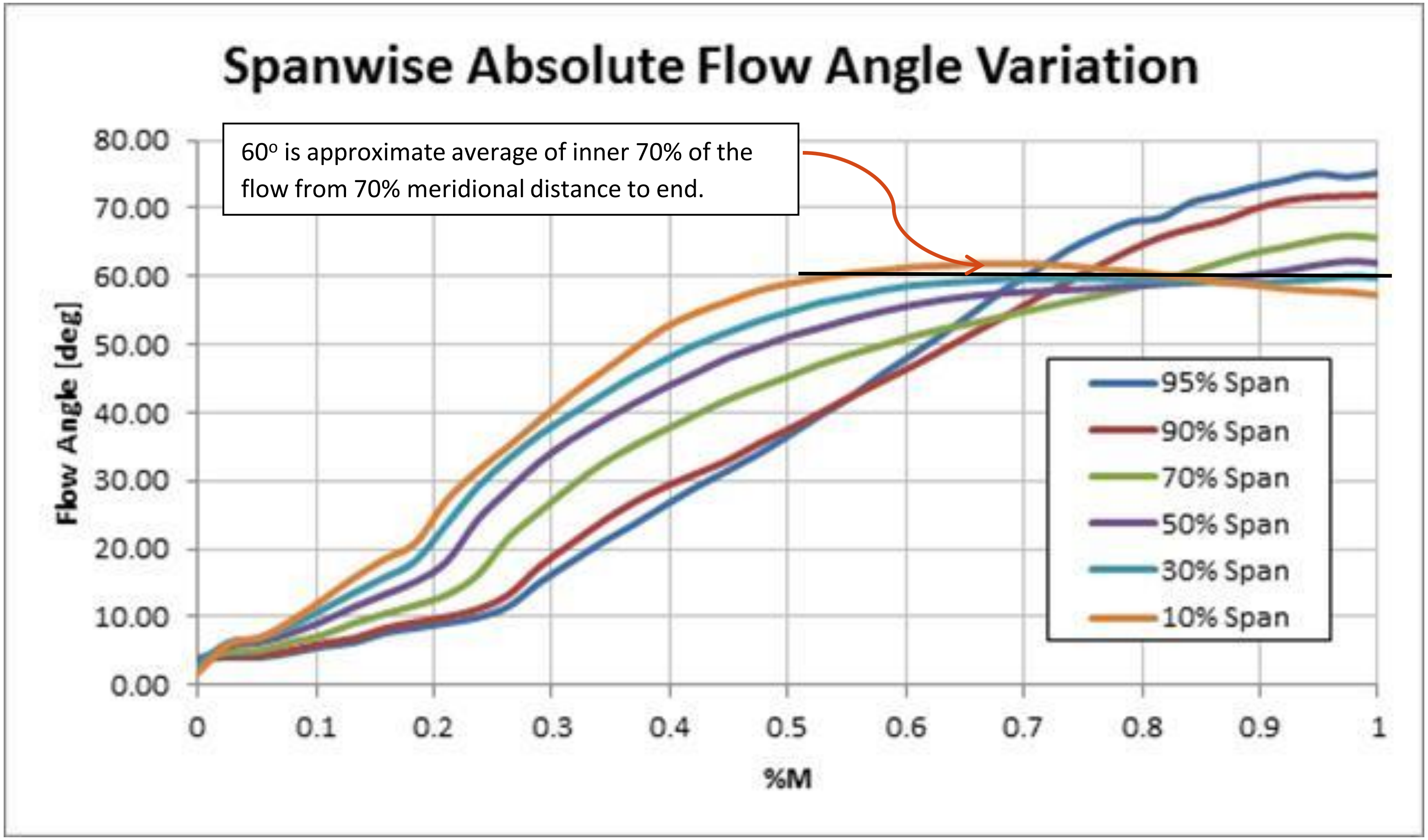
# Consortium Impeller Pitch-wise Averaged Absolute Angle Variations, i = 4°




**Blade-to-blade *averaged* flow angles plotted at various % spanwise locations showing a crossover at 70% meridional distance, a group of angle traces that settle out to a level of about 60°, and two traces that rise to higher angles. Impeller at 4° incidence.**

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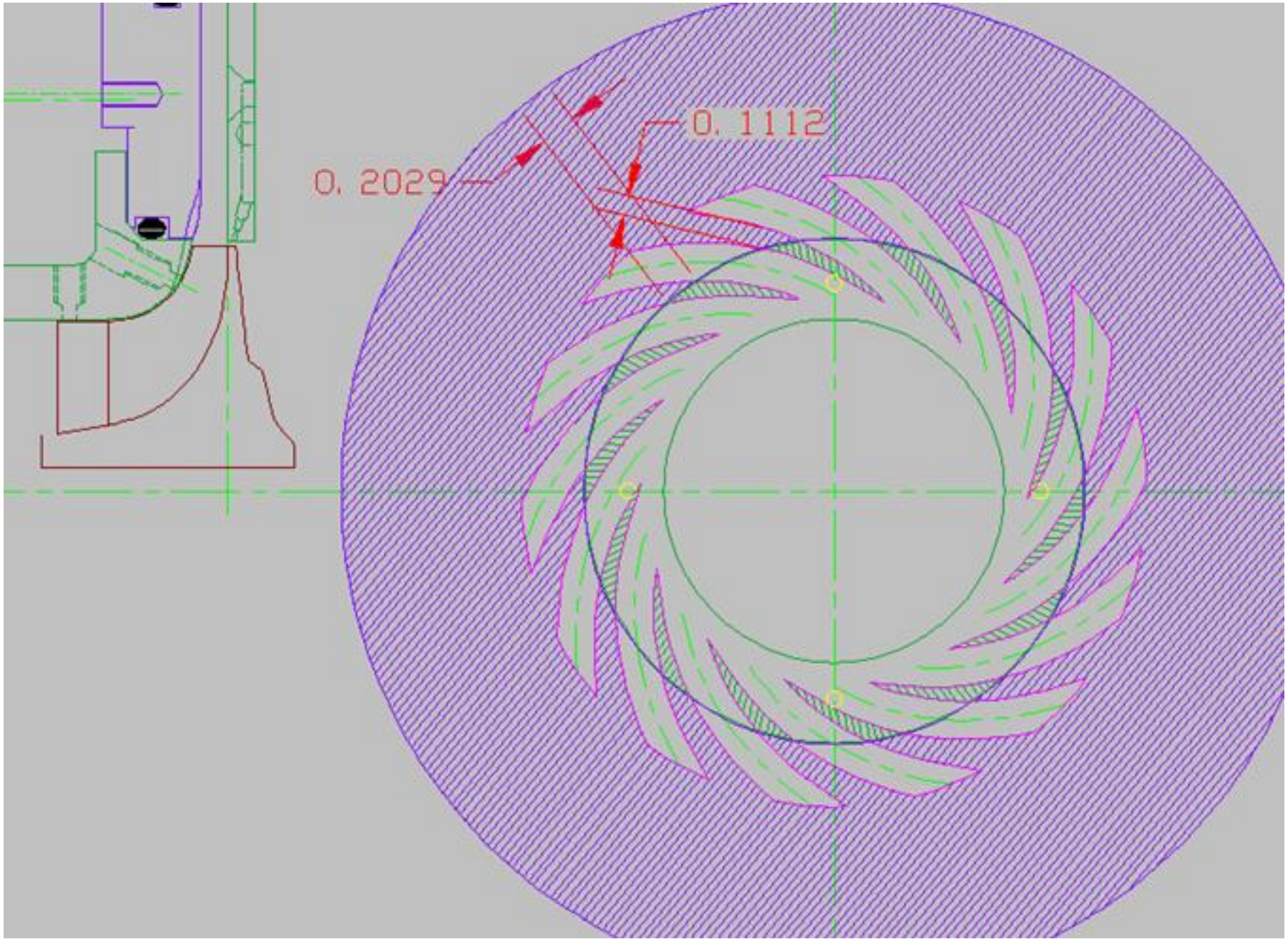
# A First Design Effort

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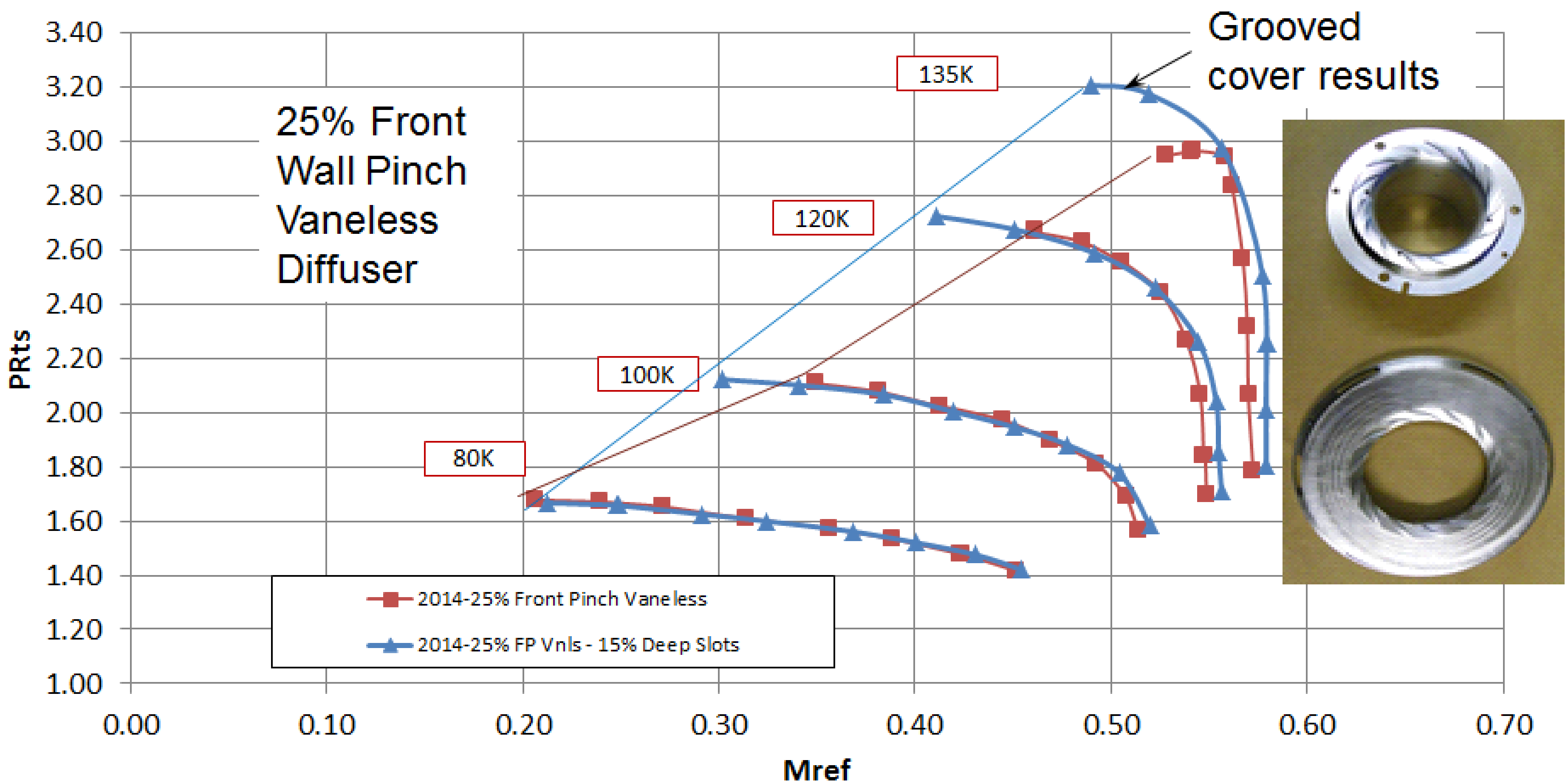
# First Flow-wise Grooved Cover Tests (1)




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

Questions: Does this extend the pr = 2.5 threshold? Can it go further? Can we raise efficiency? How does it work with vanes?

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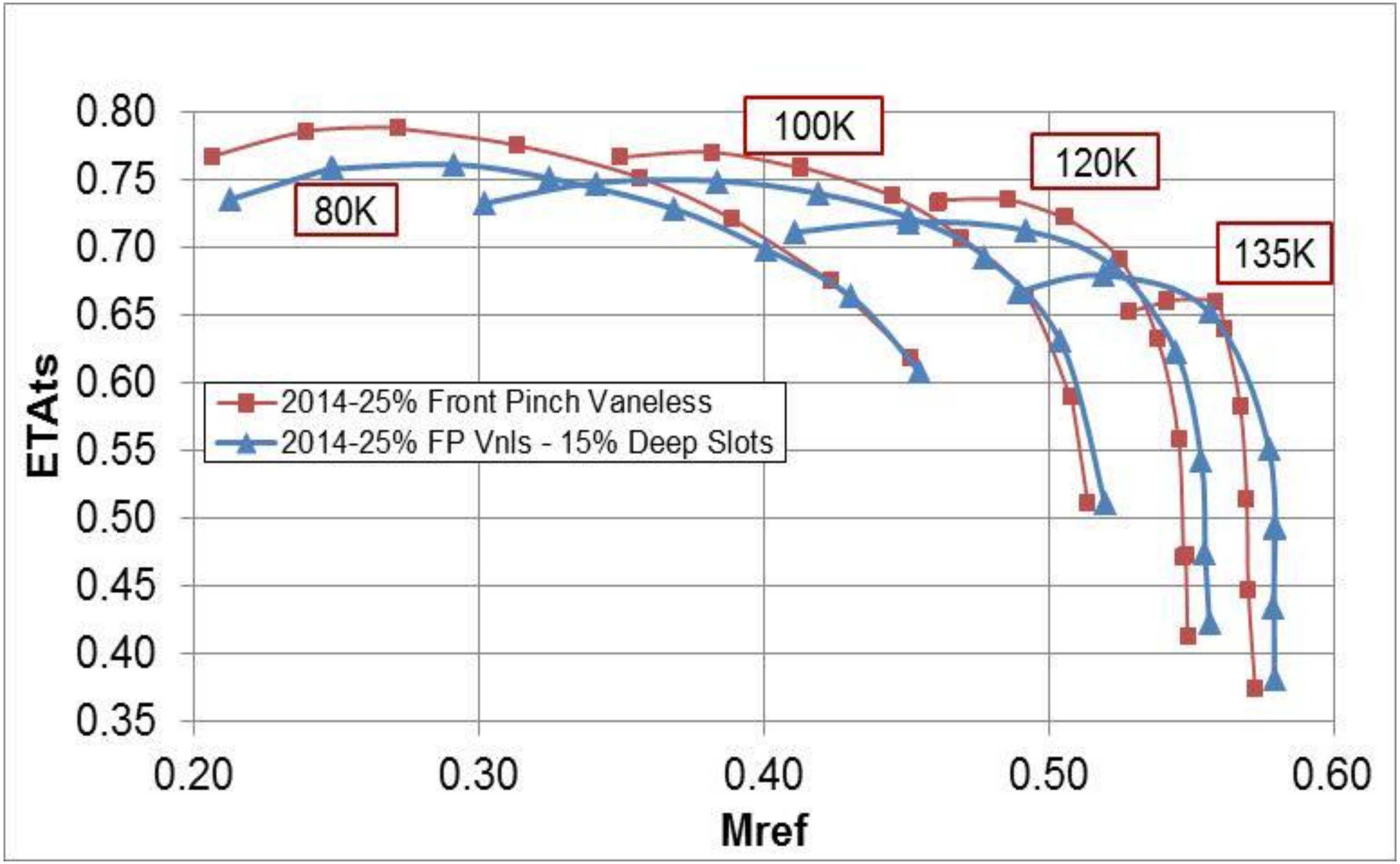
# Grooved Cover Vaneless Map Enhancement




25% front pinch vaneless diffuser with and without the flow-wise wide-grooved cover

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# New US & International Patents

Diffuser vane system overlaps impeller shroud region

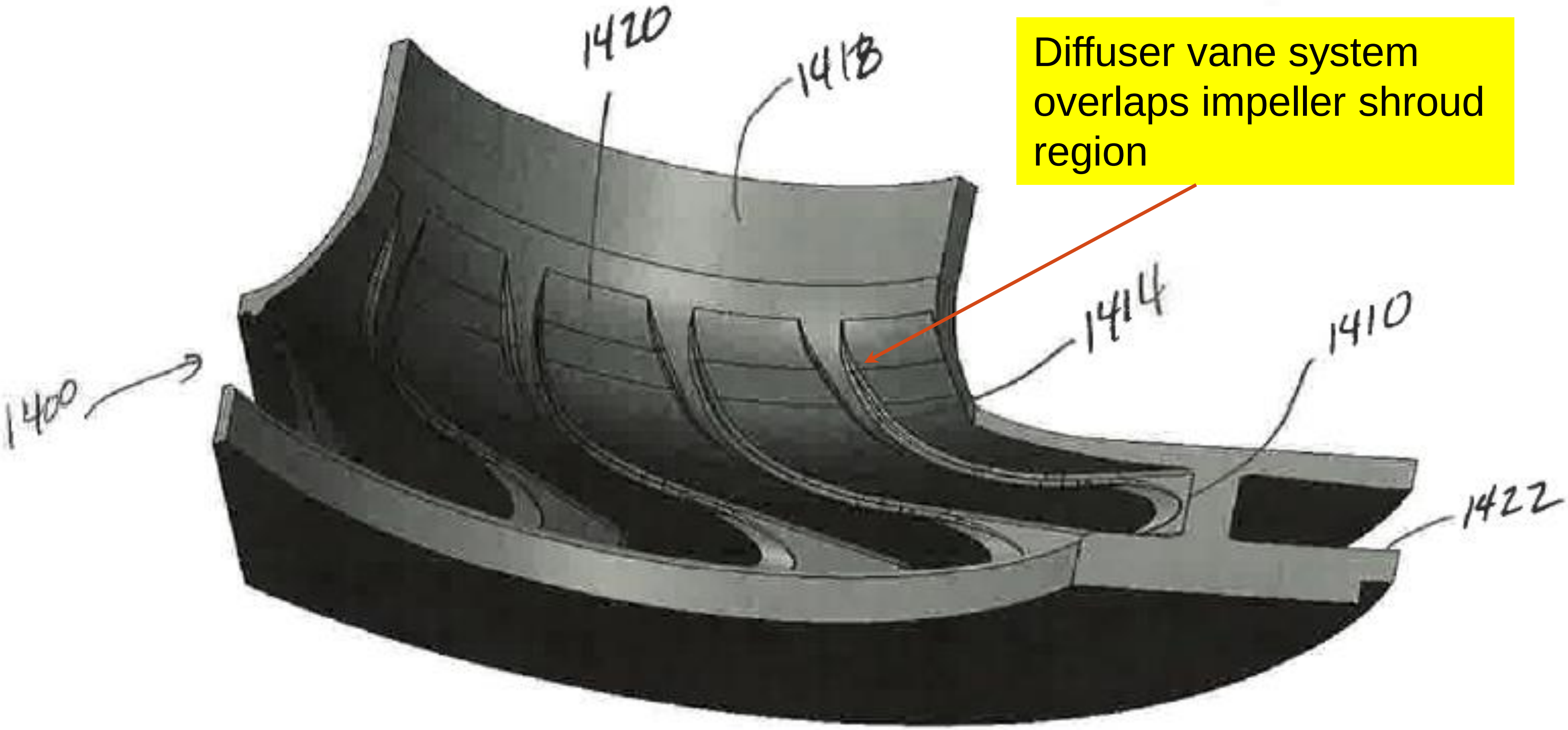


Figure 16

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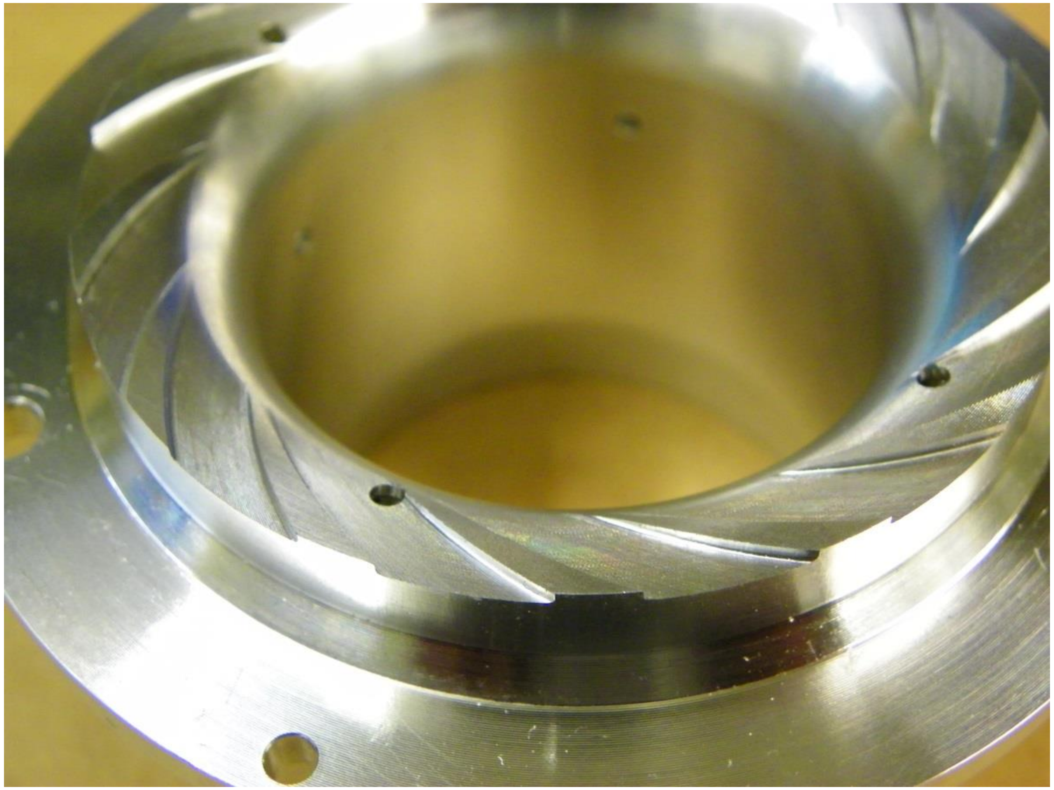
# CCFG with Ribs and Deep Channels



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

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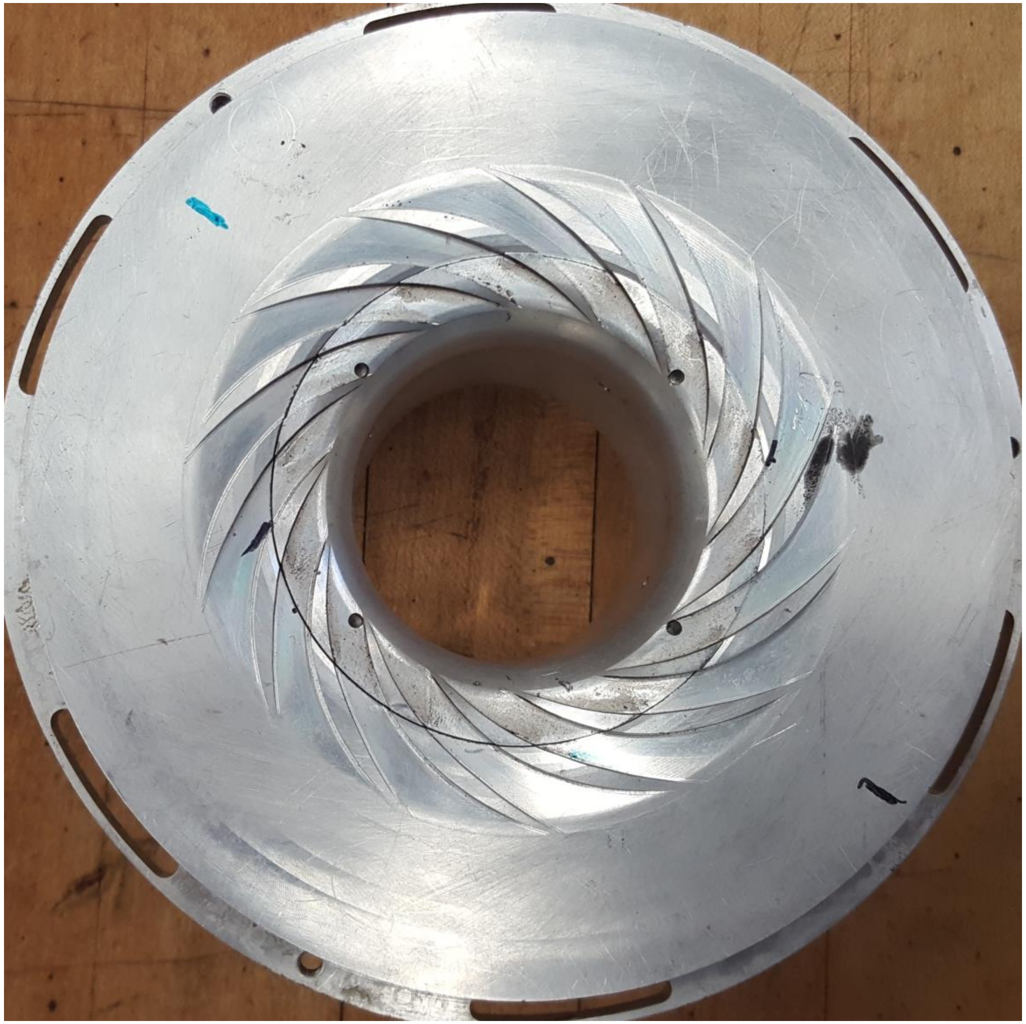
# Deep, Wide Grooves



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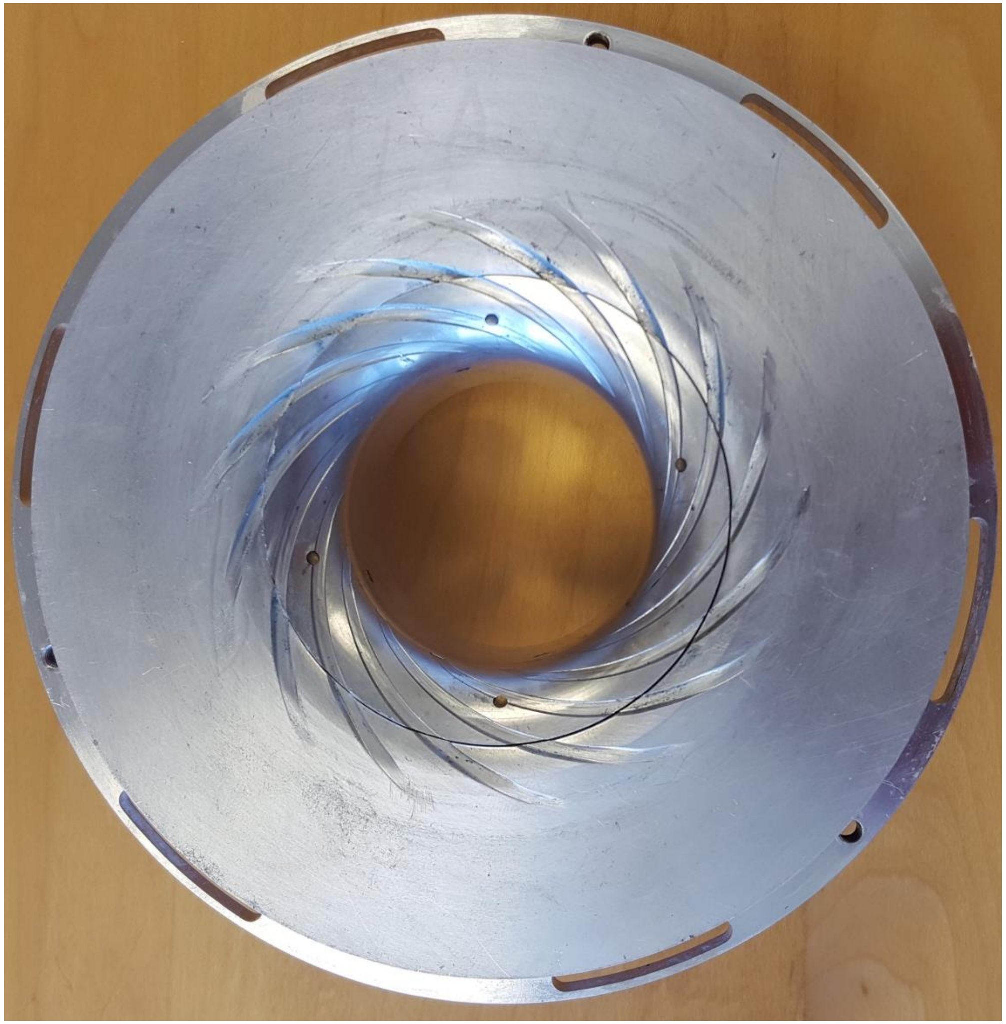
# Narrow Groove Configuration



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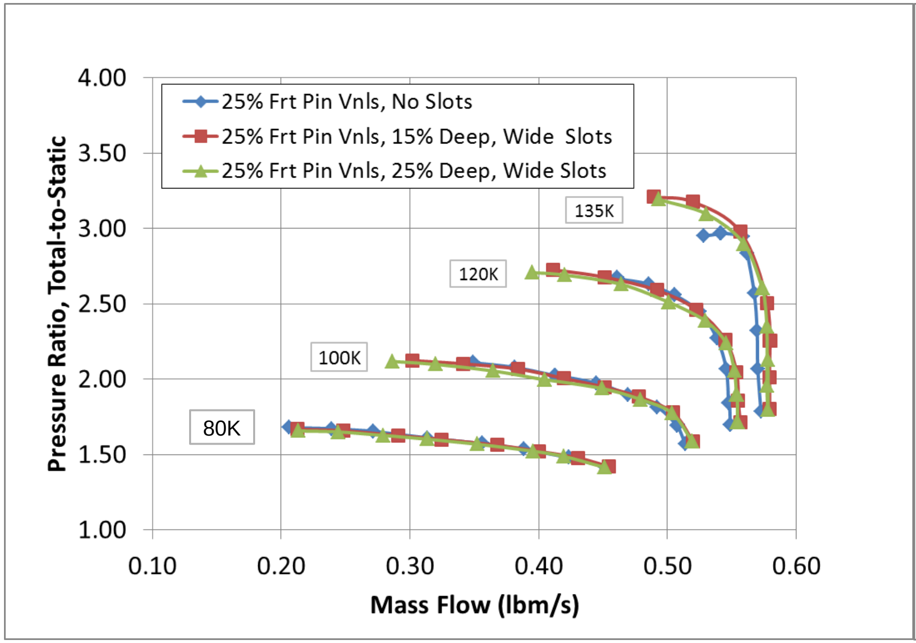
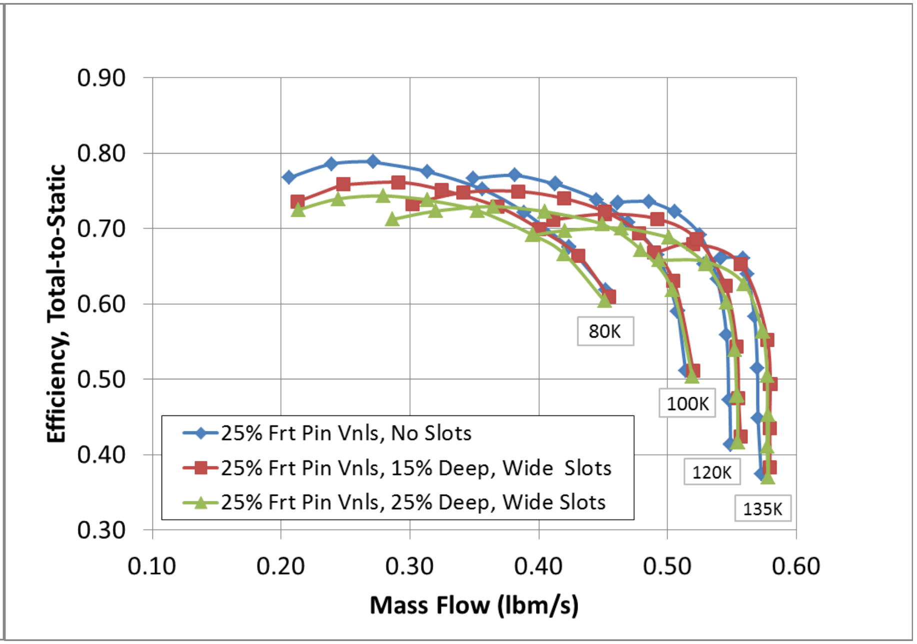
# Wide Slot Depth Variation

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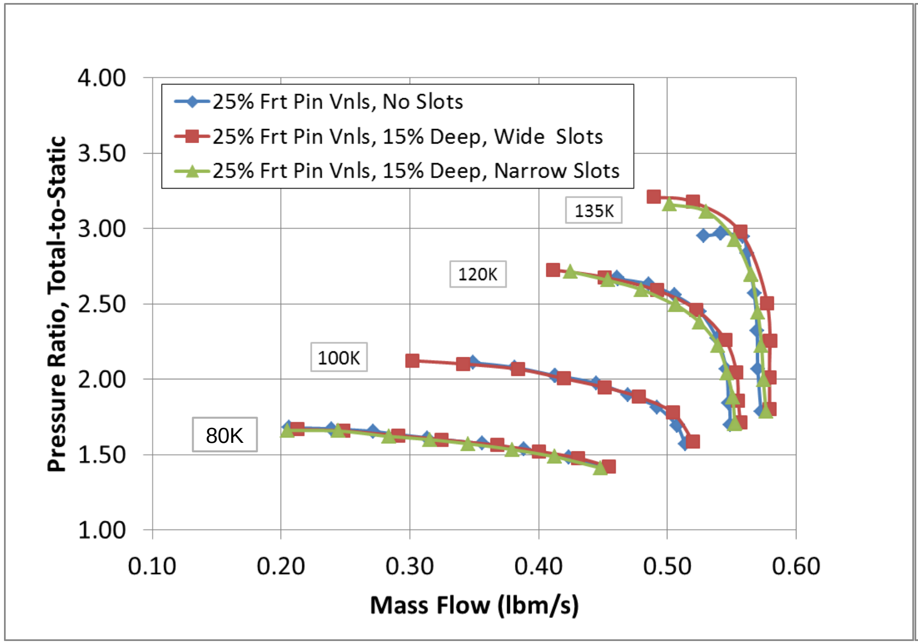
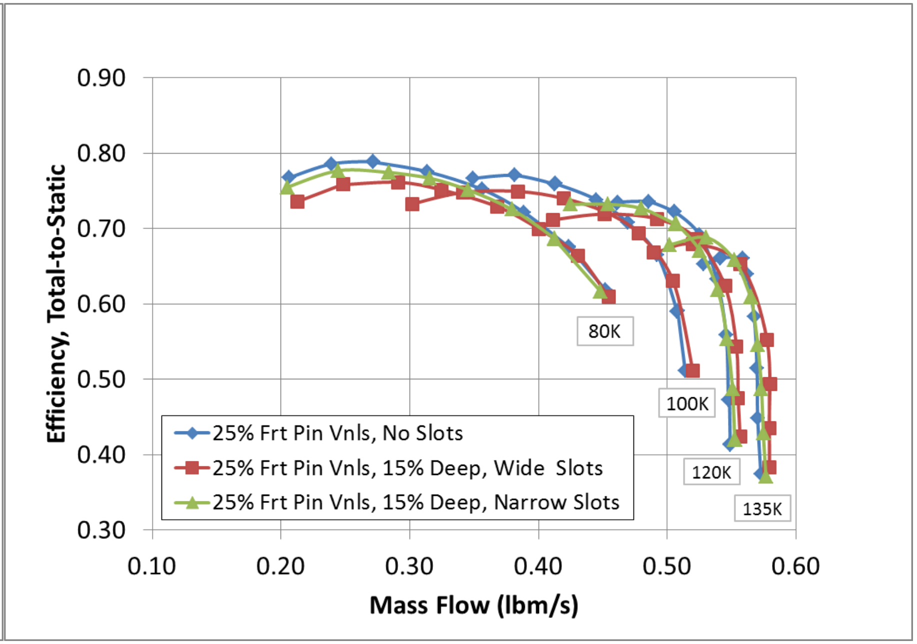
# Narrow/Wide Slot Comparison

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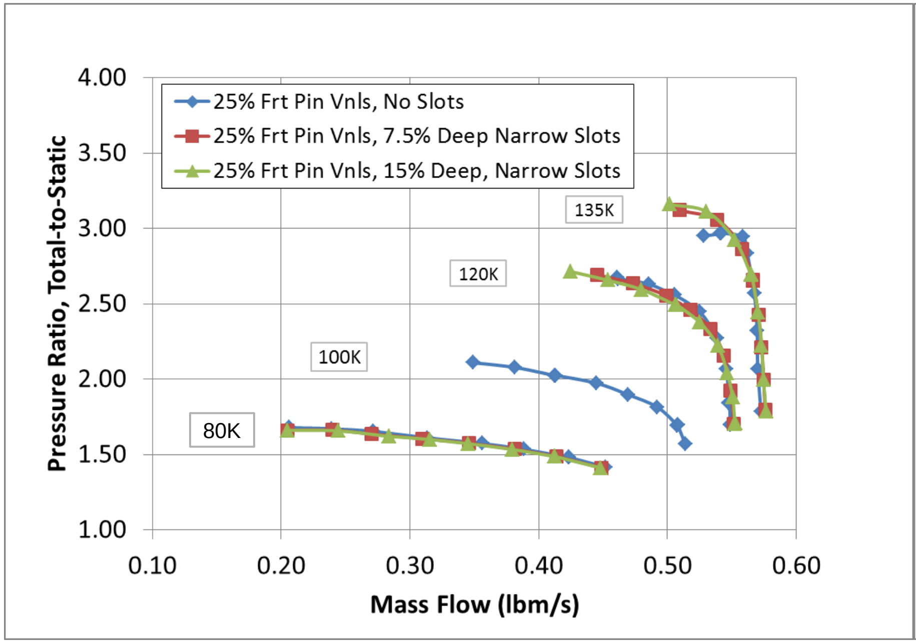
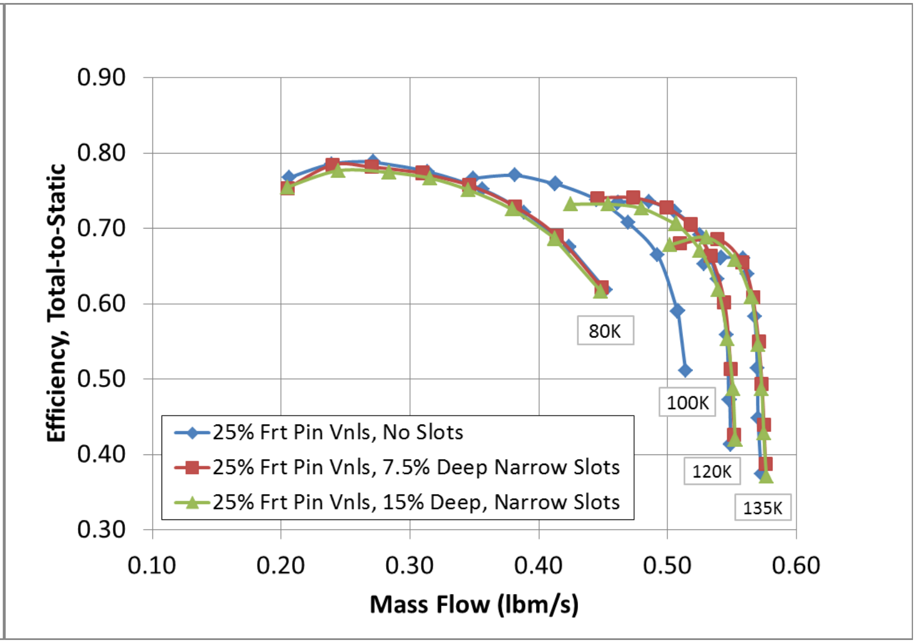
# Narrow Slot Depth

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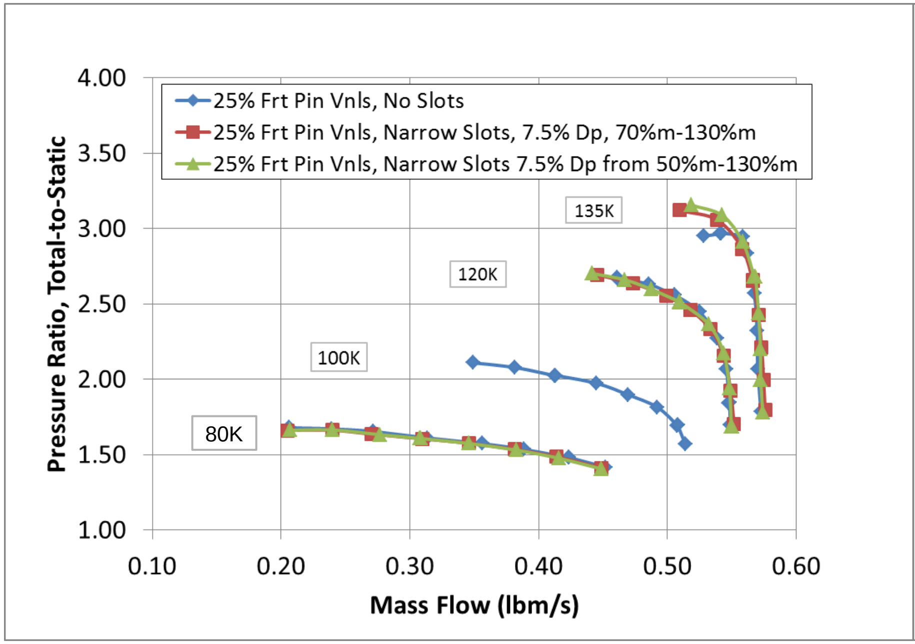
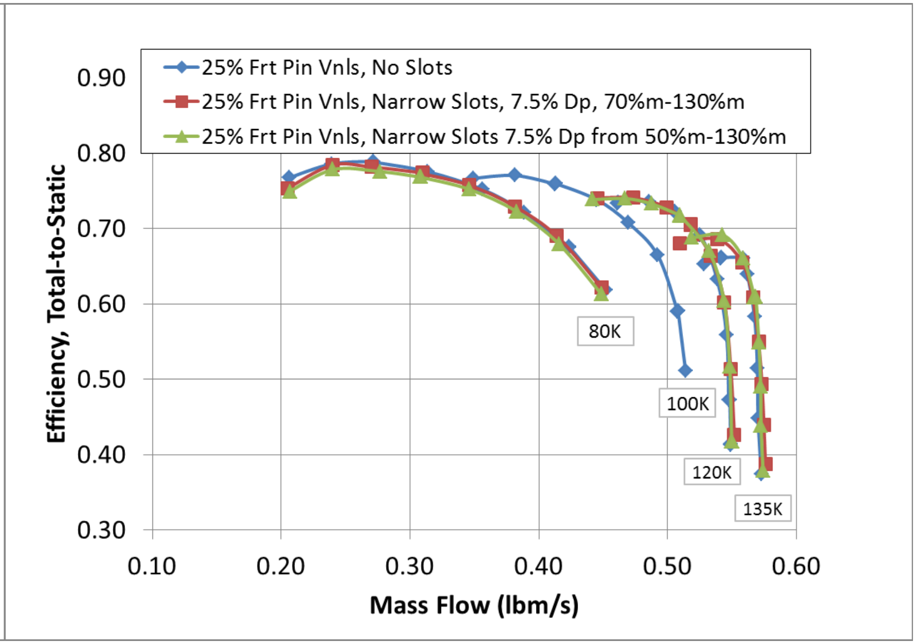
# 50% m & 70% m Slot Starting Location

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# Full Vaneless Diffuser Grooves

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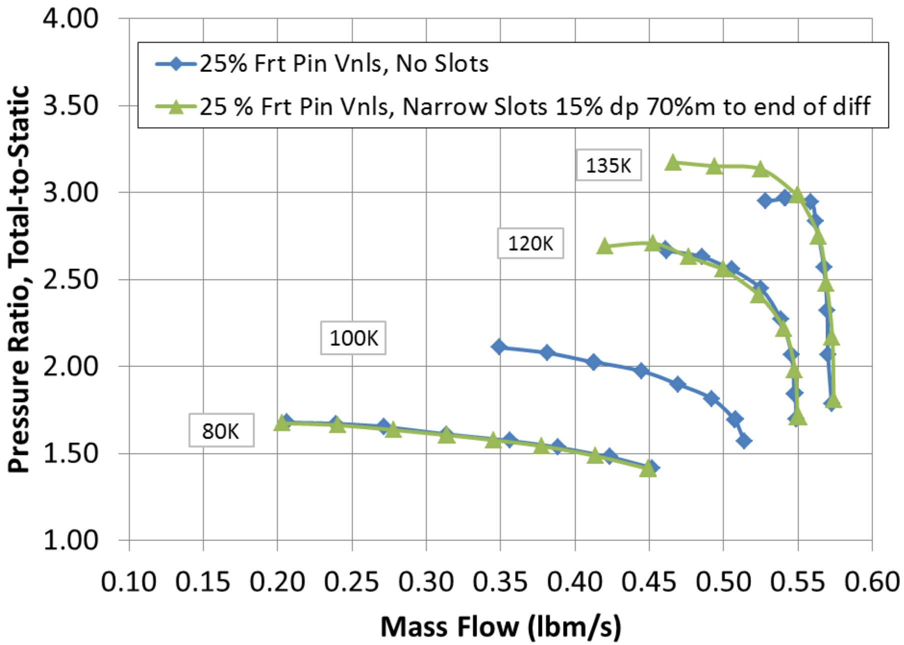
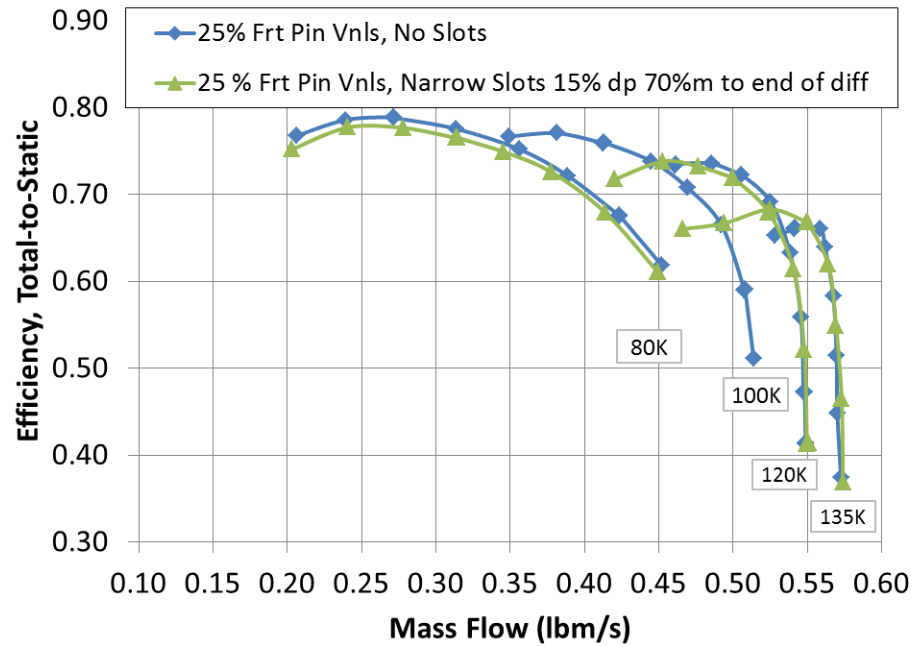
# Full Vaneless Diffuser Slots (1)

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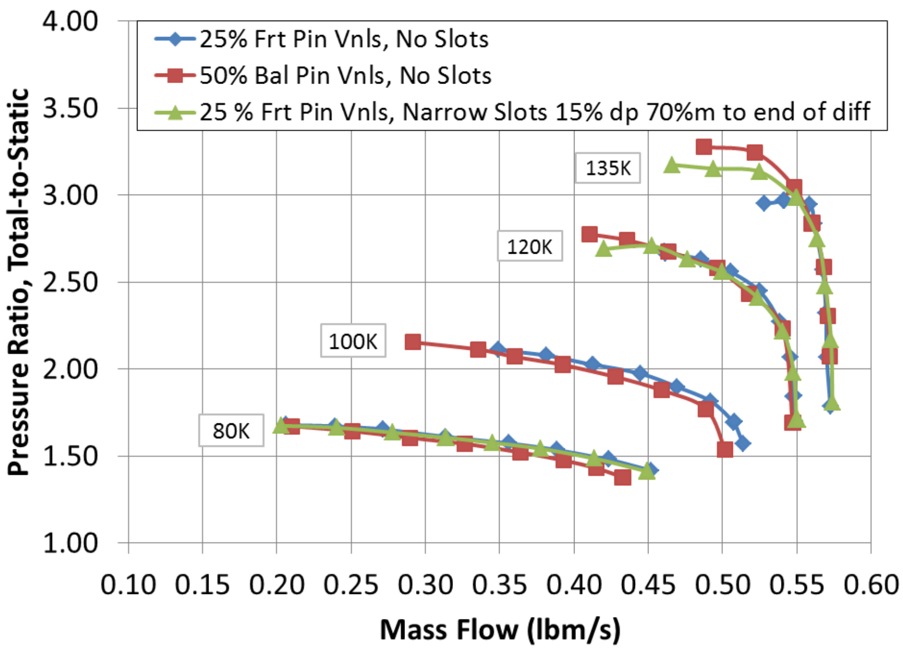
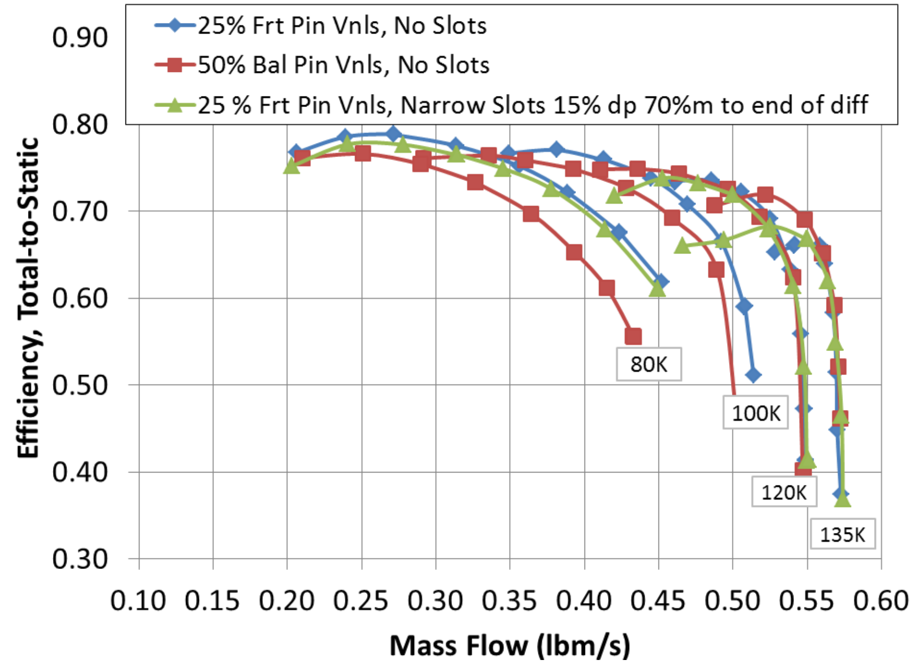
# Full Vaneless Diffuser Slots (2)

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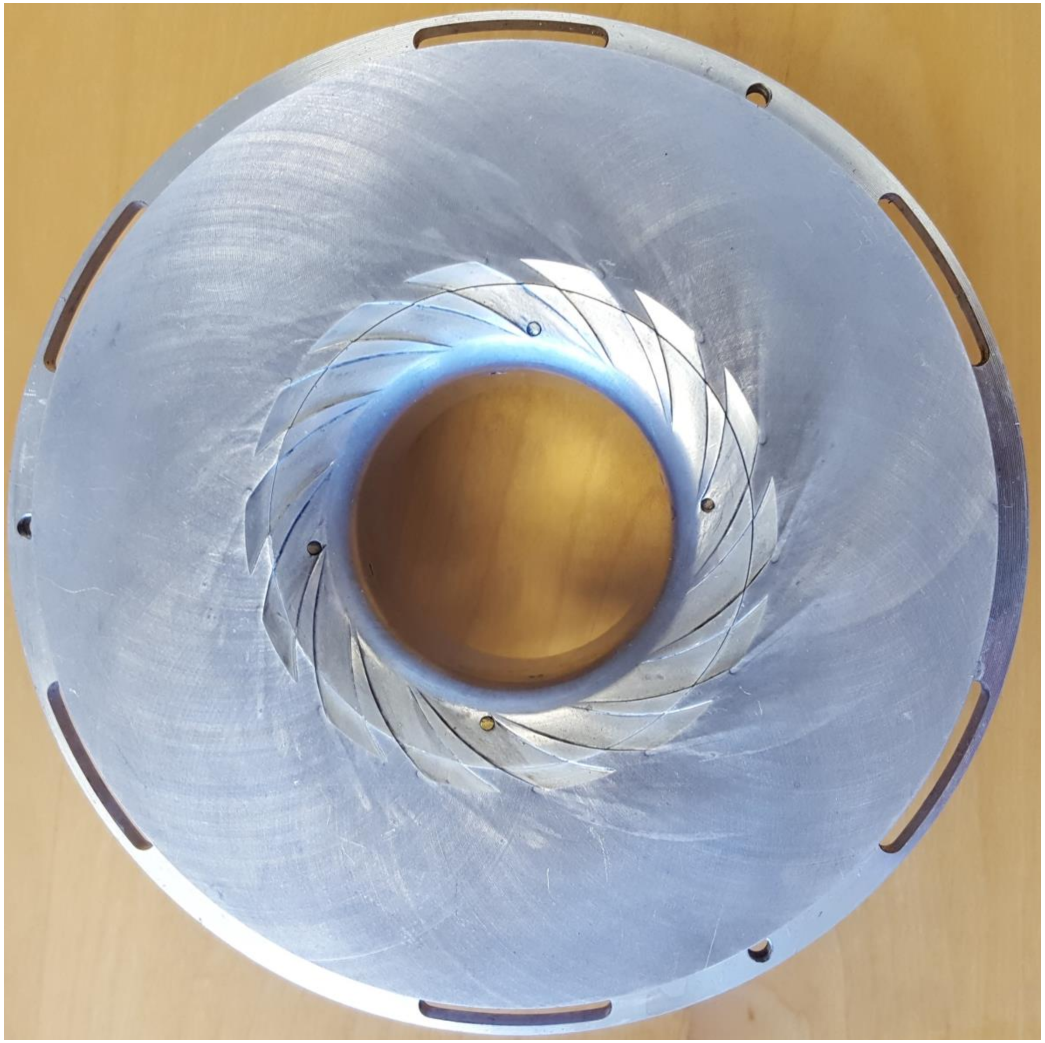
# Wide, Shallow Grooves



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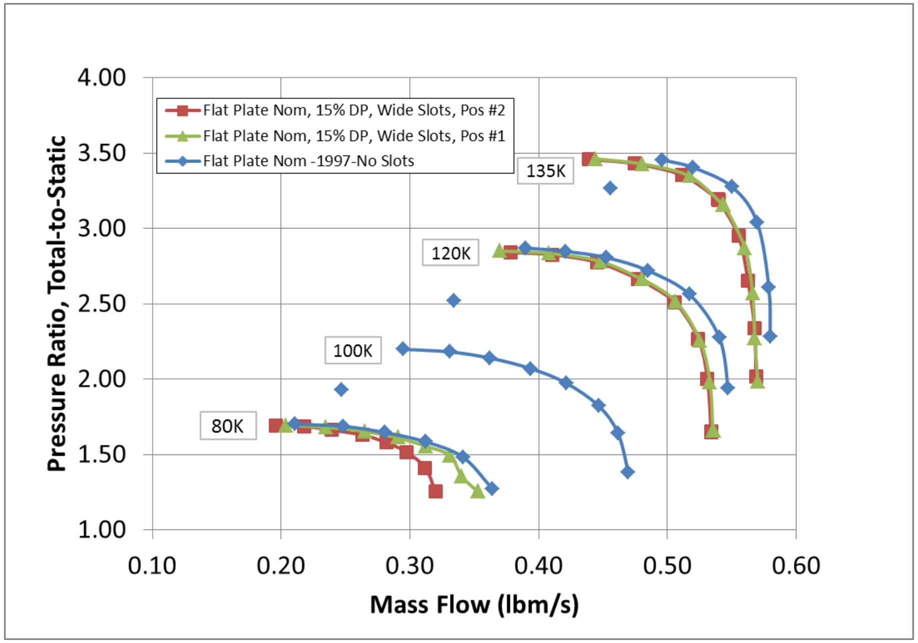
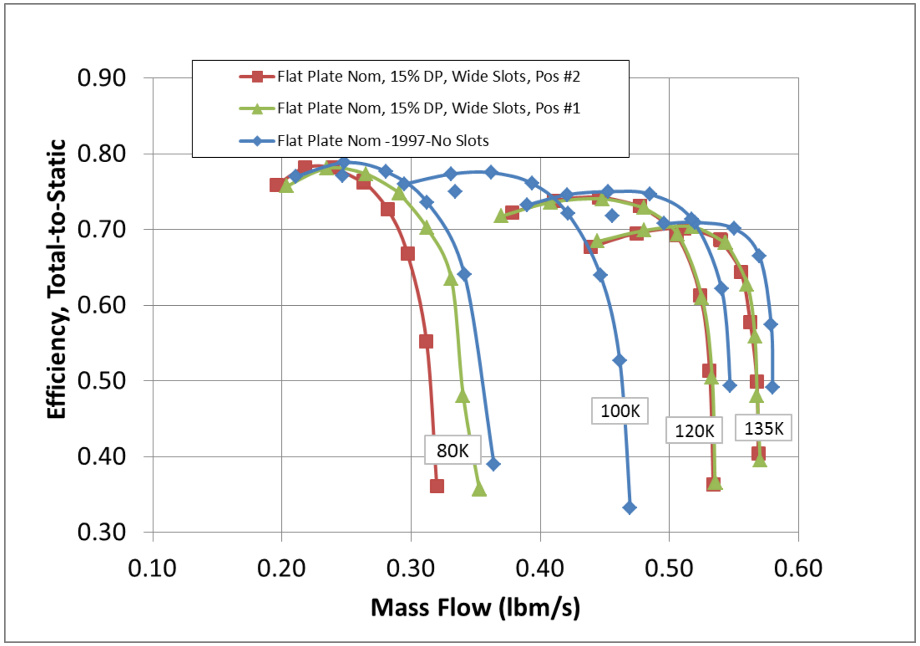
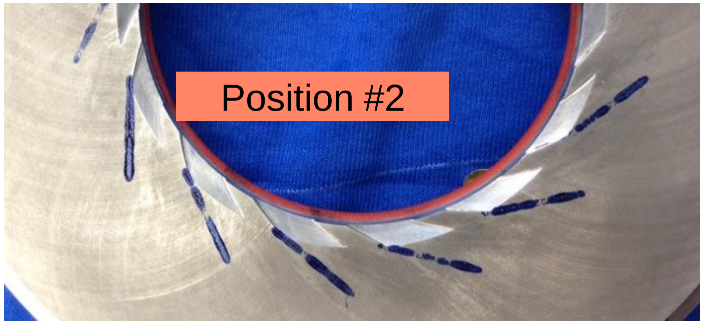
# Grooved Cover: Flat-plate Wide-groove Tests





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# Principal Groove Lessons

- Tests at 7.5%, 15%, and 25% depth point to 7.5% as being best
- Grooves starting at 50% and at 70% meridional distance work well
- Grooves ending at $R_3 = 1.3$ and $R_5$ work well
- Grooves aligned with vanes work well
- Narrow grooves work well
- Small efficiency penalties have been found; are gone with best combinations
- Excellent range extension at highest speeds found; no change at lowest speeds
- Grooves seem to reduce data variance and possibly surge line inconsistency

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# Inlet Distortion Studies

- Truly confirmed distortion existence
- Observed Flow visualization evidence
- Have begun the mathematical foundation
- Continuing on to other rigs

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# Front Pinch (25%) Vaneless Distortion

Red ticks = collector outlet ports (4)

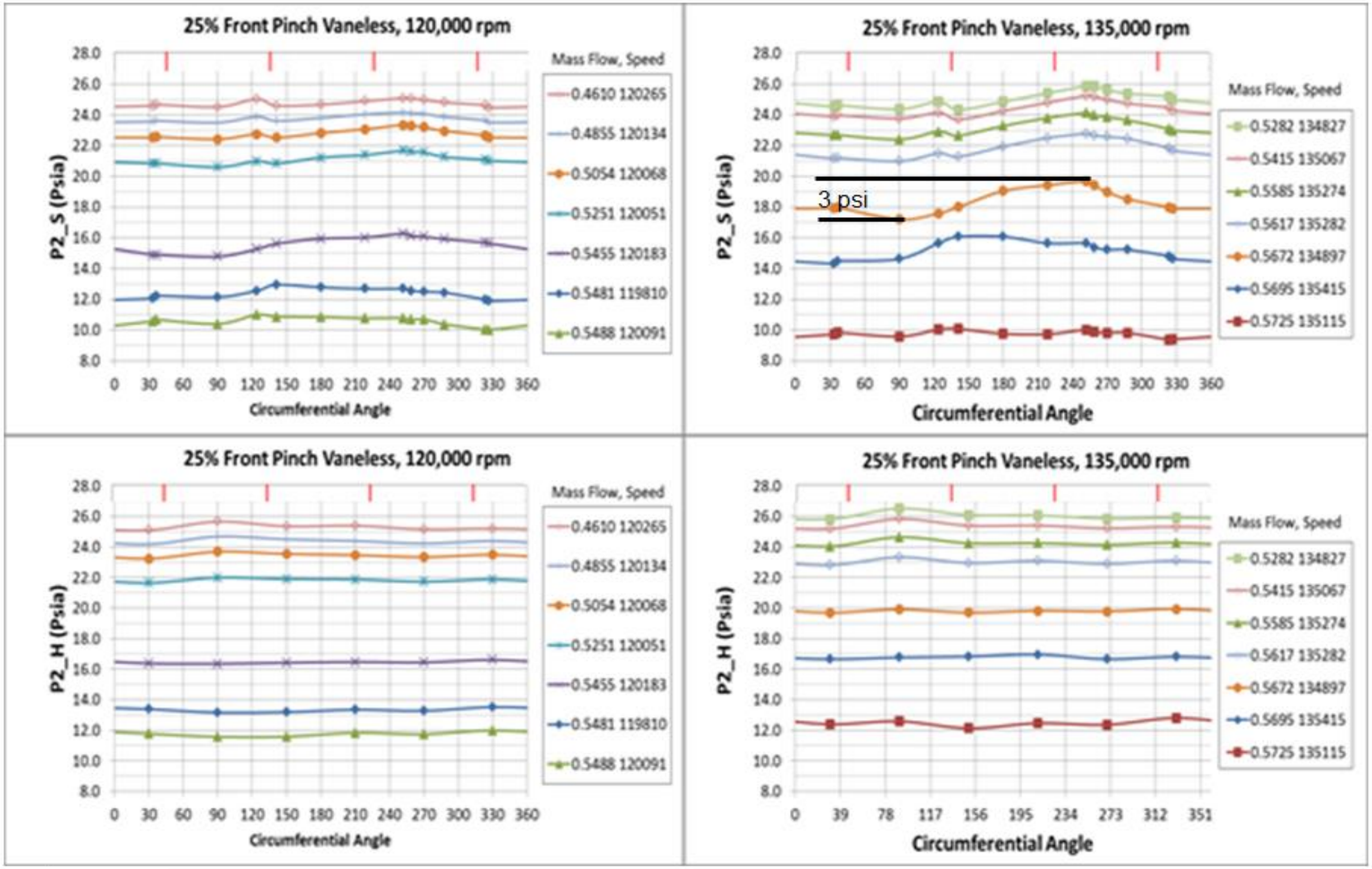


Figure 31. Circumferential pressure variations for a vaneless diffuser test set; the distortions are **NOT** traceable to any rig geometry and are considered to be a natural flow phenomenon

Now, one or two maximum and one or two minimum per line; Min about 60 deg. and max about 270 deg. Distortion NOT caused by the collector!

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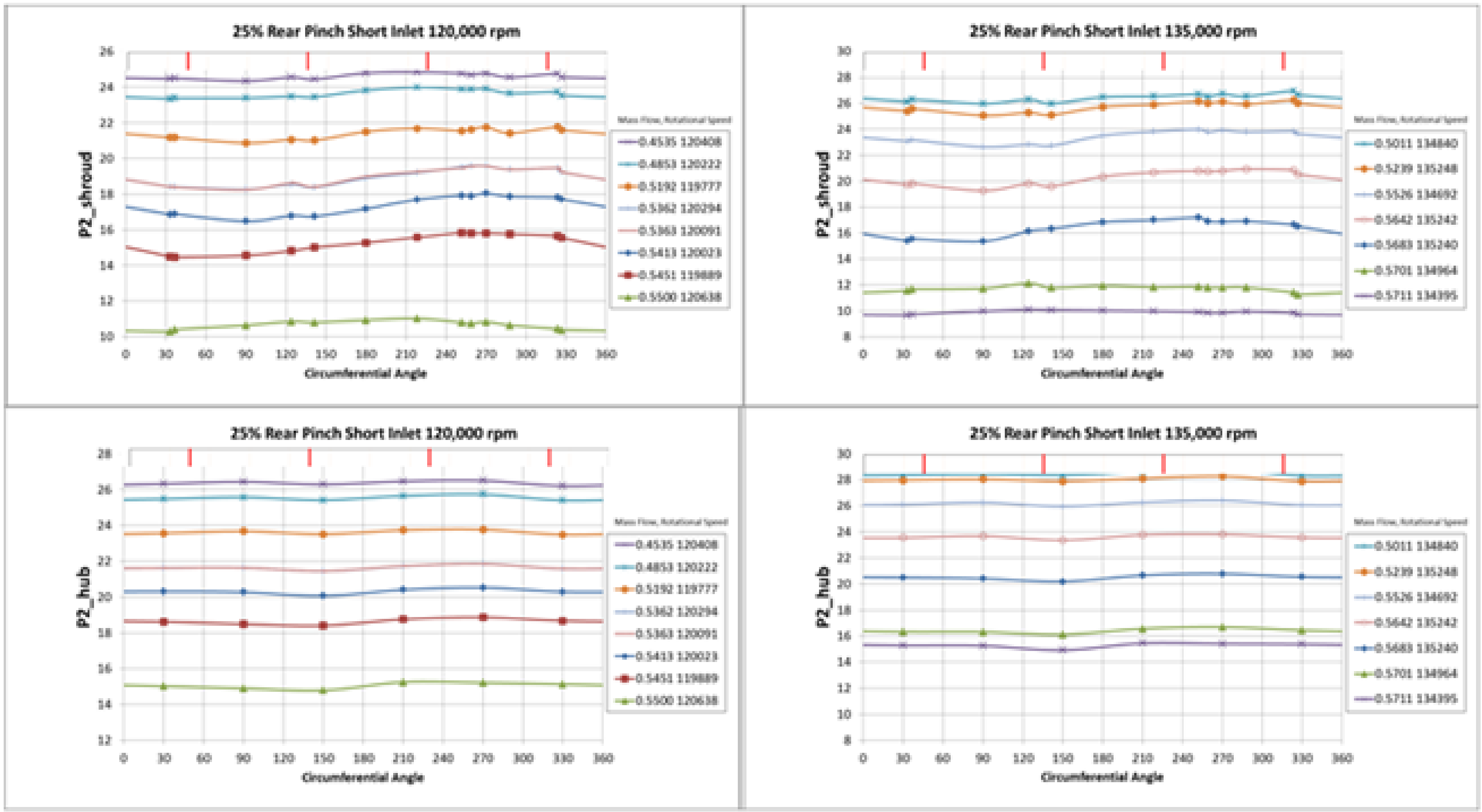
# Rear Pinch (25%) Vaneless Distortion




Peak distortions are 1.5 – 1.7 psi, peak to peak, ½ of front pinch case

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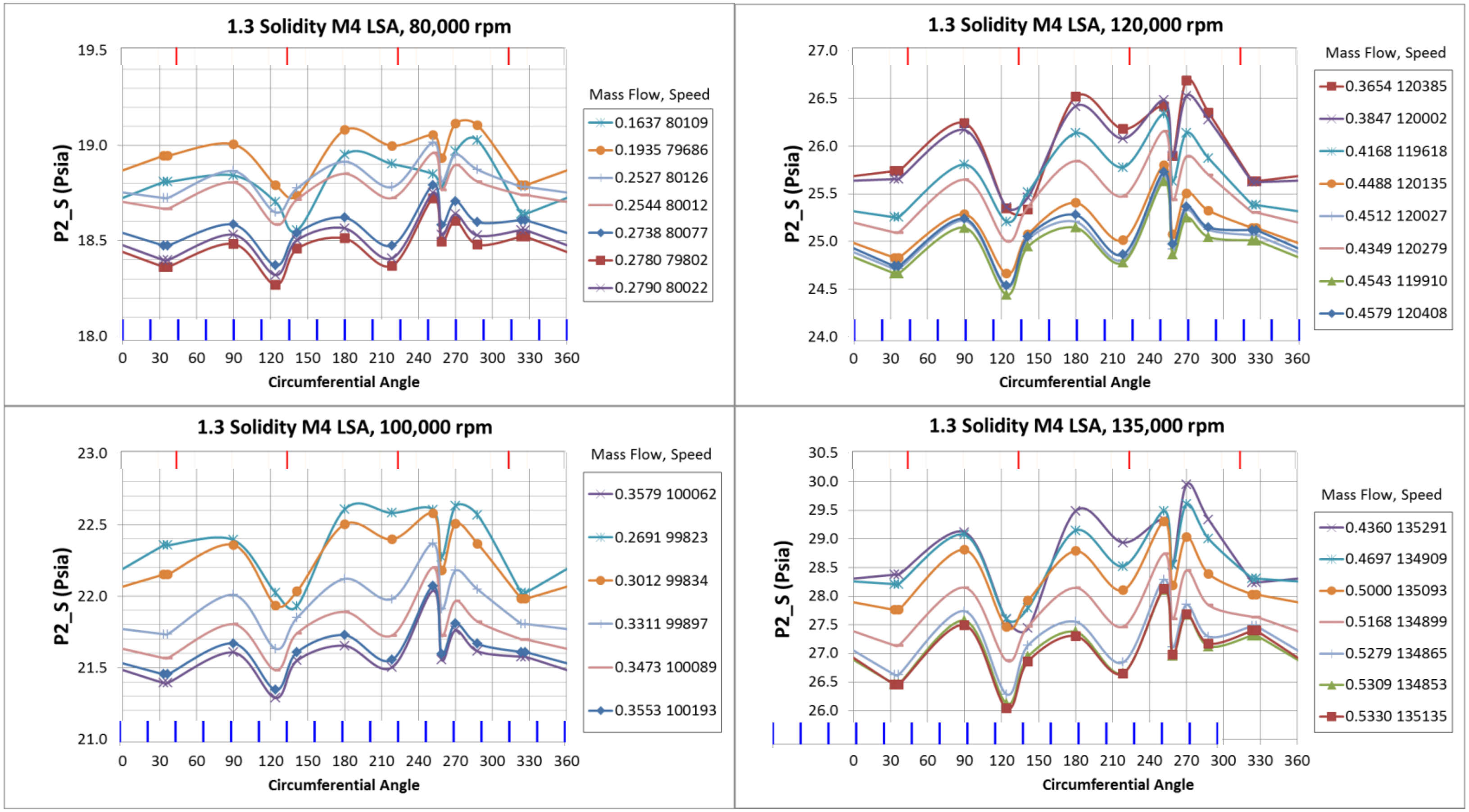
# Impeller Exit Pressures: 1.3 Solidity LSA M4 Diffuser

Red ticks = collector outlet ports (4)
Blue ticks = diffuser vane leading edges (16)




Now multiple maximum and multiple minimum per line; Min about 60 deg.

**Amplitude about twice that of the vaneless cases.**

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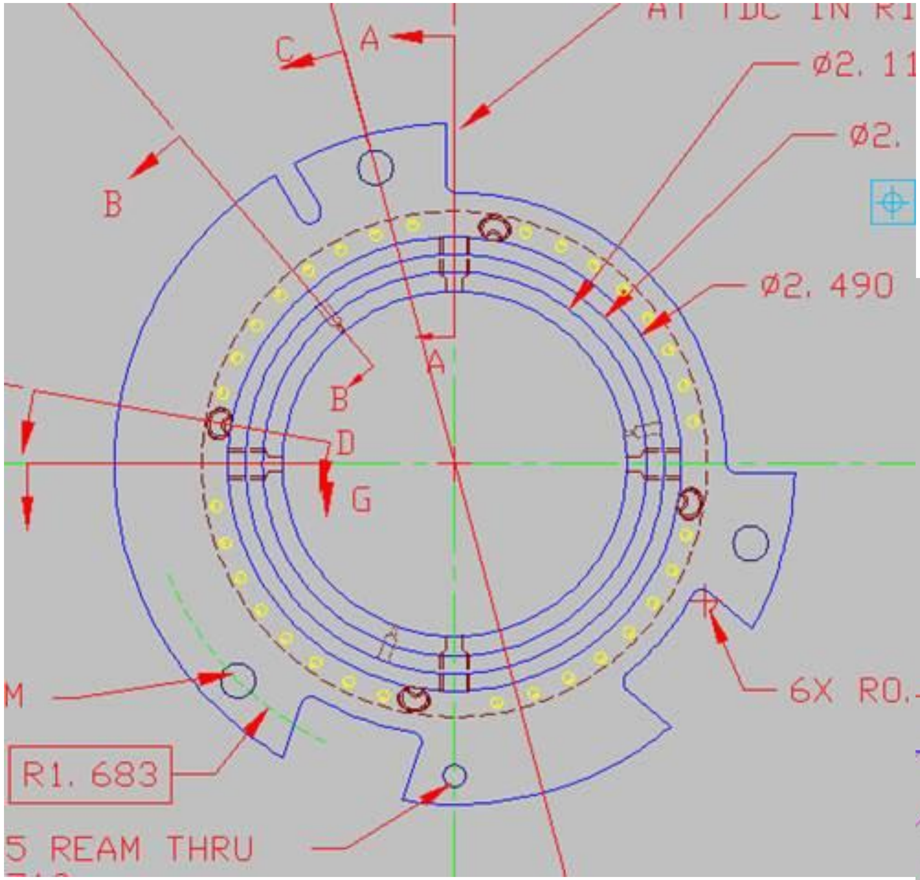
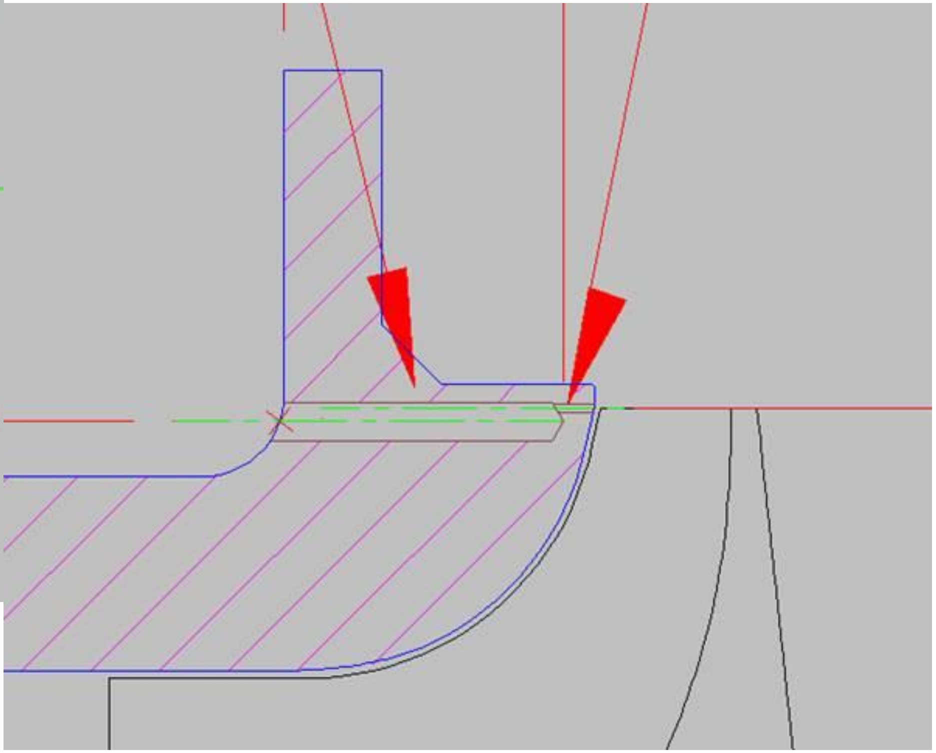
# New Cover Taps



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# Sample Results with 9° Spaced Taps

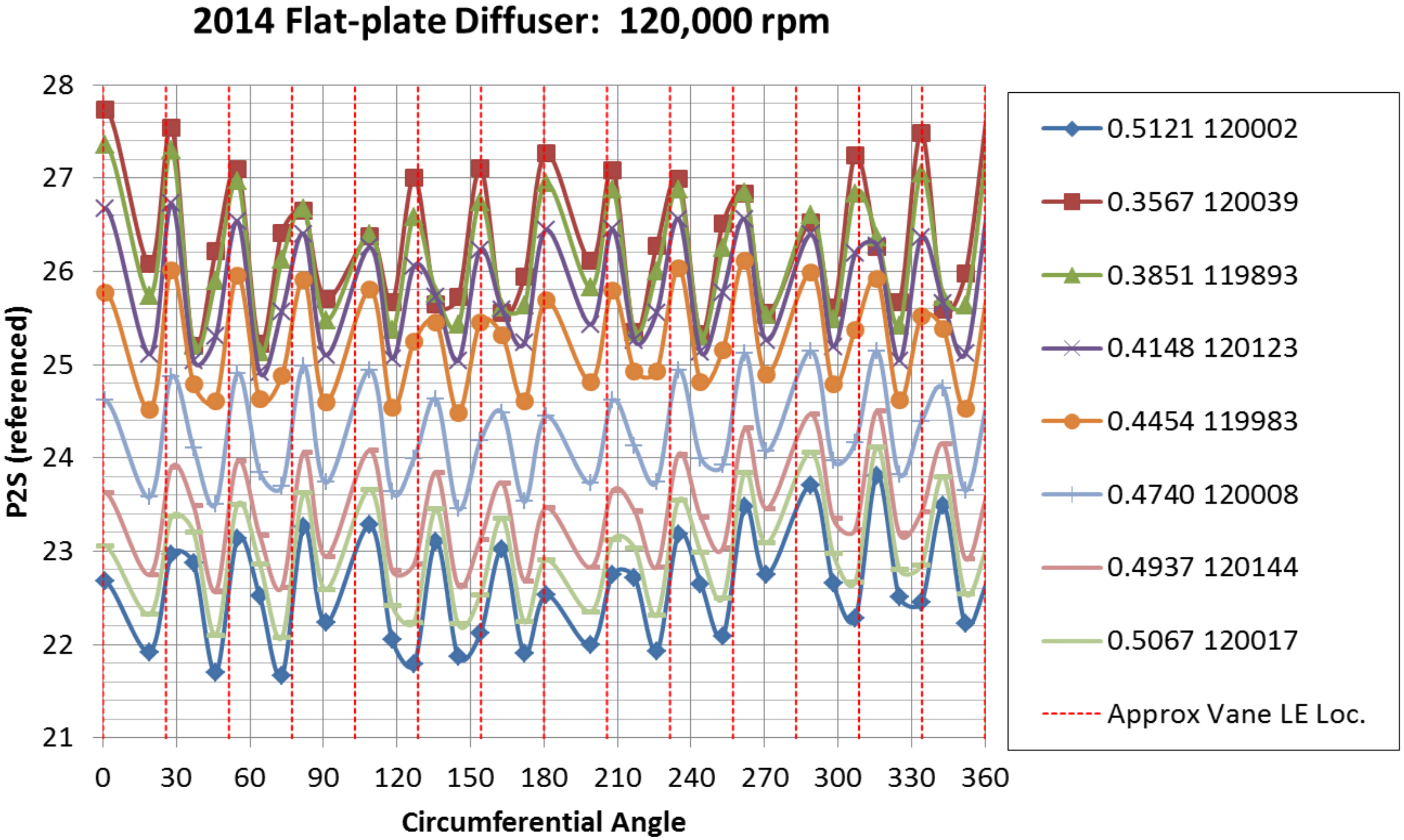


Figure 32b. Circumferential static pressure measurements at impeller tip/diffuser inlet; the saw-tooth pattern is just the diffuser vane-to-vane variation. Note, however, the 'sinusoidal' variation in peaks and valleys upon which the saw-tooth is superposed – hence there is no periodicity in the flow at the impeller tip. Each line corresponds to a different flow rate; all at 120,000 rpm.

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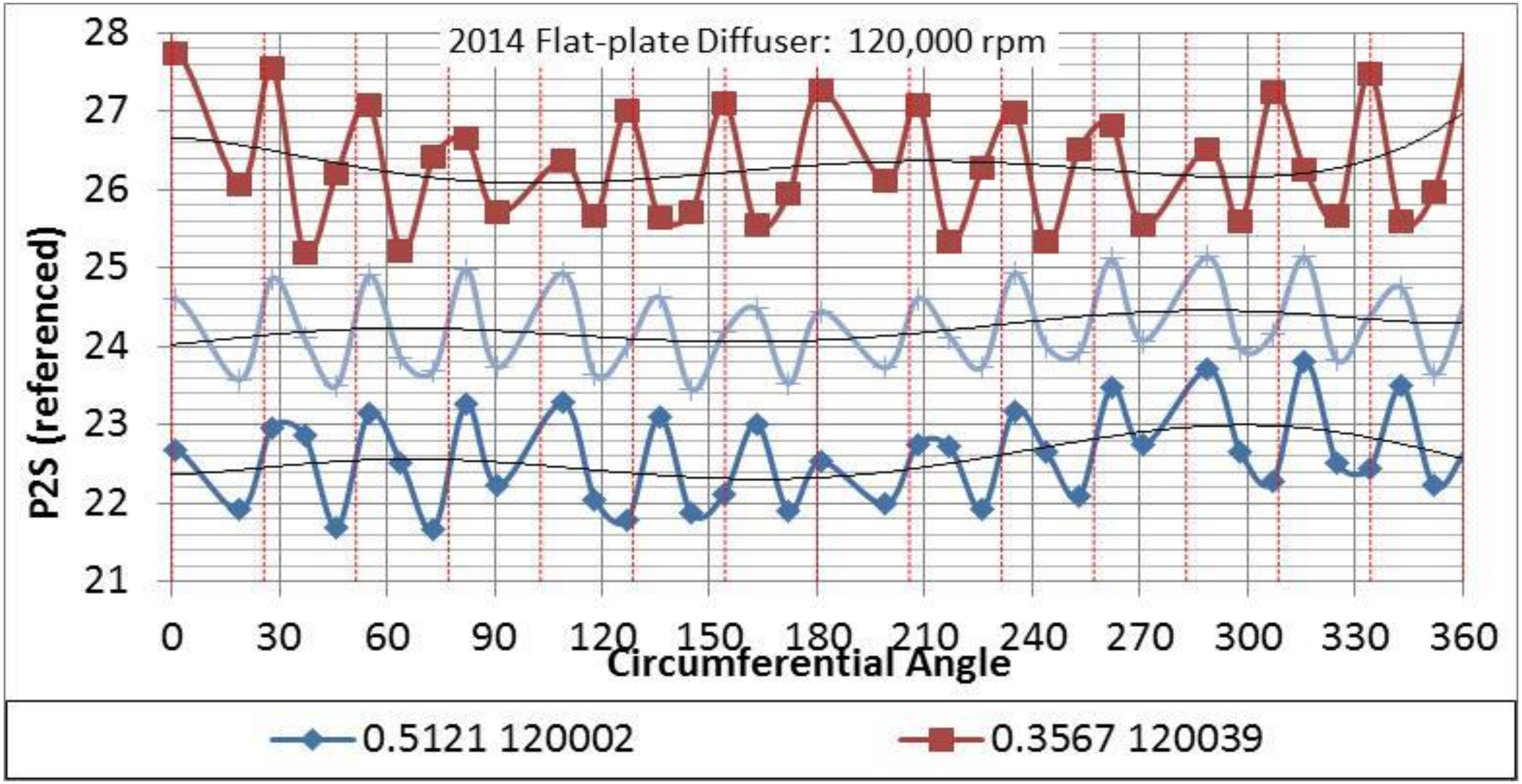
# 360° Diffuser Inlet Pressure Measurements, FP LSA




14 Diffuser Vanes; 14 pressure maxima at each flow rate; two cyclic maxima

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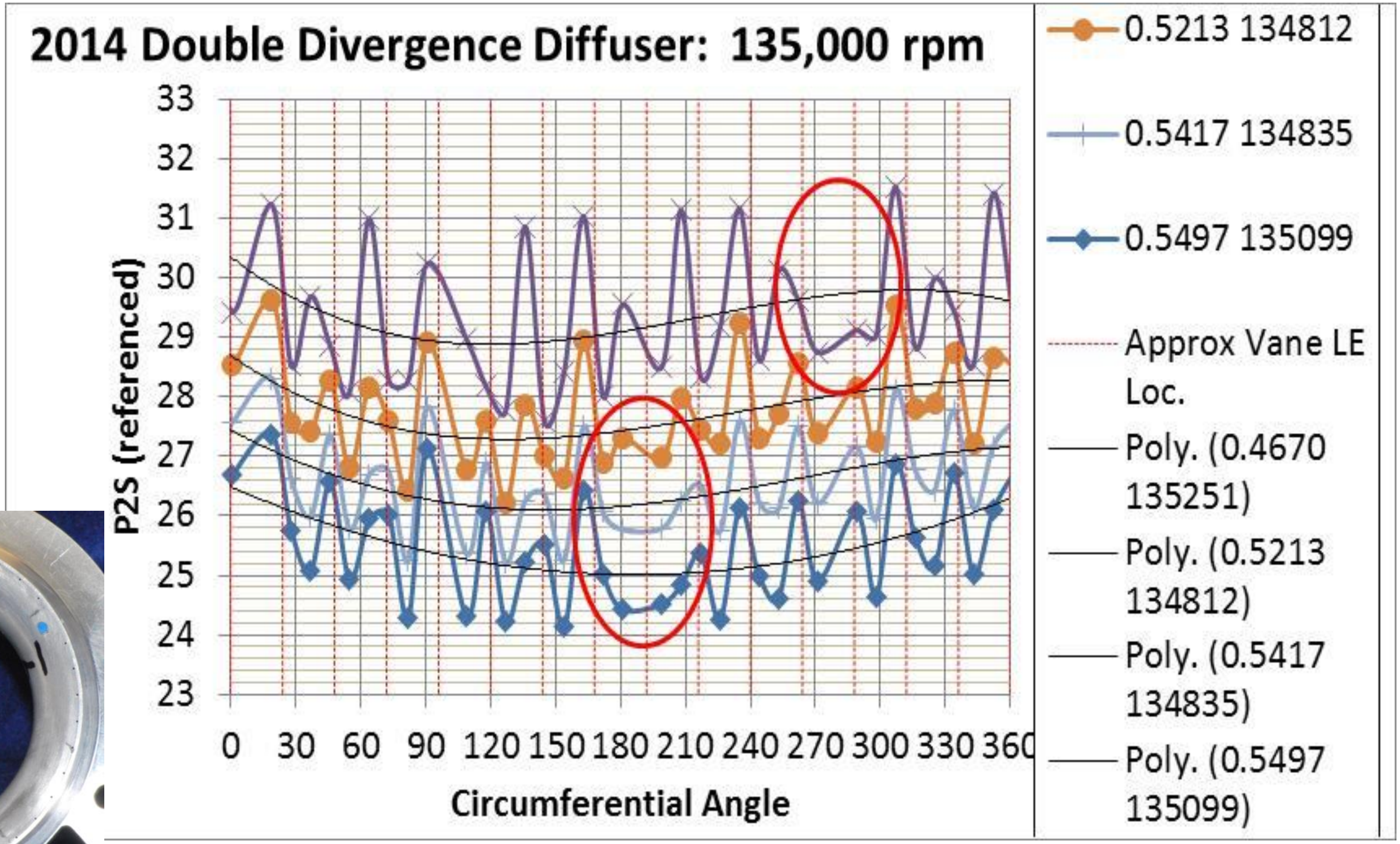
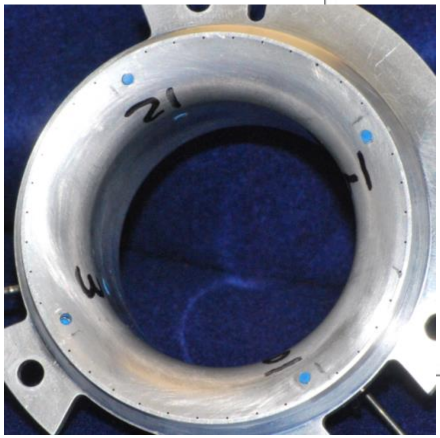
# 360° Diffuser Inlet Pressure Measurements, Channel



15 diffuser vanes; 13 – 15 maxima; two passages without a maxima

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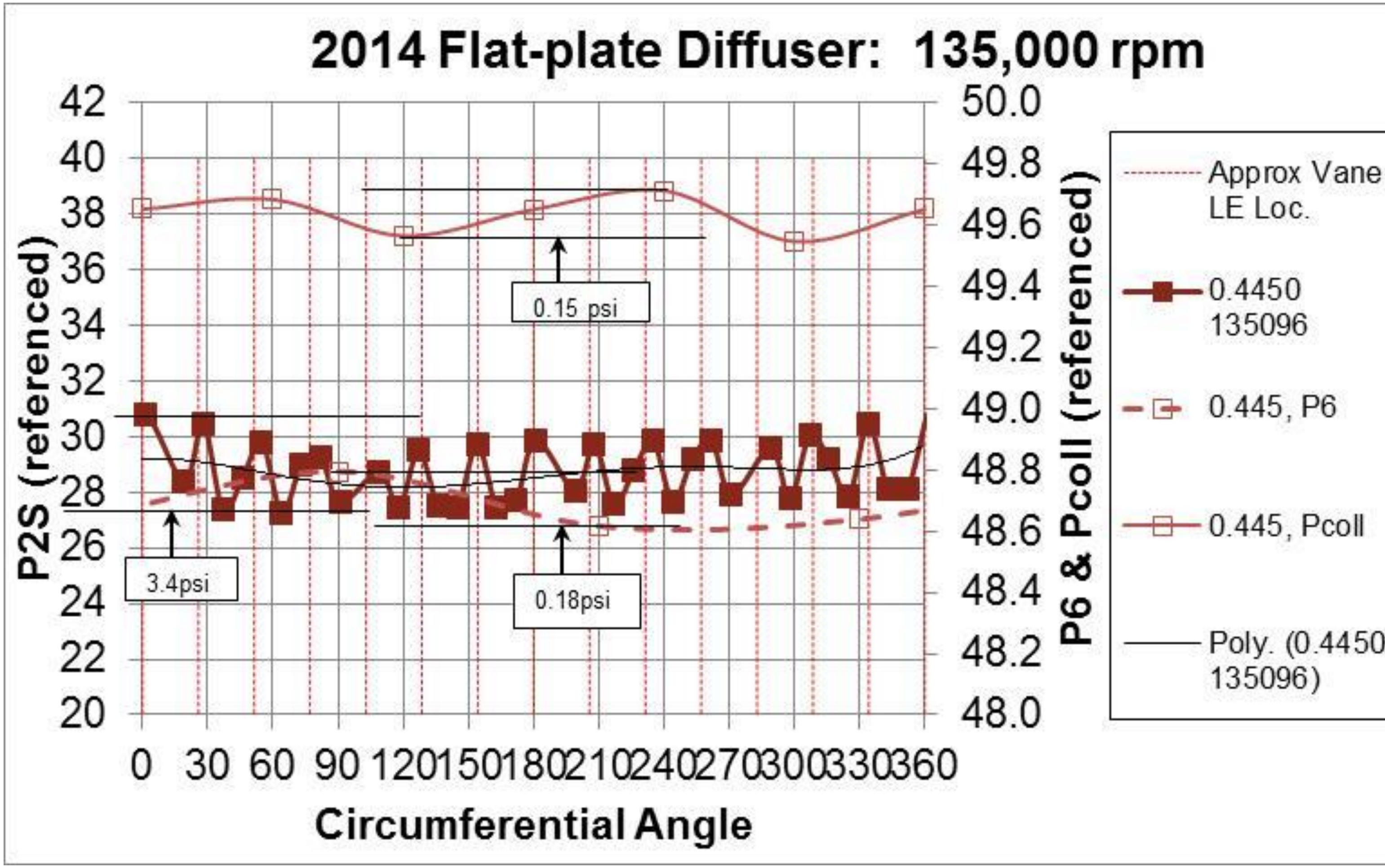
# Pressure Distortion at Various Locations




Collector distortion: +- 0.075 psi; near diffuser exit: +- 0.09 psi; diffuser inlet: +- 1.7 psi
Note: maxima locations do not line up for the three radial locations studied

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# 36 $P_2$ Tap Data for the 25% Front Pinch Diffuser, Shroud Side

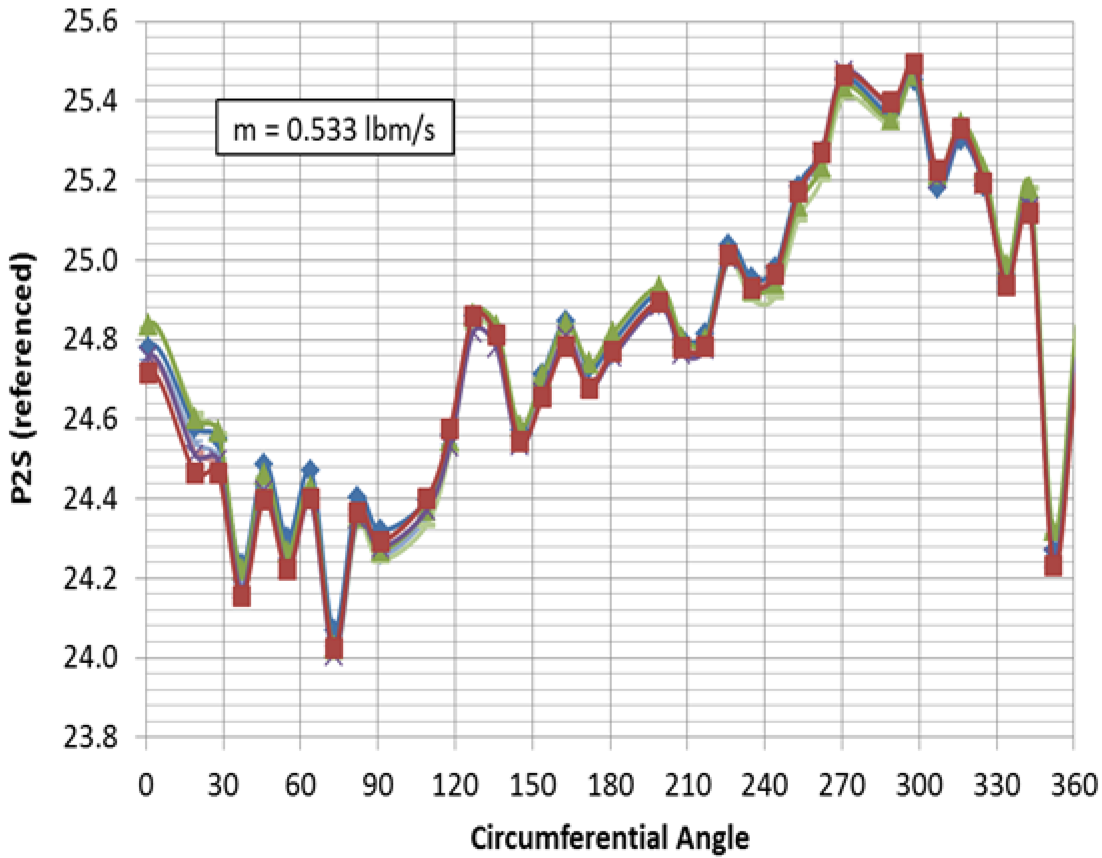


**Figure 6. Circumferential pressure traces for the 25% front pinch vaneless diffuser at seven increments of time, each taken 5 minutes apart; front side – 135,000 rpm**

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# Hub Side Data

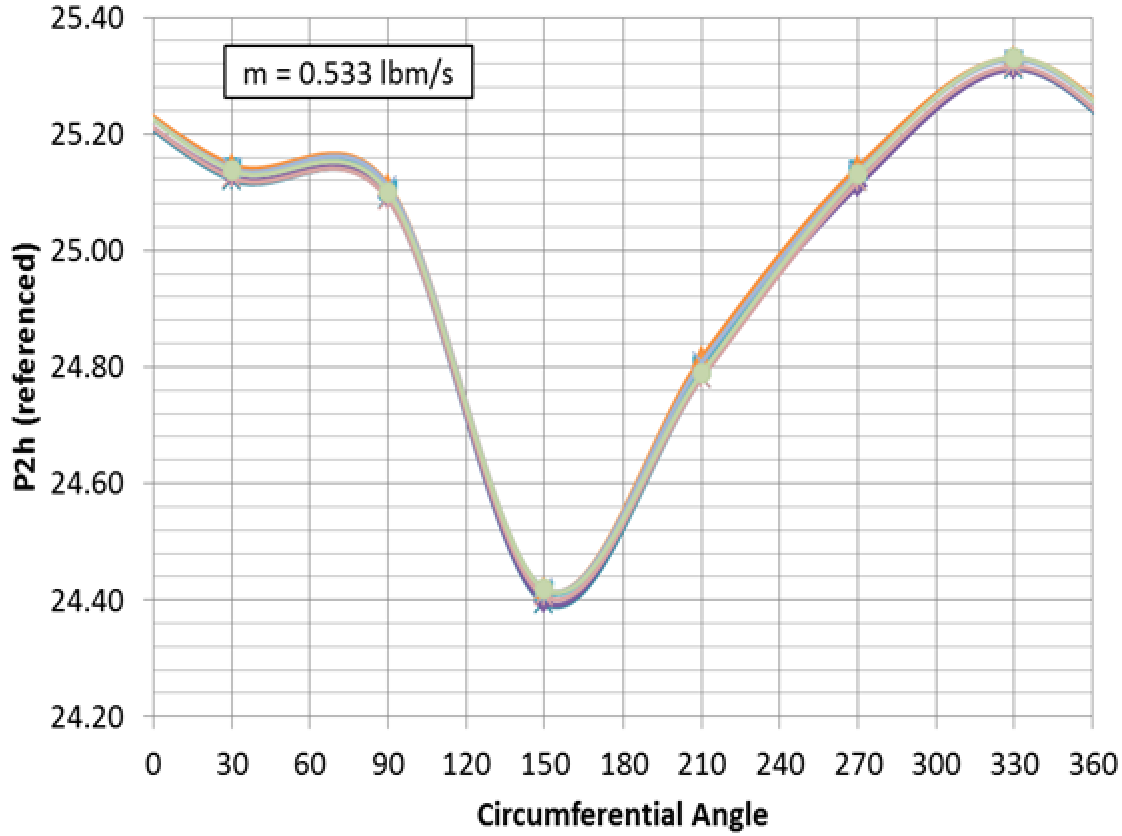


**Figure 7. Seven circumferential pressure traces for the 25% front pinch vaneless diffuser at seven increments of time, each taken 5 minutes apart; rear (hub) side - 135,000 rpm**

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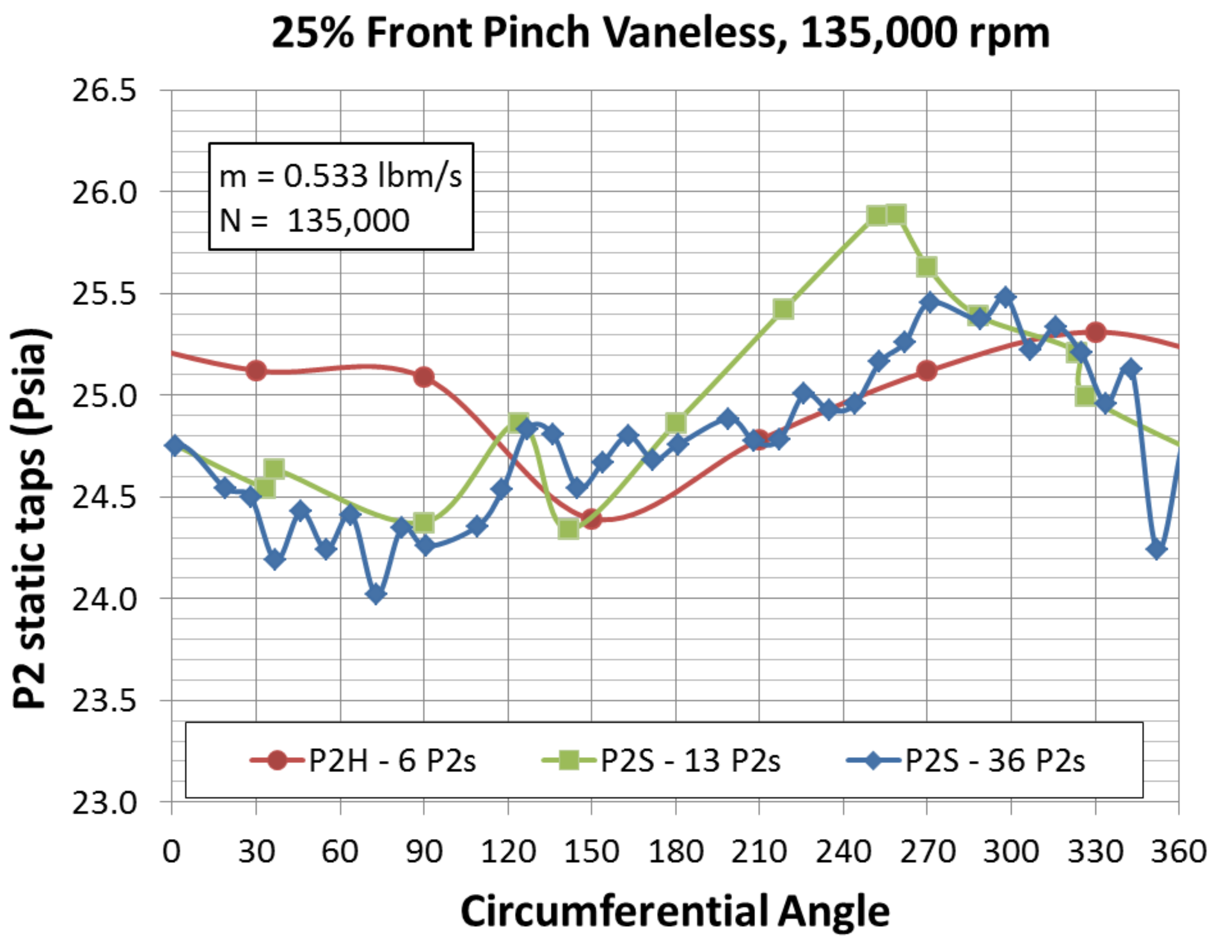
# Composite P2 Data Sets; 25% Shroud

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# Three Harmonic Representation

$$f(\theta) = a_0 + \sum_{n=1}^{\infty}\left(a_n \cos\left(n(\theta+\delta)\right)\right)$$

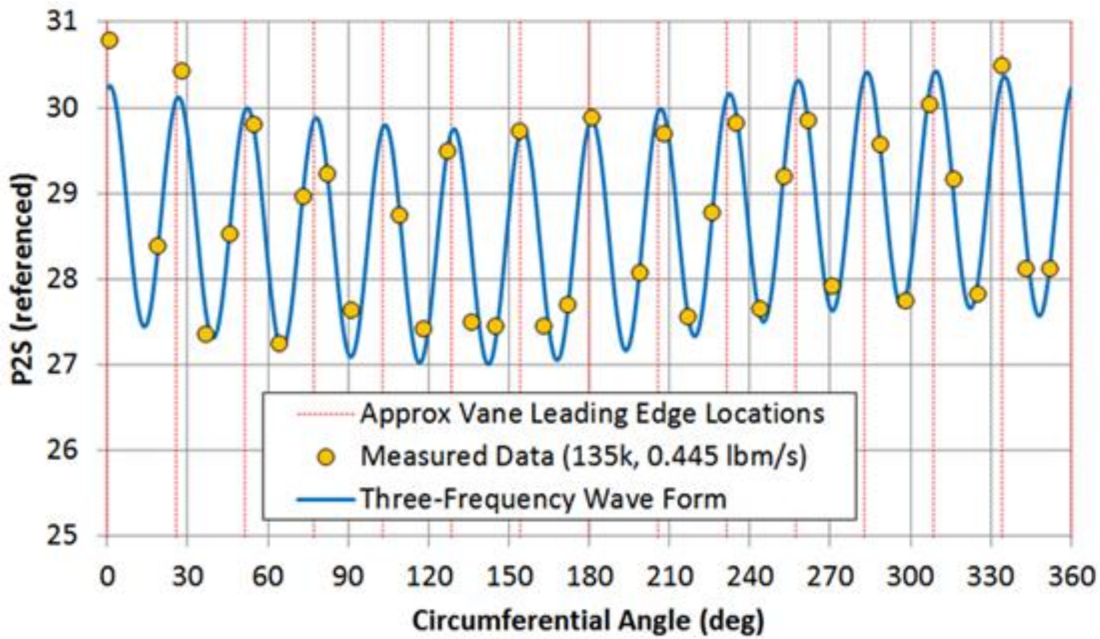


**Figure 12. Measured pressure versus circumferential location compared to sinusoidal model; 14-vane flat-plate diffuser**

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# Single Pitch Modeling

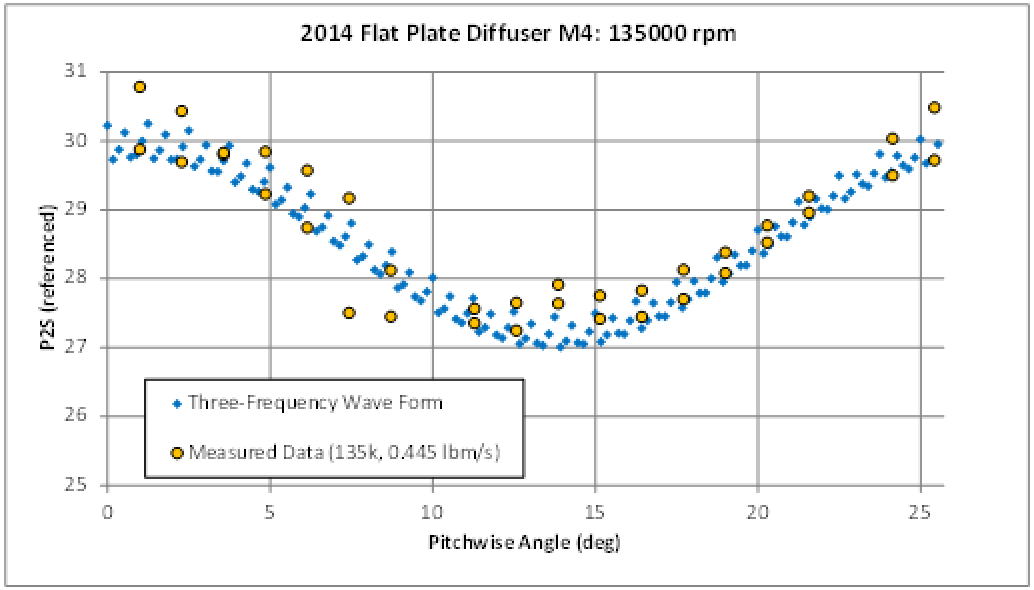


**Figure 13. Measured pressure versus pitchwise location compared to sinusoidal model; 14-vane flat-plate diffuser**

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# Phase Shift

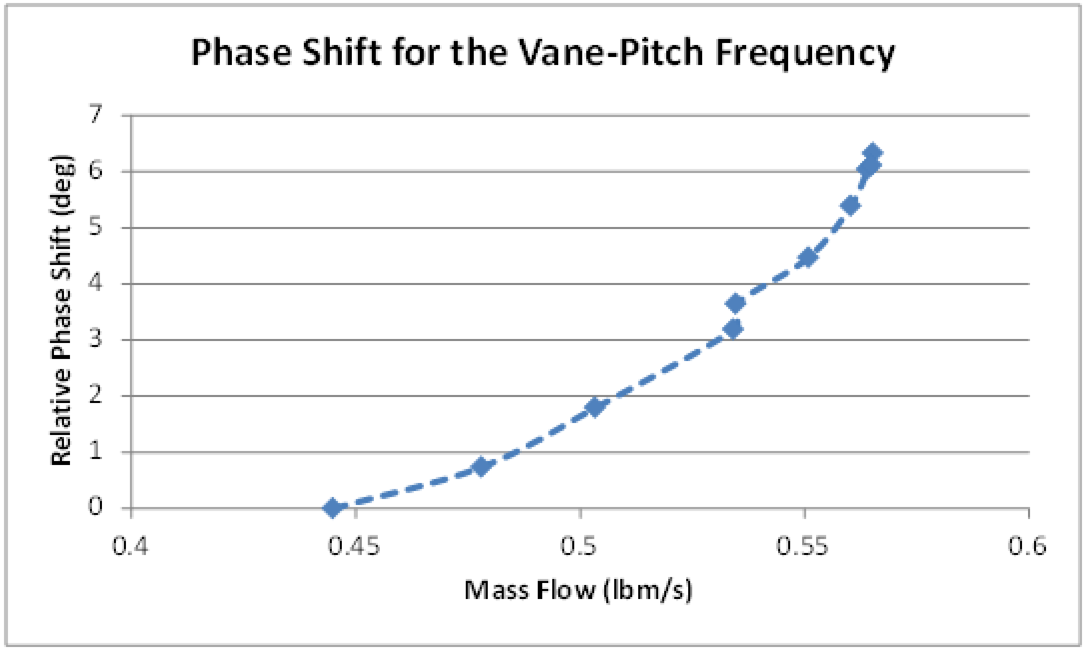


**Figure 14. Effective phase shift of the diffuser vane pressure field at impeller discharge**

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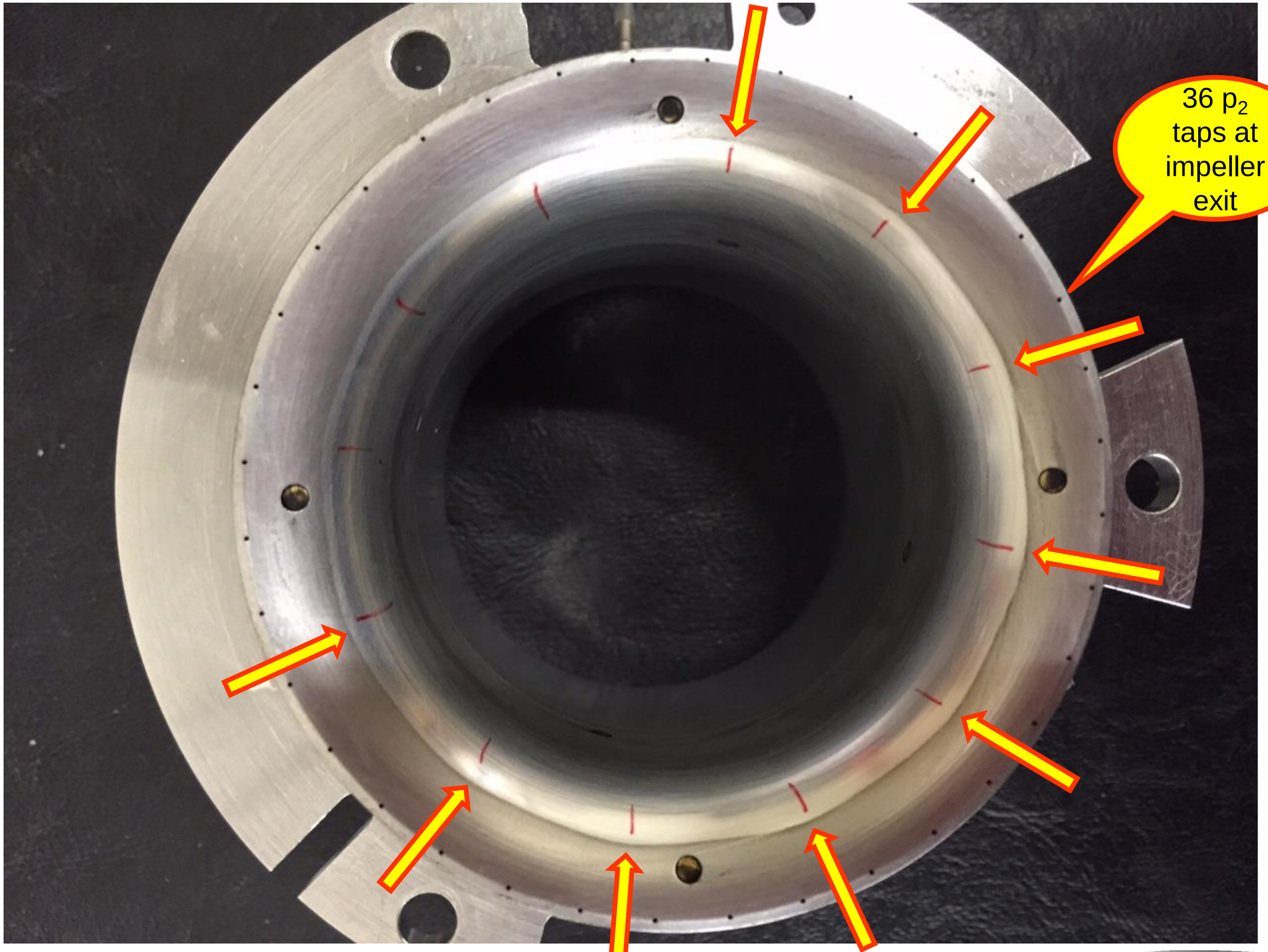
# Cover Oil Traces with a 12-vane Diffuser

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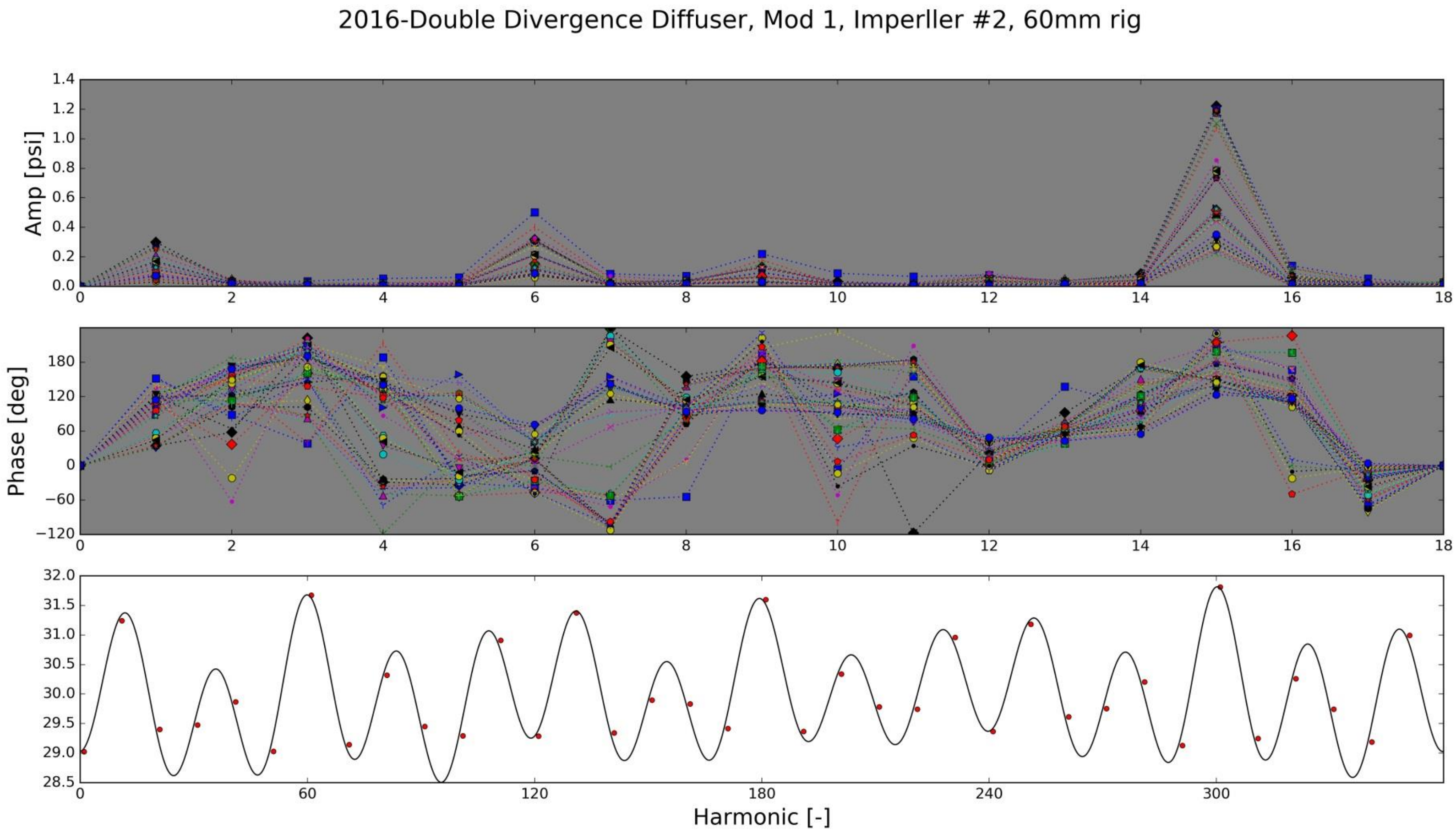
# Harmonic Analysis - DD

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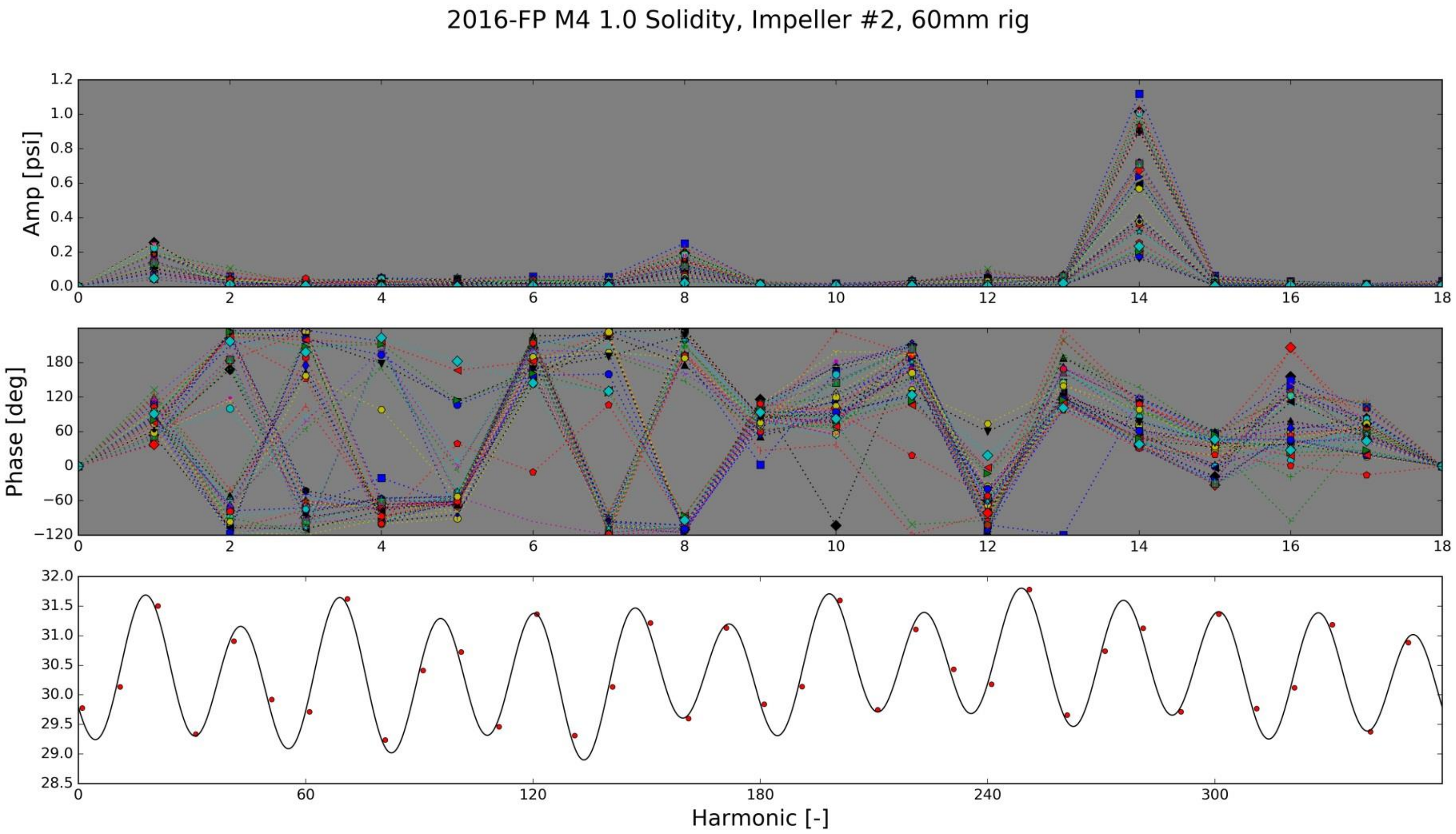
# Harmonic Analysis – M4 FP

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# New Impeller Design

1. Phase VII work requires the use of a new impeller to test out the applicability of diffusers from earlier phases of work

2. It is the explicit intent to be able to continue to use the existing best diffusers so as to give a coherent technology base

3. <u>Expectation</u>: show more of the impeller/diffuser interaction effects

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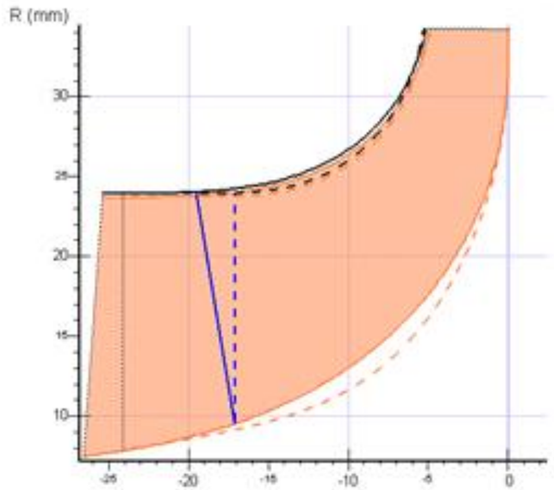
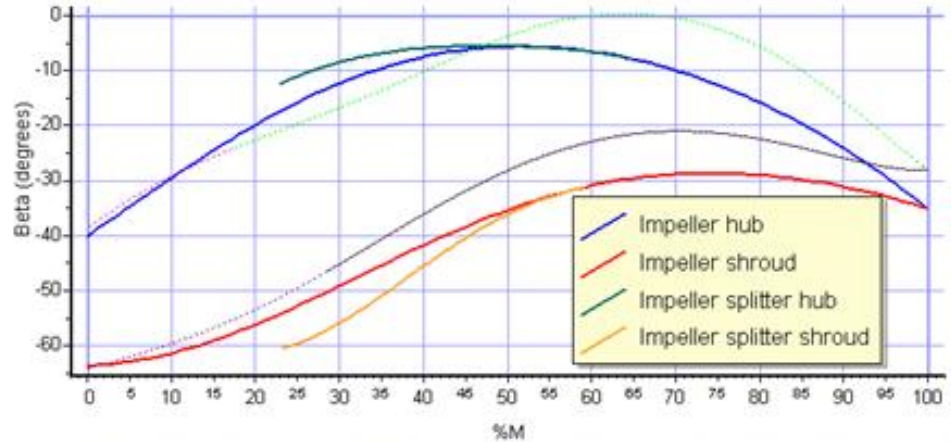
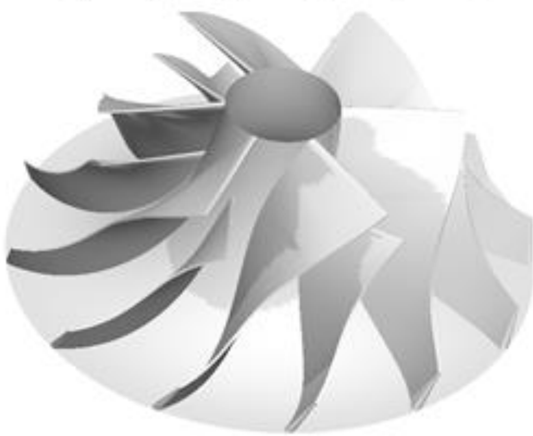
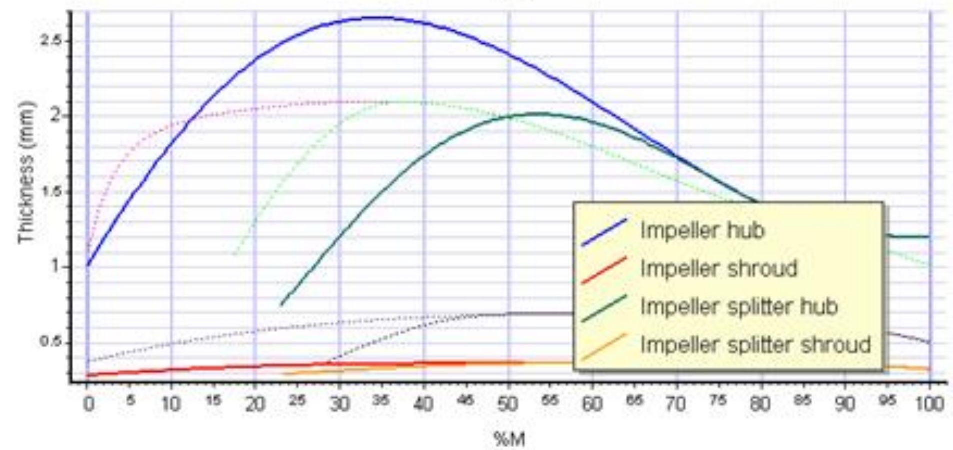
# New and Old Impeller Designs



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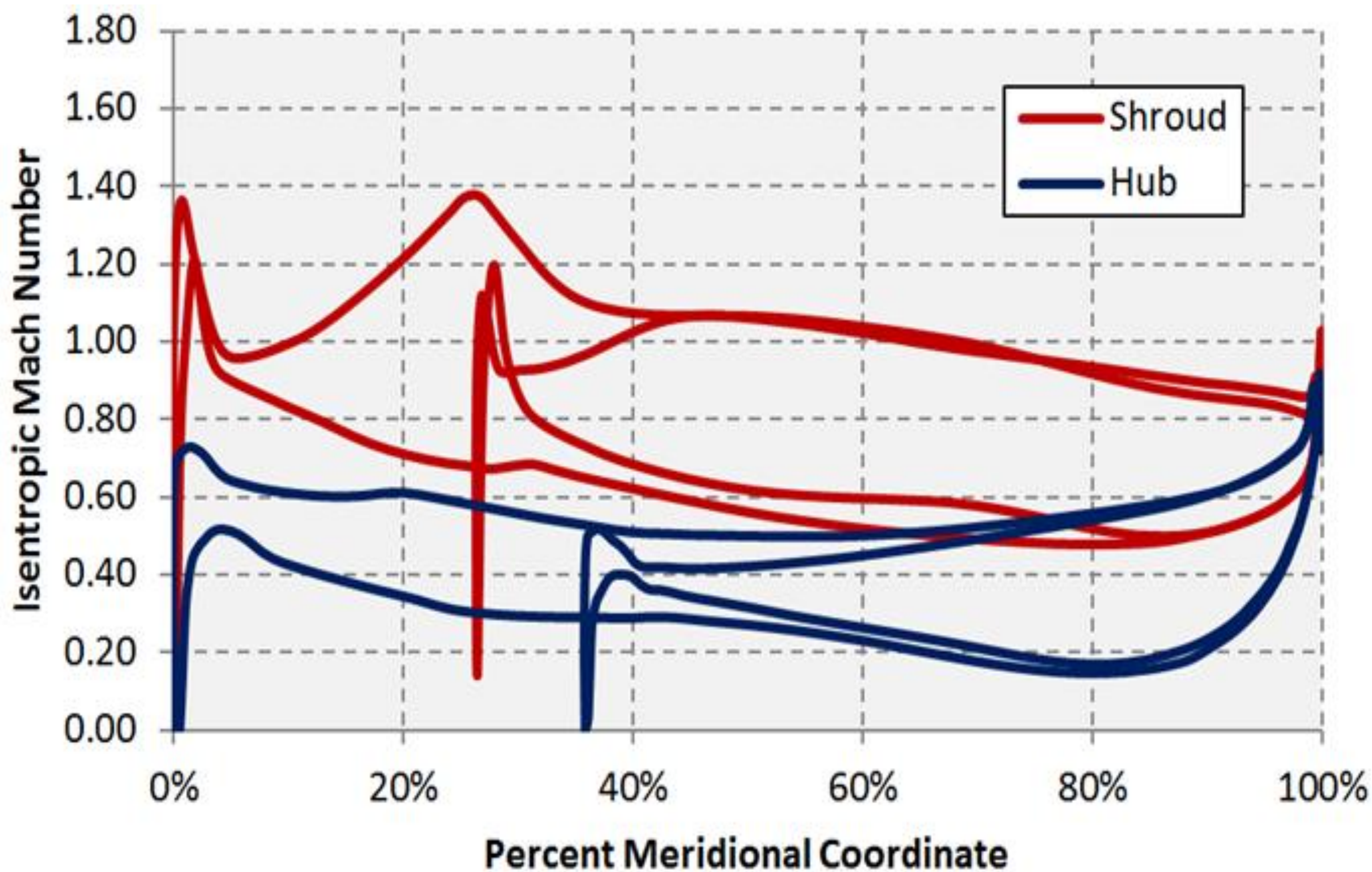
# New Impeller Loadings

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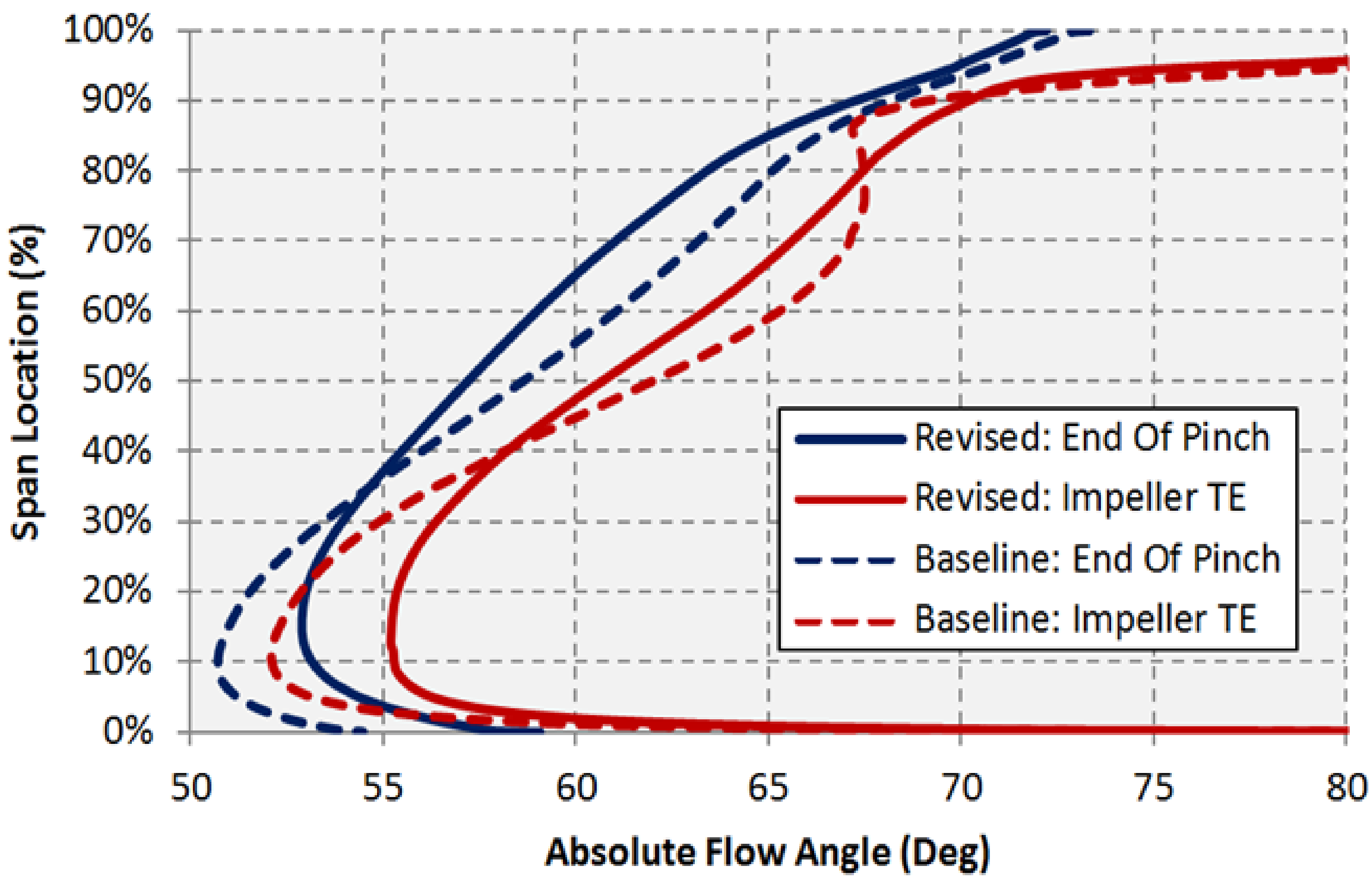
# New and Old Absolute Flow Angles

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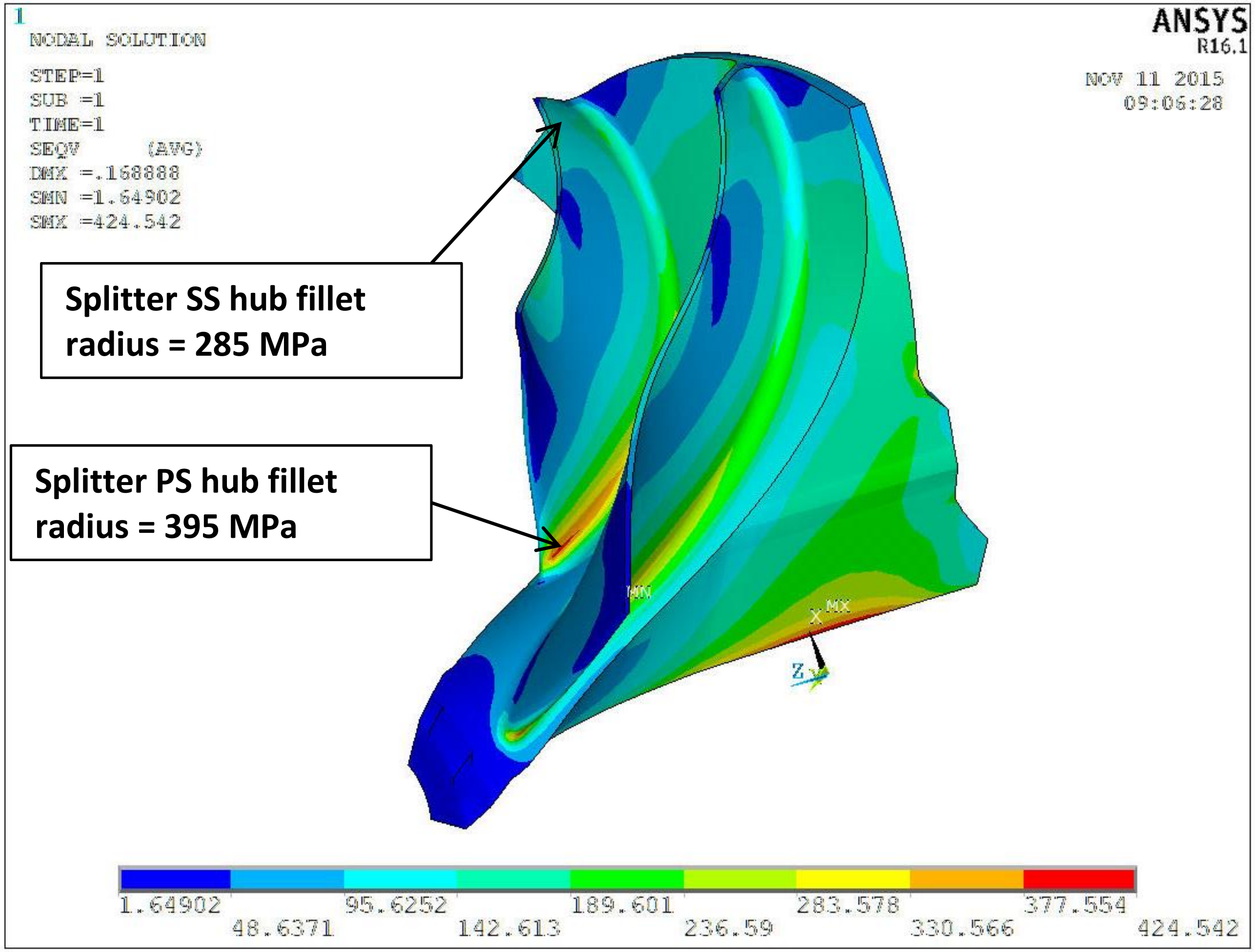
# Acceptable Steady Stress and Eigenvalues

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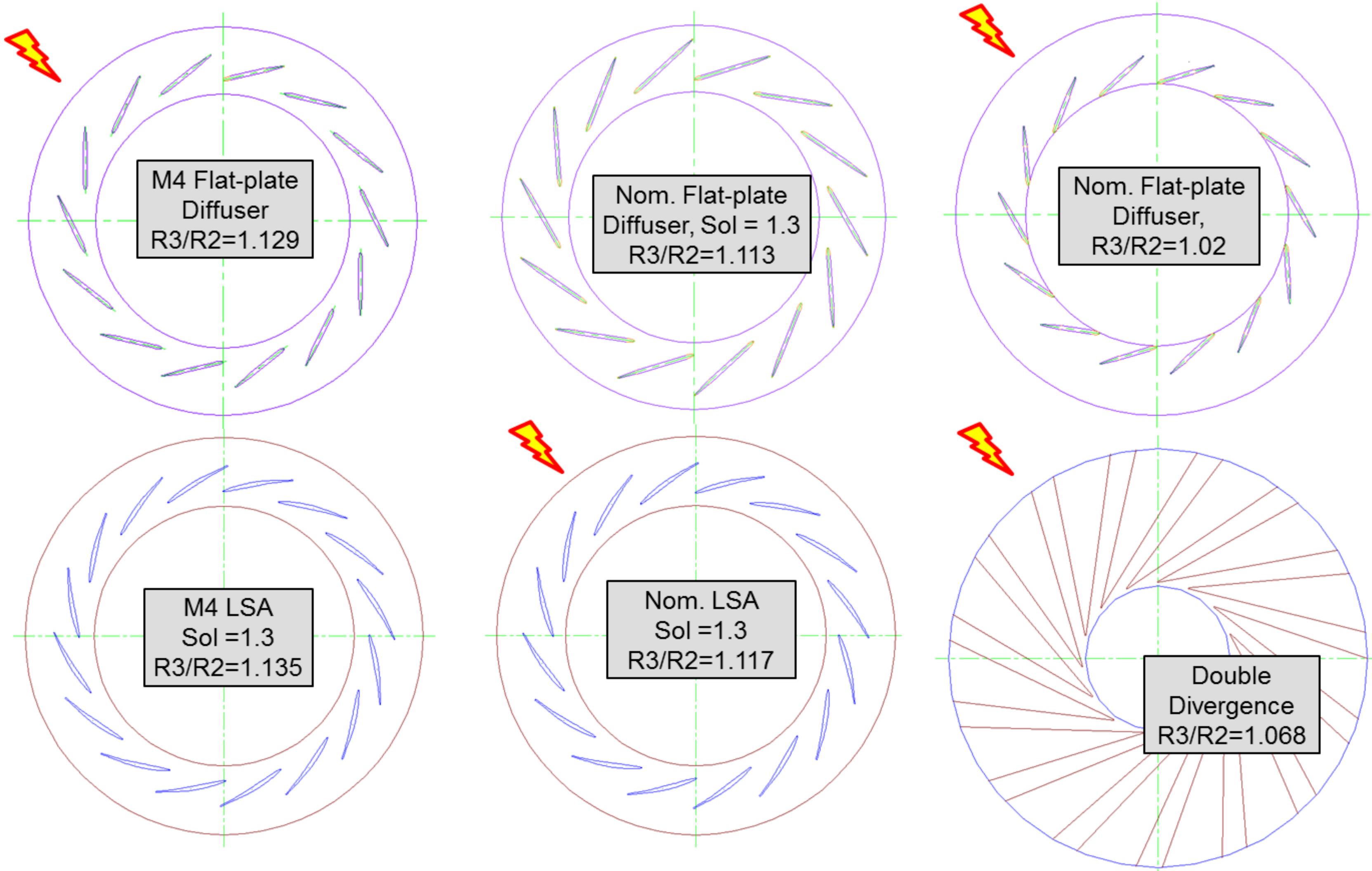
# Vane Tests with New Impeller

1. Will the best available diffusers still perform the same or similar?
2. Will any new performance *gains* be found?
3. Will any flow process be clarified?

# High-performance Diffusers

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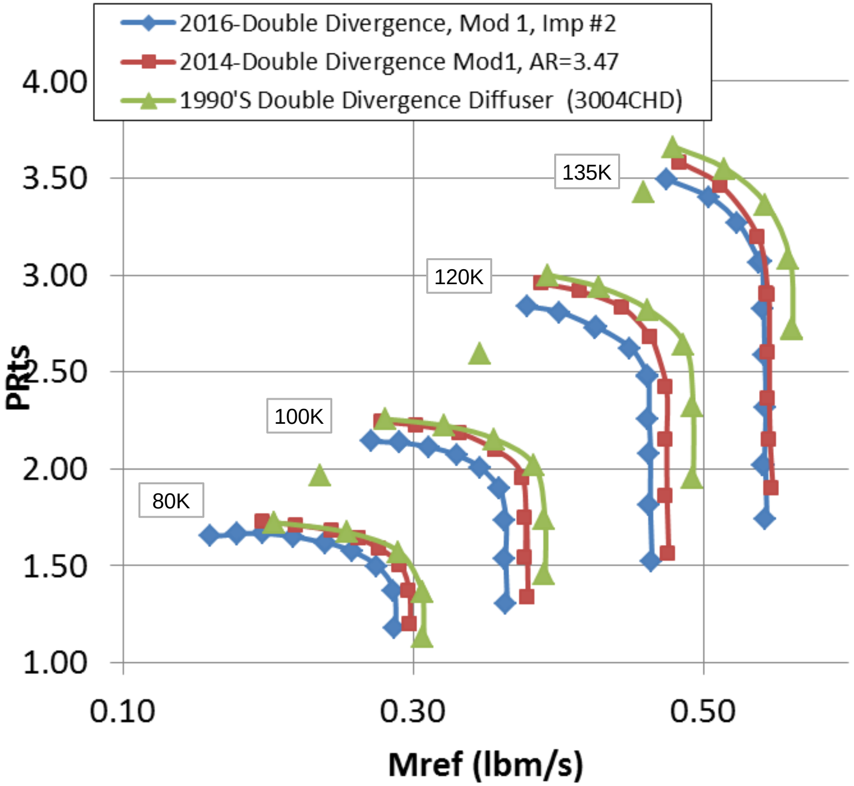
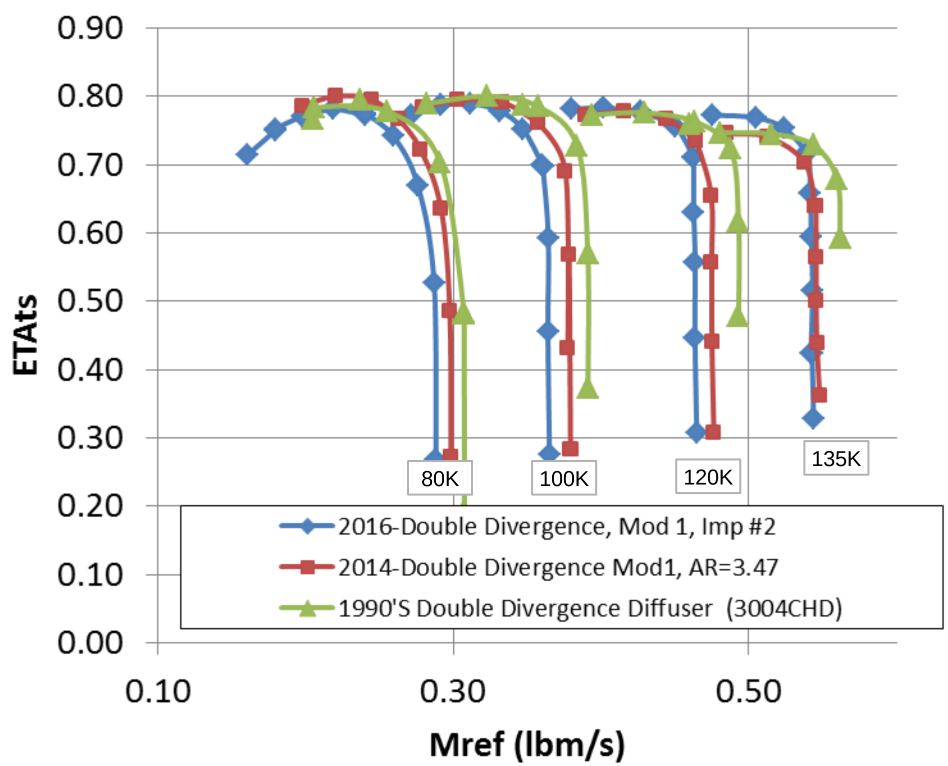
# DD Vanes with New Impeller Is Good




Performance of the double divergent diffuser with new and old impellers; n.b. different inlet ducts used.

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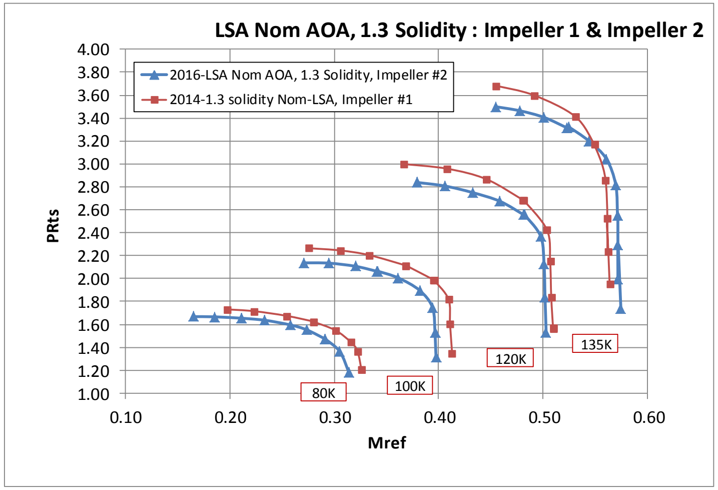
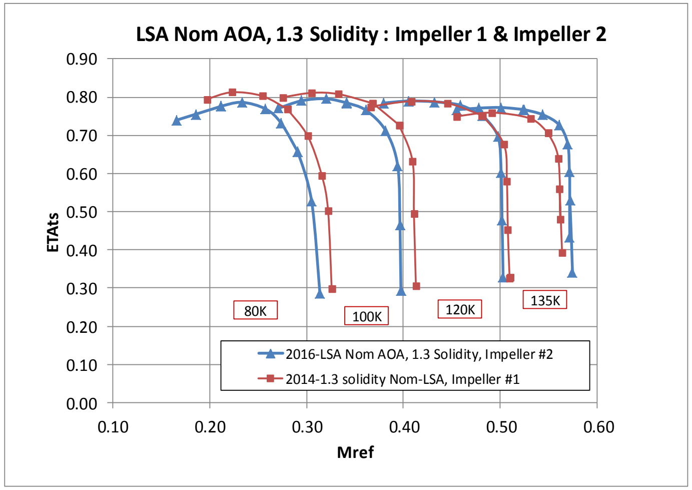
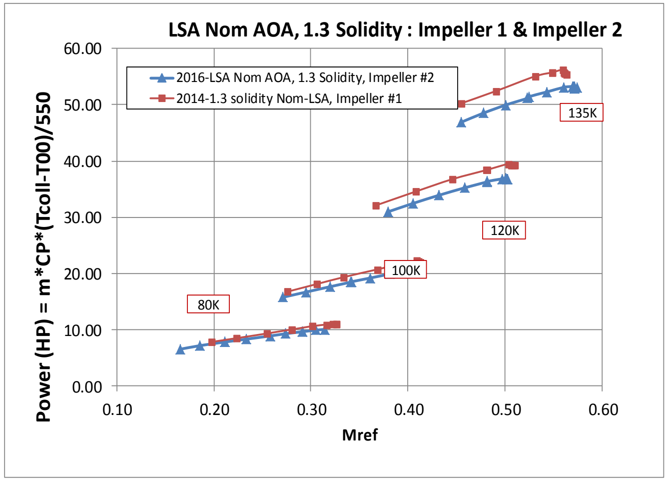
# Nominal LSA Diffuser




Performance of the LSA-1.3S diffuser with new and old impellers % work input for the LSA-1.3S diffuser with new and old impellers; n.b. different inlet ducts used.

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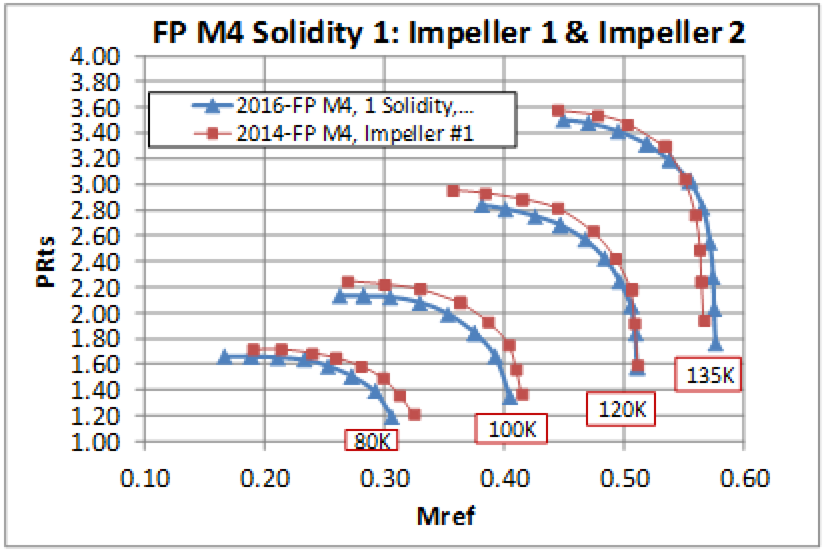
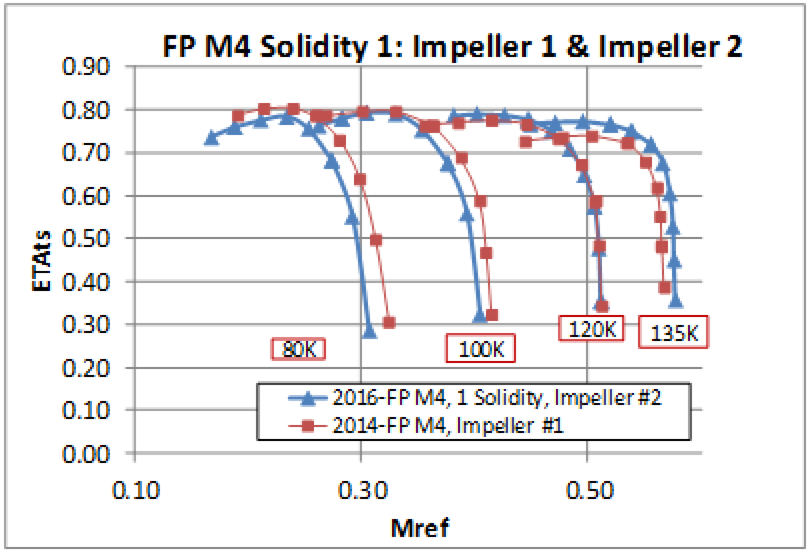
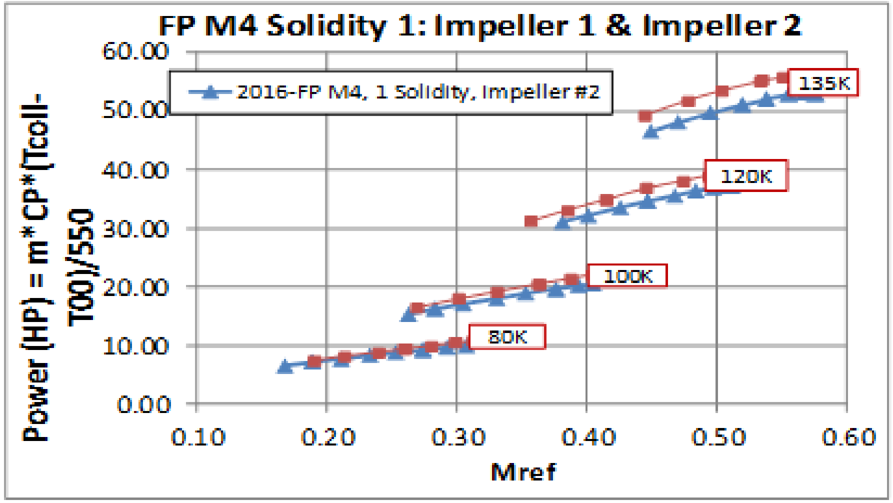
# Flat-plate Diffuser, M4




Improvement for the Flat-plate Diffuser is the best of all three; n.b. different inlet ducts used.

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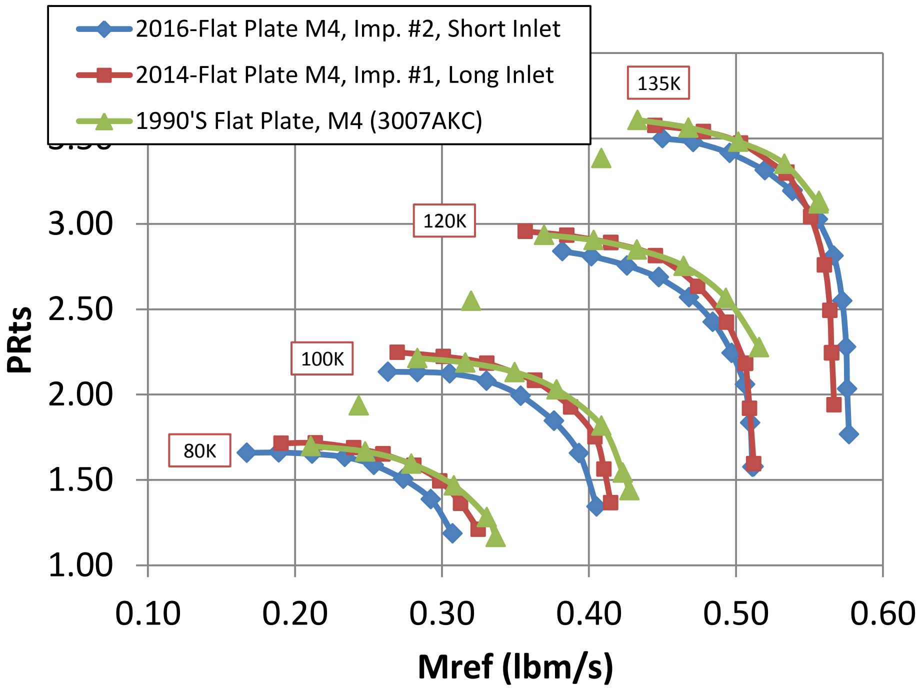
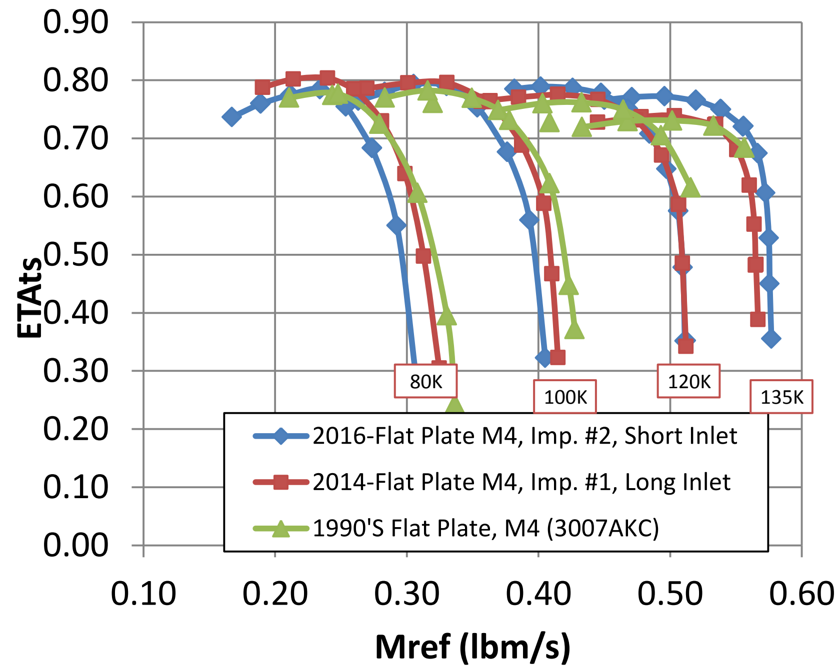
# Flat-plate and New Impeller Are Tops!

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# Summary

- Vaned diffusers are good to very high pressure ratios; vaneless diffusers have a range advantage from the choke side below pr = 2.5
- Circumferential diffuser inlet distortion definitely exists; energy content is unknown
- The LSA, flat-plate, double & tangential divergent channel, and conical diffuser all show top performance, and many with low vane numbers (12 to 17 vanes)
- The LSA & flat-plate show wide range & good efficiency
- The flow-wise grooved cover improved the surge margin nicely for the front pinch vaneless diffuser at both 25% and 50% pinch levels; it also increased range with a vane diffuser
- The alternative impeller gives similar performance to the old impeller tests for the LSA and DD diffusers but markedly improved performance for the FP diffuser; the role of CFD here is in question
- The FP diffuser might form the basis of an excellent start for a Super Diffuser
- There are multiple means for better range and efficiency

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# Super Diffusers

**Super Diffuser:** *A diffuser that distinctly stands out from the state-of-the-art (SOA) best practices by one or more of the following attributes:*

1) A stage efficiency that is about 3 points* higher than SOA due to new diffuser attributes
2) A stage pressure characteristic that gives good pressure rise at low flow and extends the stable operating range by 10% or more
3) A stage that reduces vibration and / or noise by a distinct margin
4) A stage that does several of the above

---

* For new work, this will also require >80% Cp recovery for large stages and > than 77% Cp recovery for small stages in a useful flow range.

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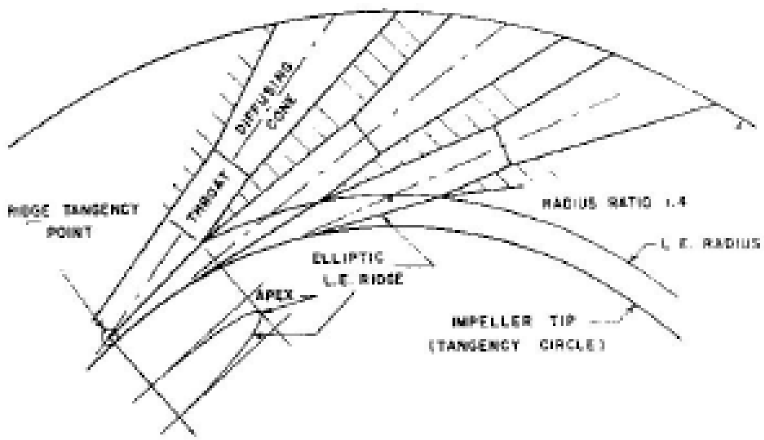
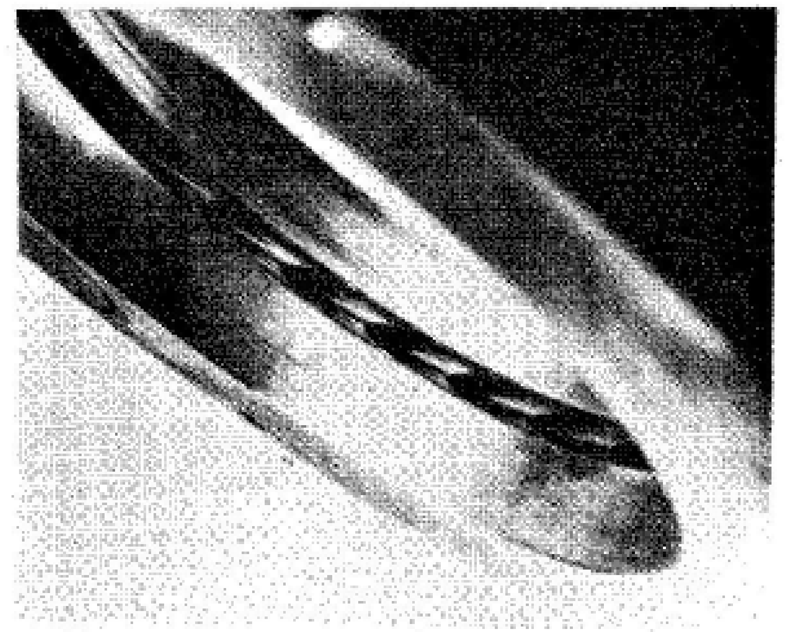
# Conical Diffusers: The First Super Diffuser




PIPE DIFFUSER GEOMETRY



PIPE DIFFUSER ENTRY
(showing swallow-tail vane leading edges)

Although superior differential performance was not well-defined historically, the dominant application of this diffuser to aircraft engines was based on its exemplary performance characteristics and can well be considered the first super diffuser.

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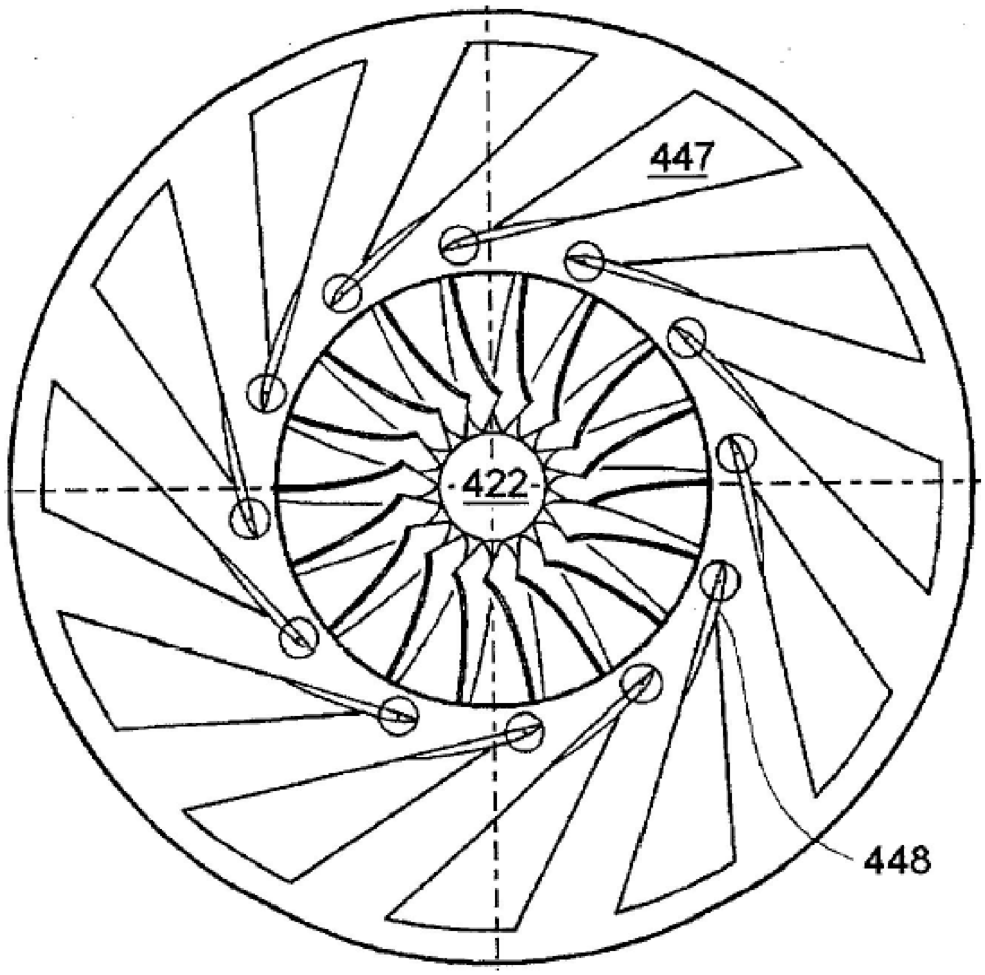
# Not this! (Blackburn ca. 1990)




Floating vanes were promising, but did not offer super performance

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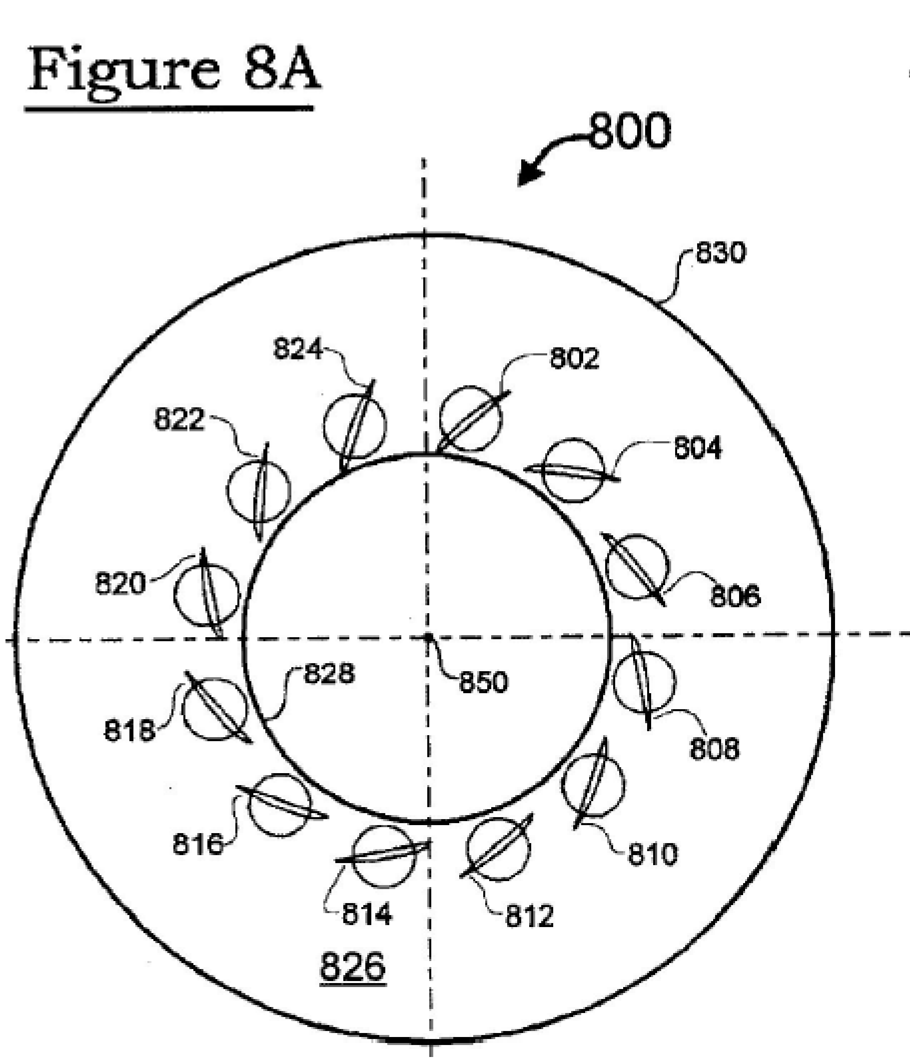
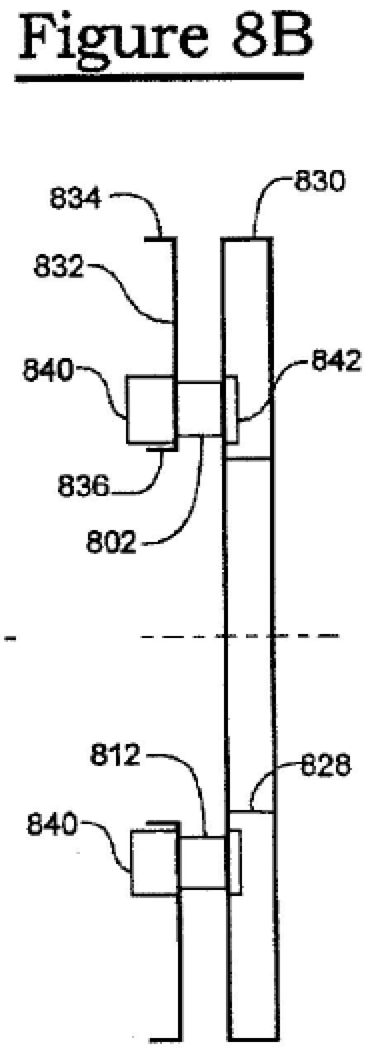
# Not this! (Japikse, US 5,730,580 1998)




Rogue vanes were promising, but did not offer super performance

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# Maybe? (Swiatek, et al. 2011/2013)

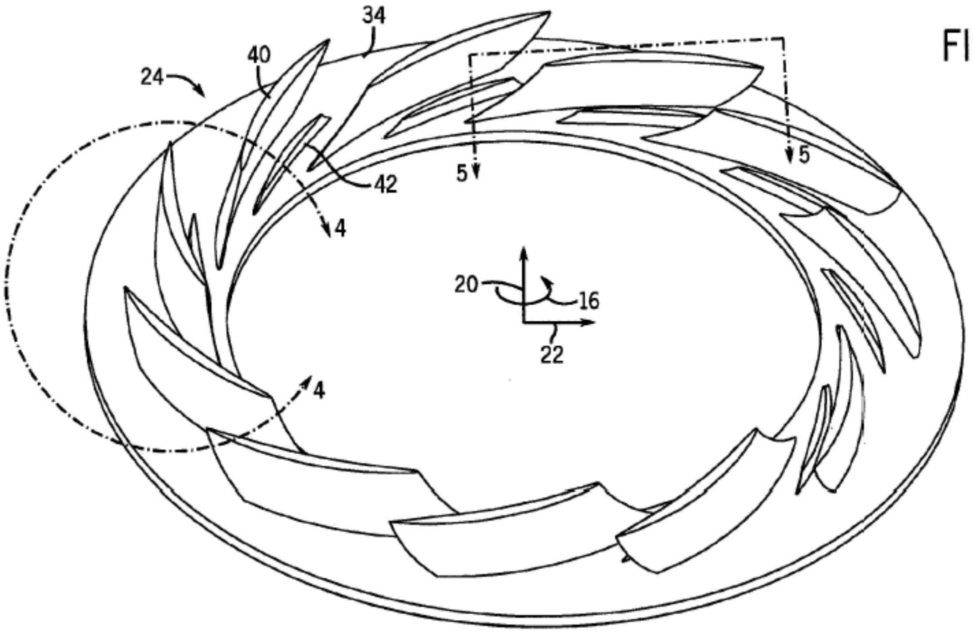
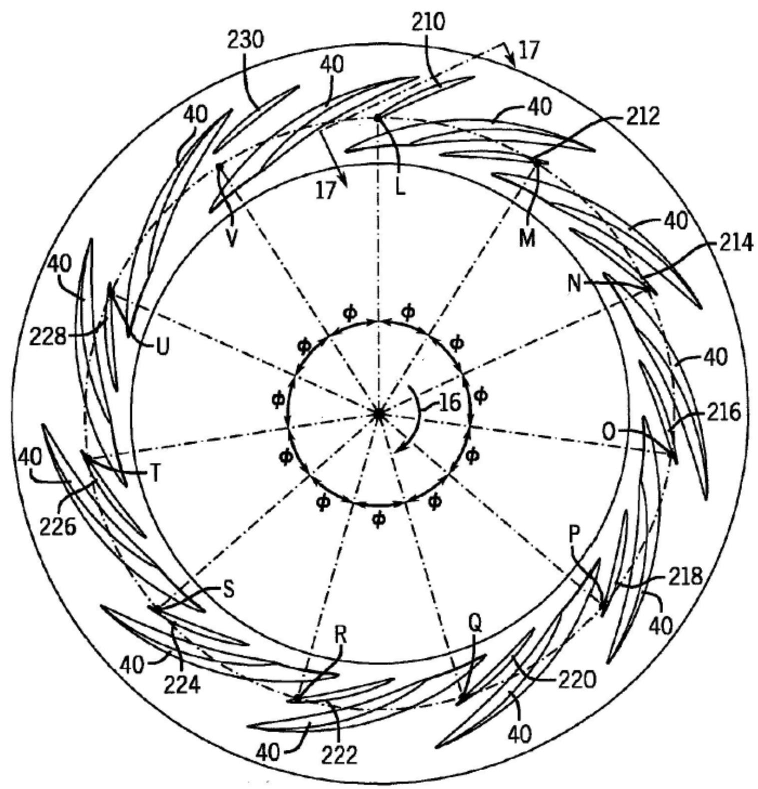



FIG. 3

US 8,602,728 B2




Partial vanes are promising; super performance is unsure at this point



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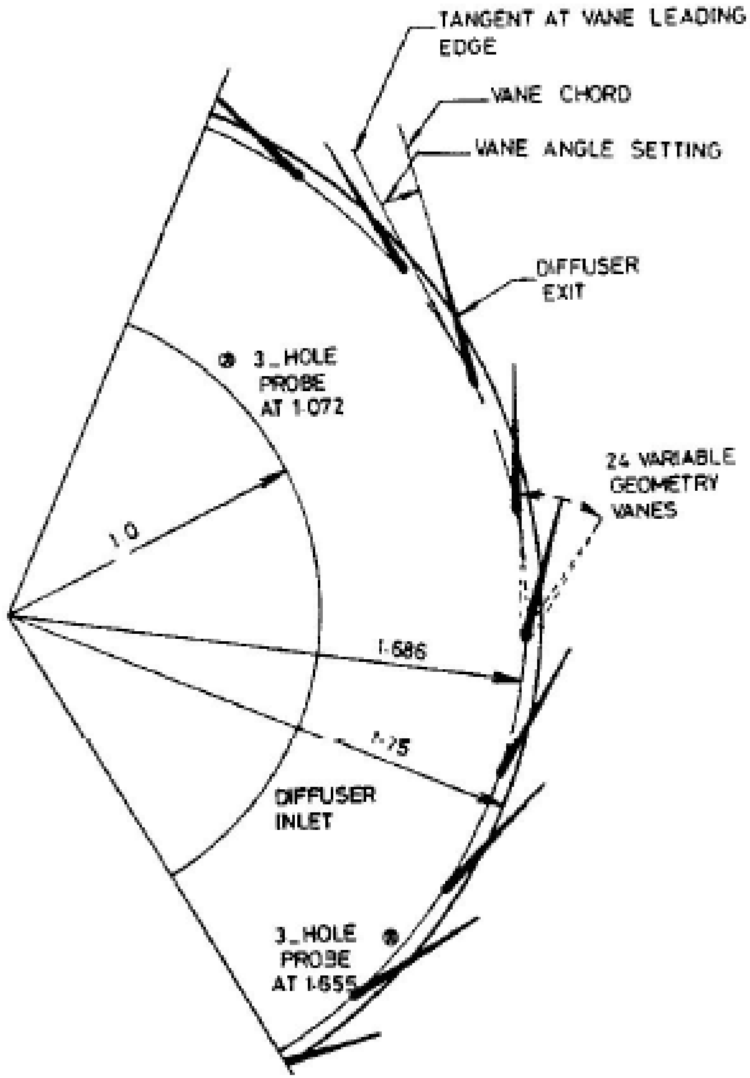
# History: Abdelhamid (ca. 1987)




This concept has rarely been tried, but might be combined with other vane types; super performance is unsure at this point

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# Super Diffuser Potential…

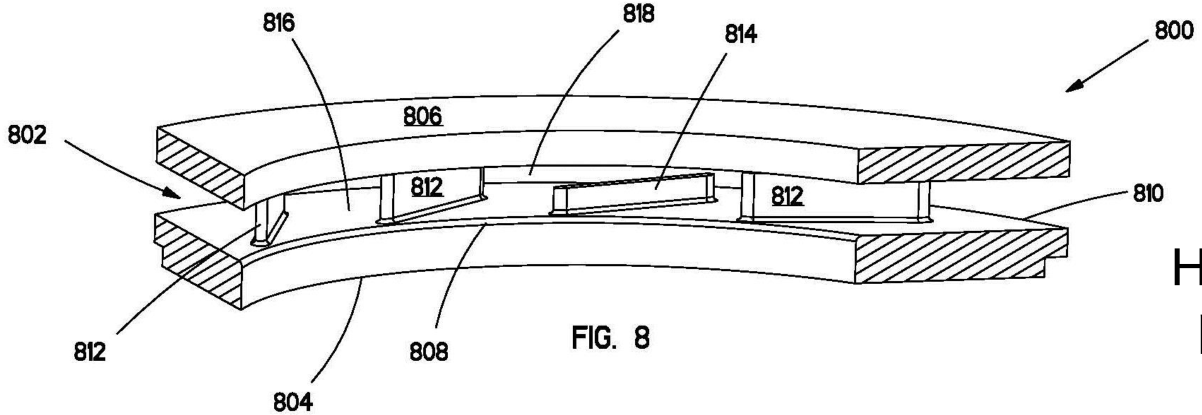


FIG. 8

Hybrid designs hold promise for super diffusers

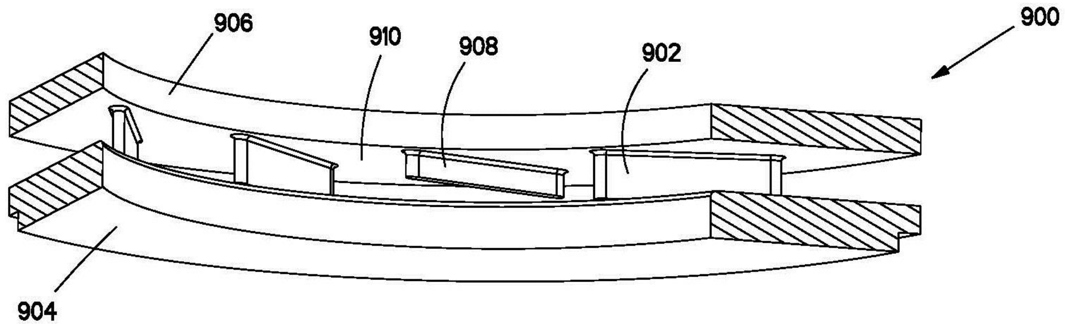


FIG. 9

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# New Vaneless Diffuser? Maybe….

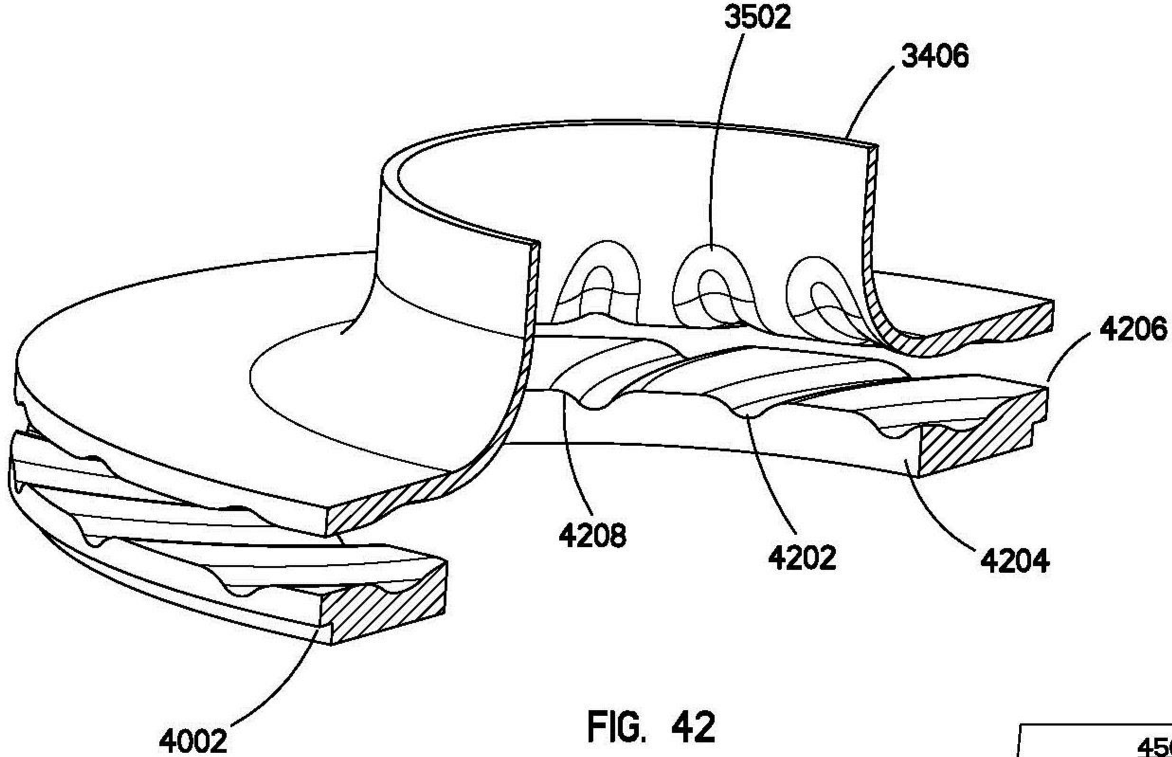


FIG. 42

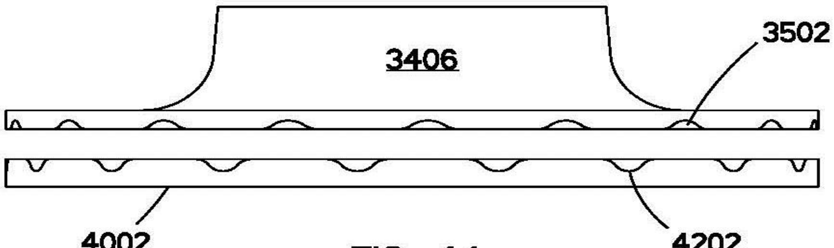


FIG. 44

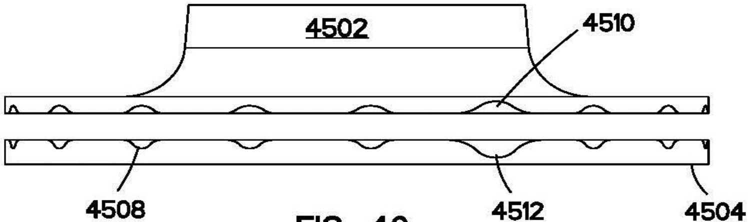


FIG. 46

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# Future Work

Is there a basis to exceed Cp = 0.80, and perhaps introduce a new super diffuser?

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# Basic Diffuser Types and Design Variables

| Vaneless Diffusers | | | | |
|---|---|---|---|---|
| Inlet coupling | $r_3/r_2$ pinch point | $b_3/b_2$ | $r_5/r_2$ | Grooves |
| **Classical Pre-1990s Design** | | | | |
| N/A | 1.2 – 1.4 | 0.8 – 0.5 | 1.6 – 2.2* | No |
| **1990s Consortia, Phases I – V** | | | | |
| N/A | 1.3 – 1.8 | 0.8 – 0.5 | 1.6 – 2.2* | No |
| **2013 – 2016 Consortium, Phase VI, Phase VIIa** | | | | |
| Yes, 0.7 – 1.8 ? | 1.8 | 0.8 – 0.5 | 1.6 – 2.2* | Likely use |
| **2016 – Consortium, Phase VIIb, Phase VIII** | | | | |
| ***Super Diffusers*** | | | | |
| Yes, 0.7 – 1.8 ? | 1.8 | 0.8 – 0.5 | 1.6 – 2.2* | Use |

| Low Solidity Airfoil (LSA) Diffusers | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Inlet coupling | $r_3/r_2$ | $r_4/r_2$ | $r_5/r_2$ | $AOA_D$ (°) | $C_L$ | $\sigma$ | $Z_d$ | Shape | Grooves |
| **Classical Pre-1990s Design** | | | | | | | | | |
| N/A | 1.15 | 1.25 | * | 6.5° per NACA | 0.4 – 0.8 | 0.9 – 1.0 | Dependent | LSA - airfoil | No |
| **1990s Consortia, Phases I – V** | | | | | | | | | |
| N/A | 1.05 – 1.2 | 1.2 – 1.3 | * | -4 to 4 | 0.4 – 0.8 | 0.9 – 1.3 | Dependent | LSA or FP LSA | No |
| **2013 – 2016 Consortium, Phase VI, Phase VIIa** | | | | | | | | | |
| First priority | 0.7 – 1.05 | 1.2 – 1.3 | * | -4 to 4 | 0.4 – 1 | 0.9 – 1.5 | First order choice? | Consider FP first | Likely use |
| **2016 – Consortium, Phase VIIb, Phase VIII** | | | | | | | | | |
| ***Super Diffusers*** | | | | | | | | | |
| First priority | 0.7 – 1.05 | 1.2 – 1.3 | * | -4 to 4 | - | 0.9 – 1.5 | 1st choice – low distortion | FP Variant | Use |

| Channel Diffusers | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Inlet coupling | $r_3/r_2$ | $r_5/r_2$ | $2\theta$ | $\theta_A$ | L/W | $AS_4$ | $Z_d$ | Grooves |
| **Classical Pre-1990s Design** | | | | | | | | |
| N/A | 1.06 – 1.12 | * | 7 – 8° | n/a | 16 – 18 | 0.6 – 1.5 | Dependent | No |
| **1990s Consortia, Phases I – V** | | | | | | | | |
| N/A | 1.02 – 1.08 | * | 5 – 8° | ca 2° | 10 – 14 | 0.6 – 2 | Dependent | No |
| **2013 – 2016 Consortium, Phase VI, Phase VII** | | | | | | | | |
| First priority | 0.7 – 1.06 | * | 5 – 7° | < 7° | 10 – 14 | 0.6 – 2 | First order choice? | Likely use |
| **2016 – Consortium, Phase VIIb, Phase VIII** | | | | | | | | |
| ***Super Diffusers*** | | | | | | | | |
| First priority | 0.7 – 1.06 | * | 5 – 7° | < 7° | 10 – 14 | 0.6 – 2 | FP Variant? Conical? | Use |

* maximum $r_5$ is usually desired, but practical size limits often interfere. The final portions of most diffusers still provide useful pressure rise.

1 – May break diffuser design into an inlet, an exit and an intermediate segment
2 – Much has been learned about the inlet segment
3 – Little is yet know about controlling the exit segment
4 – The intermediate segment could become clear as the exit segment is clarified
5 – The final diffuser may not look much like the common diffuser classes

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# Future Diffuser Designs

1. Impeller exit – diffuser inlet is probably the most important area for diffuser design
2. All other design parameters may come second
3. Vane count is wide open as a variable, and likely important
4. Reasonable chance of a standardized design, perhaps a flat-plate variant
5. Much more work is needed to learn the complete physics of impeller exit distortion; role for L2F investigations
6. Some major rebuilding of CFD may be needed!
7. Strong probability of using Flow-wise Grooved Covers as part of future designs, whether vaneless or vaned !!

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# Steps to the Consortium *Super Diffuser*

1. Biased passage: variable stagger case; variable height
2. Offset partial height vanes, biased vanes, groupings
3. Conformal variants (14, 11, 7 vane count – same shape and same LE location)
4. Exit diffuser vanes
5. Flow-wise grooves; biased flow passages
6. Leading edge shapes

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# Patents

1. A large family of patents is evolving
2. This family gives deep protection to consortium members
3. Ultimately, it will be a *serious stumbling block* to non-sponsors

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# Sponsors

| Concepts NREC Advanced Diffuser Consortium | |
|---|---|
| **Sponsoring Company** | **Sponsorship** |
| GE Aviation - Lynn Fan & Compressors | Enterprise License |
| GE Global Research | Enterprise License |
| GE Oil & Gas (AC Compressor) | Enterprise License |
| GE Oil & Gas (Nuovo Pignone) | Enterprise License |
| GE Transportation Systems | Enterprise License |
| Hangzhou Hangyang Turbomachinery | Divisional |
| Honeywell Transportation Systems - Turbo Technology | Divisional |
| Hyundai Heavy Industries Co., Ltd. | Divisional |
| IHI Corporation - Yokohama | Divisional |
| Ingersoll Rand Italiana S.p.A | Divisional * |
| IR Climate Solutions (Trane) | Divisional * |
| IR Cameron Compression Systems | Divisional * |
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| MAN Diesel &Turbo - Augsburg | Divisional * |
| MAN Diesel &Turbo - Oberhausen | (in process) * |
| MAN Diesel &Turbo - (third division TBD) | (in process) * |
| Samsung Techwin America | Divisional |
| Shenyang Blower | Divisional |
| Siemens (Dresser-Rand) | Divisional |
| Siemens (Rolls Royce Energy Systems) | Divisional |
| Siemens Oil & Gas (KK&K) | Divisional |
| Solar Turbines, Inc. | Divisional |
| Sulzer Pumps Ltd - Winterthur | Divisional |
| **Total** | **19** |

* to be converted to Enterprise License

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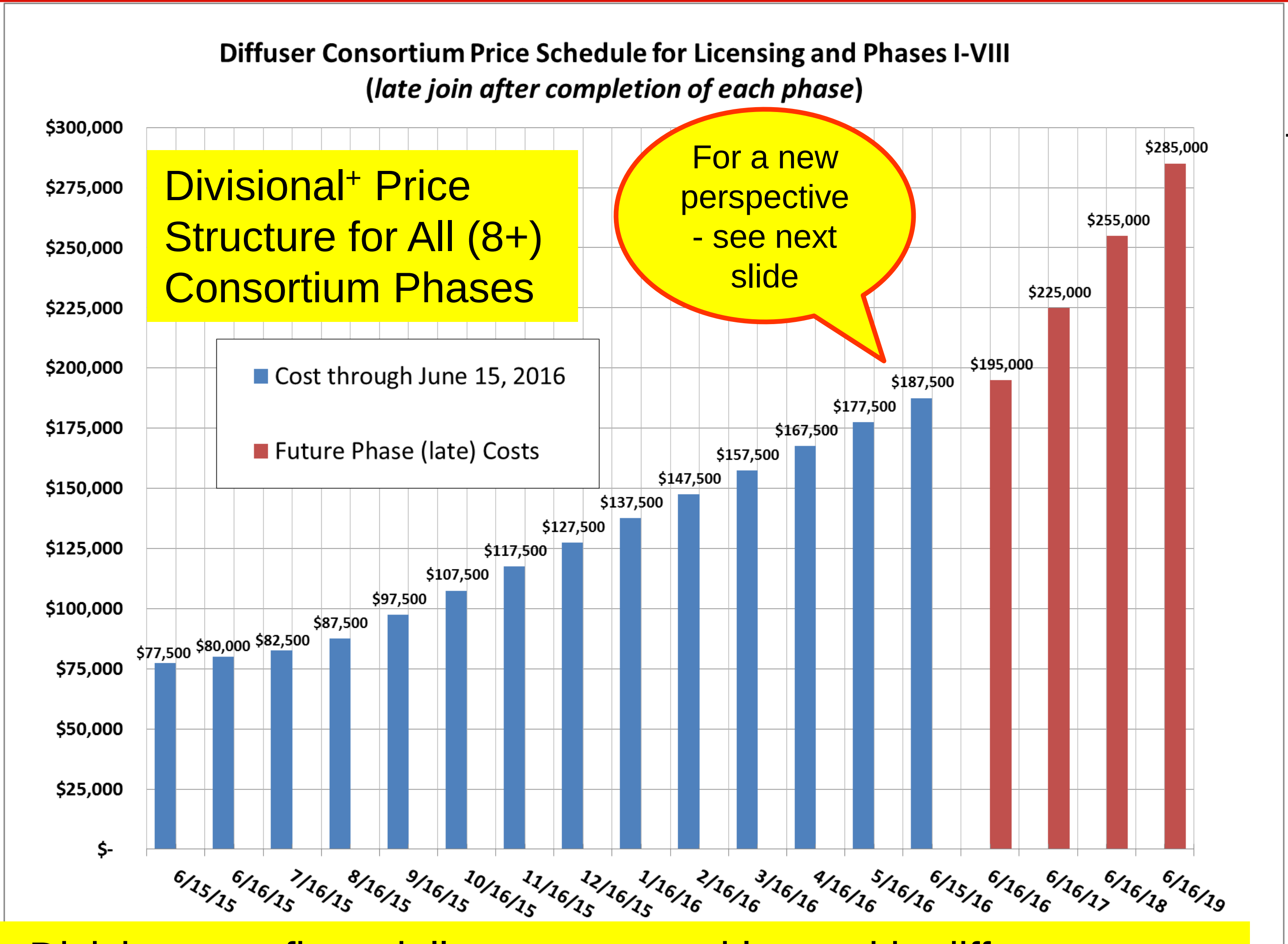
# Avoid the Penalties!! (We Will Help)




Participation with full penalty costs – rates announced about 1.5 years ago based on 1975 consortia criteria

+ Divisions are financially separate and located in different towns

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# New Approach

- Current members continue at $15,000 per year; receive patent licenses *as issued* (multiple patents in process).
- New members also welcome at $15,000 per year, starting *now*. Patent licenses will be granted *after choosing the full (8 phases) sponsorship payment.*
- Past (early phase) sponsors who are not current: some discounts may still be available, so it may be better to catch up now rather than to wait. Just ask.
- Offer is open until September 15, 2016. After that date, all past discounts are closed out. Patents will be *strictly* enforced.

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# Closure

- The Diffuser Consortium series is on schedule
- Strong evidence of coupling is now clear
- Strong pressure asymmetries exist at the diffuser inlet
- Flow-wise grooves work very well and have more potential
- Biased passages are being explored
- Continued increases in stage efficiency and range have been shown: a) 0.78 and 0.74 at low and high speeds for the small impeller, ca. 1994, vs. b) 0.81+ and 0.77+ at low and high speeds in 2016. Low vane numbers used.
- Further advances expected soon on larger scale rigs (now running)
- Outline exists to pursue new super diffusers
- This an excellent time for new companies to join in the consortium effort!!

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