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# *Experimental and Numerical Investigation of the NASA High Efficiency Centrifugal Compressor Vaned Stage Geometry and Aerodynamic Performance*


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# Outline

- Background and Objectives
- Historical perspectives

- 2024 LDV aero test campaign
- Experimental Results
- Numerical Results
- Conclusions

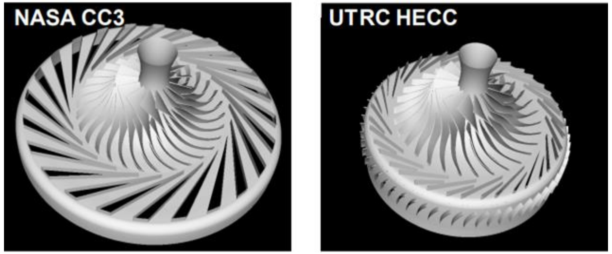
# Background

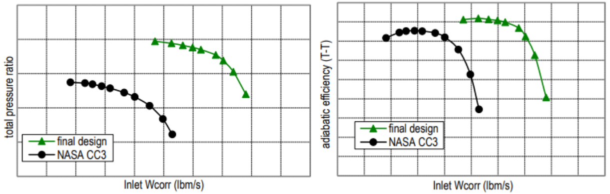
- Background:
  - Dr. Trey Harrison led an effort to create an open-source archive for the NASA HECC vaneless and vaned diffuser geometry and experimental data
    - Intent is to create an open-source validation case that the turbomachinery community can use to advance design and modeling of centrifugal compressors
  - As part of the process geometric differences were found between the manufactured components (As-Manufactured) and the design-intent (published section data in design report)

# Objectives

- Objectives:
  - A brief review of previous work
  - Introduce the new experimental campaign
  - Define the newly identified geometric differences
  - Present new experimental data compared to previous experimental campaigns
  - Present a new numerical baseline based on geometrical findings

# History of NASA HECC

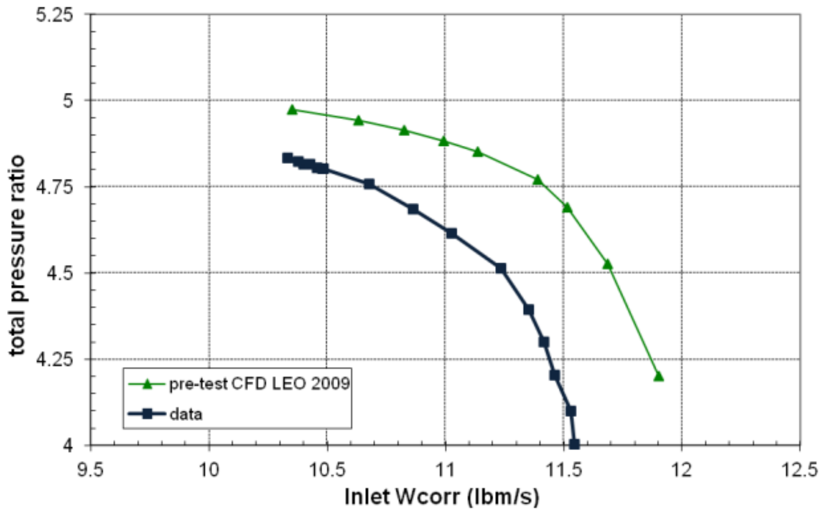




***Medic, G. et al, 2017, "High Efficiency Centrifugal Compressor for Rotorcraft Applications"***

- The HECC was designed in a joint project between NASA and UTRC
- Design Objectives:
  - Increase efficiency, work factor, and stall margin
  - Reduce maximum diameter
  - Maintain same rotational speed as CC3
- Design Approach:
  - Impeller blade lean, bow, and leading edge/trailing edge shaping
  - Diffuser fillets, elliptical leading and trailing edges and splitter vanes
- Design Outcome:
  - Pre-test CFD design assessment was promising and achieved goals relative to CC3
  - Pre-test CFD was performed using ADS CFD Code Leo

# History of NASA HECC: Experimental Campaign Results




***Medic, G. et al, 2017, "High Efficiency Centrifugal Compressor for Rotorcraft Applications"***

- Experimental Testing Outcome:
  - Test performance was significantly lower than pre-test results from Code Leo
- Root cause analysis:
  - Suppressed inlet plays a detrimental role
  - Geometry sensitives
    - Step in flowpath on the shroud between impeller and diffuser
    - Restagger of diffuser splitter vane
    - Manufactured impeller checked against CAD and no differences were found
  - Turbulence modeling
    - Strain-rate based k-w model avoids issues from vorticity based model

# Perspective

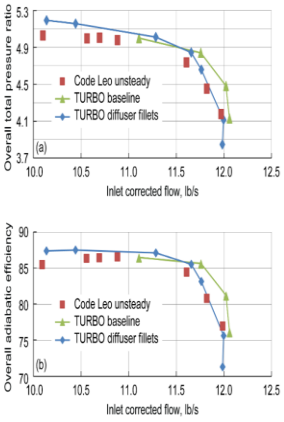



Figure 5.—Computed design speed performance of High Efficiency Centrifugal Compressor (HECC) with and without diffuser fillets. (a) Pressure ratio. (b) Efficiency.

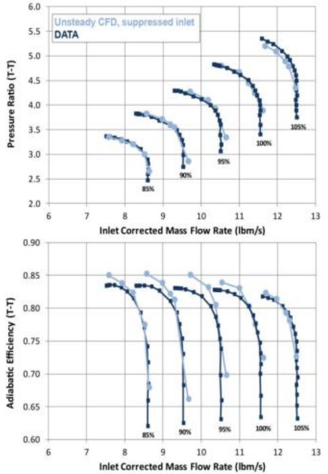
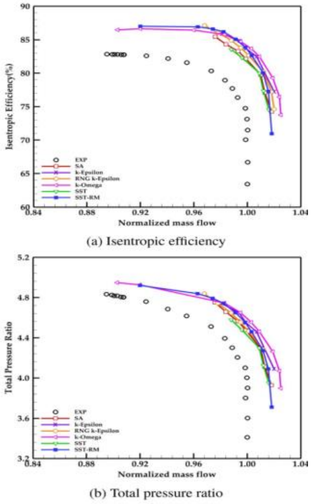



Figure 164.—Full compressor map for speeds 85 to 105 percent obtained during unsteady post-test CFD analyses using suppressed inlet conditions, (fixed 12 mil clearance), and the strain-rate based k-ω model as compared to data at suppressed inlet.




(a) Isentropic efficiency

(b) Total pressure ratio

FIG. 7. The stage characteristics obtained with smooth surfaces.

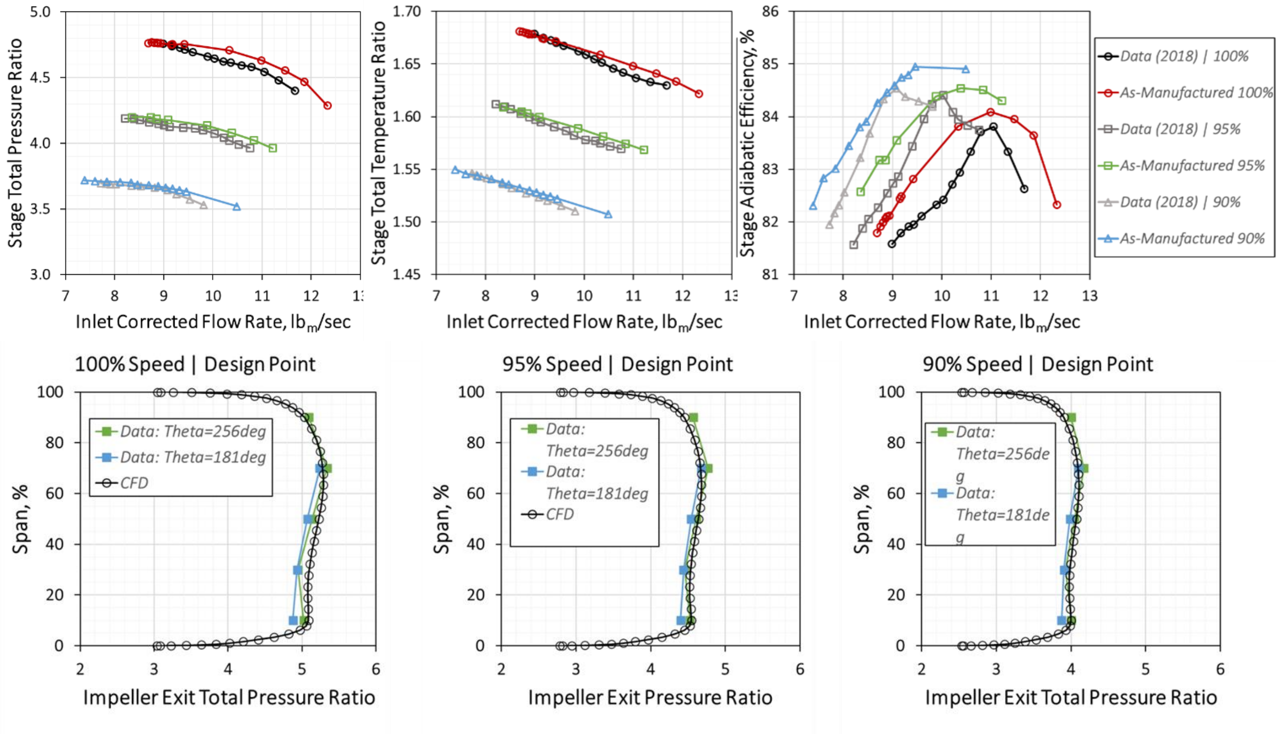
- Many groups involved over the years to understand the miss. With over 66+ papers referencing the HECC, including NASA, UTRC, NWPU
- Summarization of findings include:
  - Mesh density, turbulence models, fillets, steady vs unsteady, wall roughness factors
- ***None adequately addressed the miss***

***Liu, J. et al, 2023, "Investigation of turbulence models for aerodynamic analysis of a high-pressure-ratio centrifugal compressor"***

***Kulkarni, S. and Beach, T. , 2017, "Progress of High Efficiency Centrifugal Compressor Simulations Using TURBO"***

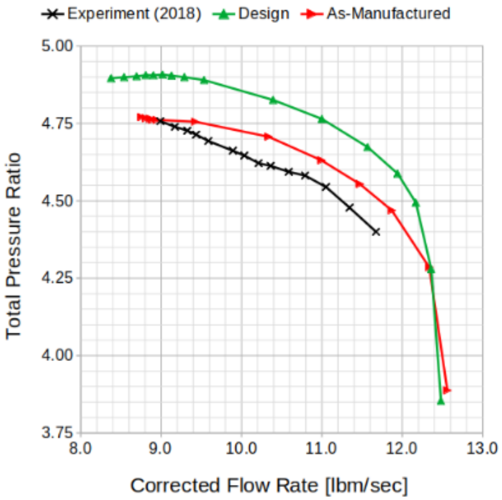
***Medic, G. et al, 2017, "High Efficiency Centrifugal Compressor for Rotorcraft Applications"***

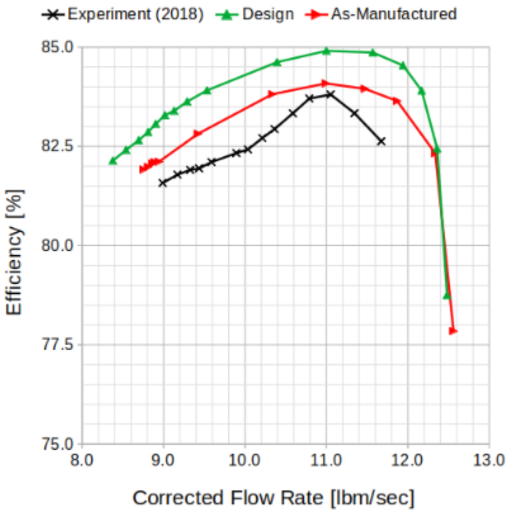
# History of NASA HECC: Vaneless Configuration




- Collaboration between NASA and ADS explored modeling vaneless diffuser
- Simulations were conducted with sections data extracted directly from the CAD which included the fillets
- Simulations showed good agreement with data at multiple speeds and spanwise profiles

# History of NASA HECC: Impeller Geometric Differences

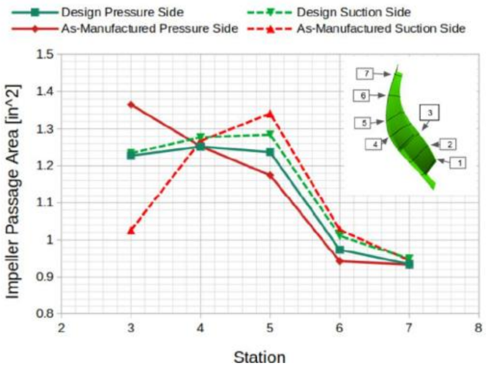


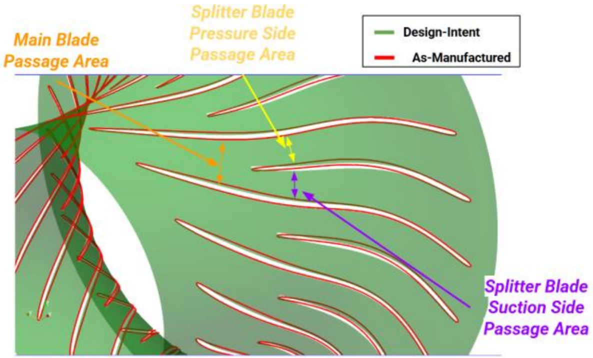




- As part of the same effort the same mesh and solver setup was applied to the section data reported in design report
- Solution showed drastically different performance between two inputs

ADSCFD

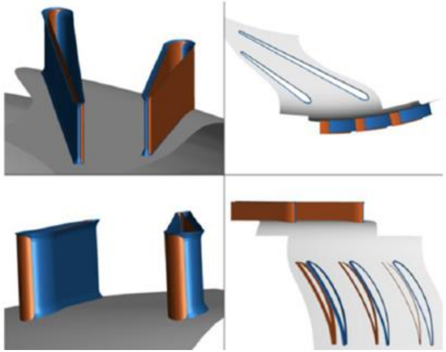
# History of NASA HECC: Impeller Geometric Differences

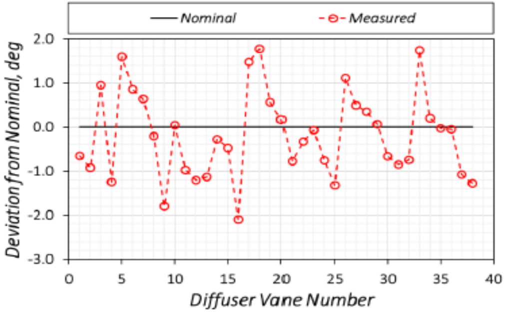


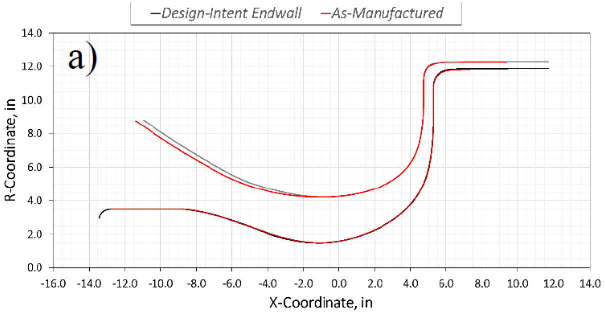



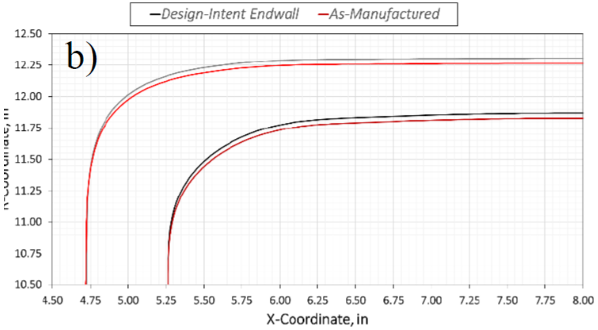

- Performance difference led to finding of impeller geometric differences
- CAD was confirmed to match the manufactured components at NASA Glenn using a coordinate measuring machine
  - This agreed to the findings in the design report
- However, section data in the design report is not the same impeller geometry as CAD
- As-Manufactured (AM)
  - Section data extracted directly from CAD
  - CAD was confirmed to match manufactured components
  - Best representation of manufactured components
- Design-Intent (DI)
  - Official section data from HECC design report
  - Geometry used for pre-test prediction
  - Different than manufactured component used in experiment

# Geometry Verification of Vaned Diffuser



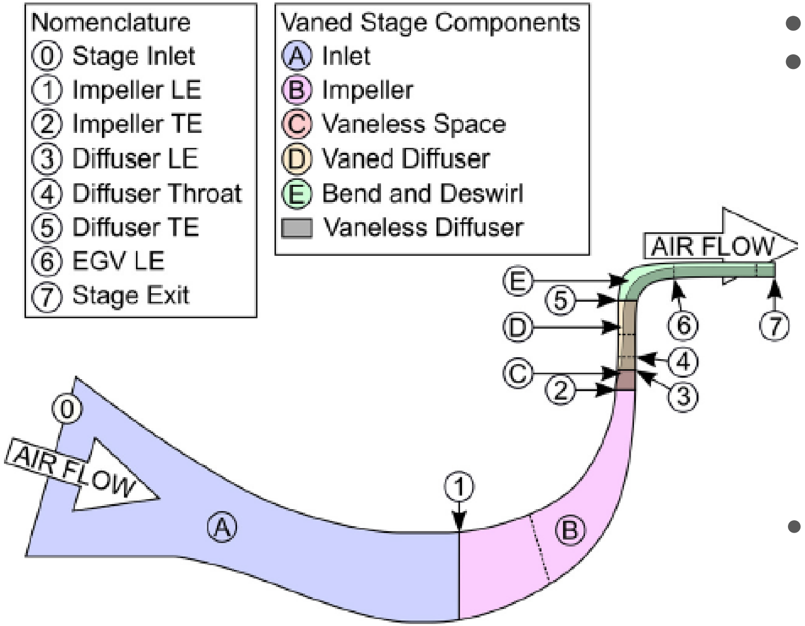



- Impeller differences warranted a detailed look at rest of vaned diffuser components
  - All other components extracted from CAD
- Diffuser/EGV differences
  - Diffuser appears visually similar
  - Inspection report shows relatively large variations from vane to vane
    - 1.770º to -2.096º
  - EGV clocking offset by ¼ pitch
  - Trailing edge shape changes between AM and DI
    - Sharp cut-off to rounded TE
- Endwall
  - Differences in inlet shroud radius
  - Differences in bend radius

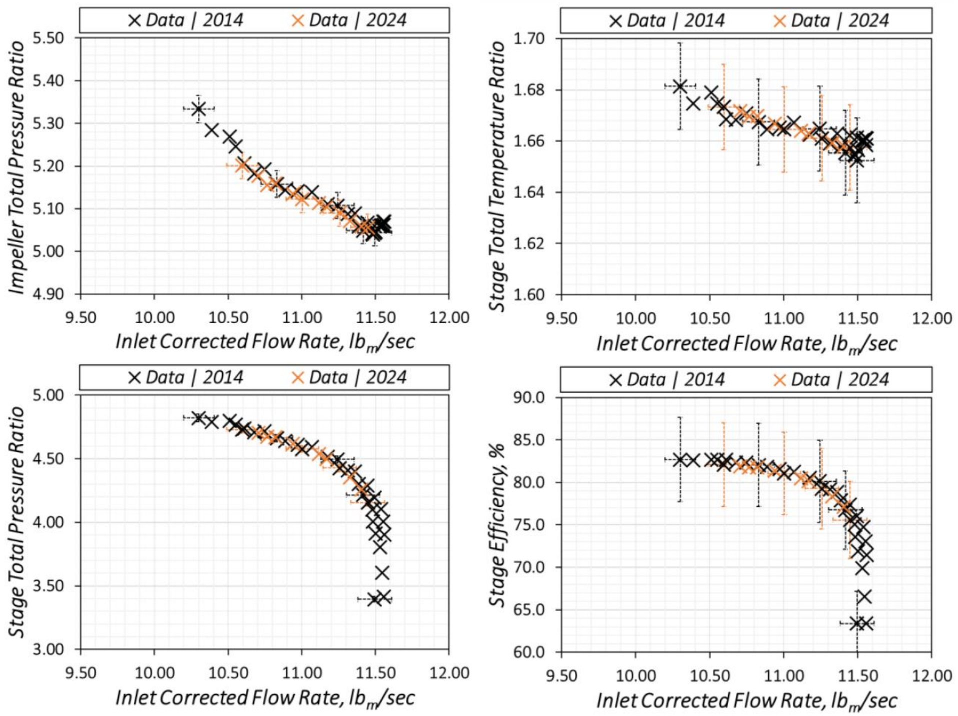
# LDV Aero Checkout (2024)




***Harrison, H. M. et al, 2023, "NASA Small Engine Components Compressor Test Facility: High Efficiency Centrifugal Compressor Vaneless Diffuser and Transition Duct Configurations"***

- Original experimental data acquired from 2012-2014
- In preparation for an upcoming LDV test campaign, vaned diffuser data was reacquired for verification of repeatability after major facility and test article modifications:
  - New pressure ADC system (legacy NASA ESP replaced with Netscanner)
  - New temperature ADC system (updated to Scanivalve DTS)
  - Entirely new DAQ system (legacy ESCORT replaced with COBRA)
  - Metal shroud cut to separate impeller and inlet shrouds (transition duct testing)
  - Optical access port added to vaned diffuser for LDV test
  - Full personnel turnover with the exception of a single mechanical technician
- Performance measurements exhibited excellent repeatability (within the measurement uncertainty)

# Experimental Data

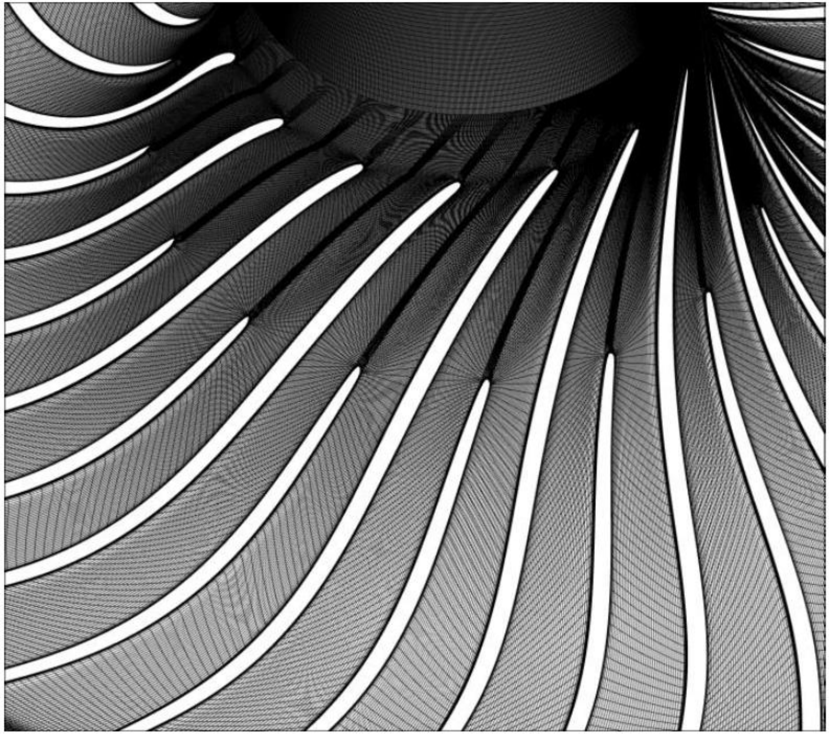



- Experimental data was collected in 2014
- Data was collected 2024 for the vaned configuration in preparation for a now postponed LDV measurement campaign
- In the context of this work, the 2024 experimental data was used to show repeatability
  - 2024 data was not pushed deep into choke or stall
  - 2024 data uses new instrumentation
  - Data taken a decade apart agrees well with each other
  - Error bars shown on select points to illustrate uncertainty of measurements

# Numerical Simulations

- Given the geometry differences a new numerical baseline was warranted
  - Two geometries evaluated with exactly the same modeling approach (mesh settings, initialization and solver settings)
    - Design-Intent
    - As-Manufactured
- Numerical Investigation:
  - Steady simulation with mixing plane at standard day conditions
  - Effect of suppressed and standard day inlet conditions
    - Suppressed conditions: PT=10.6 psi | TT=516.9 °R | 21,751.4 rpm
  - Effects of full-wheel unsteady simulation with sliding plane
    - Post-processing performed on time-averaged solution (1rev) in similar manner as experimental averaging procedure

# Mesh Generation

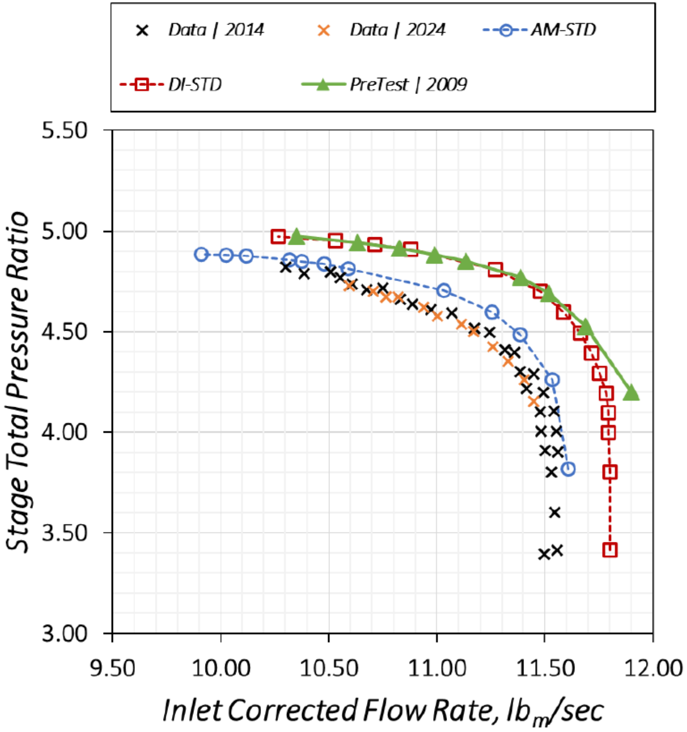


- Meshes generated using Code Wand
  - Structured multi-block meshes
  - Wall integration
- Mesh convergence study:
  - Three mesh densities
    - 2.6M to 12.9M nodes
    - Medium mesh
- Final mesh counts:
  - Single row:
    - 3.59M Nodes | 3.33M Elements
  - Full-wheel:
    - 76.78M Nodes | 70.94M Elements

# Solver and Computational Times

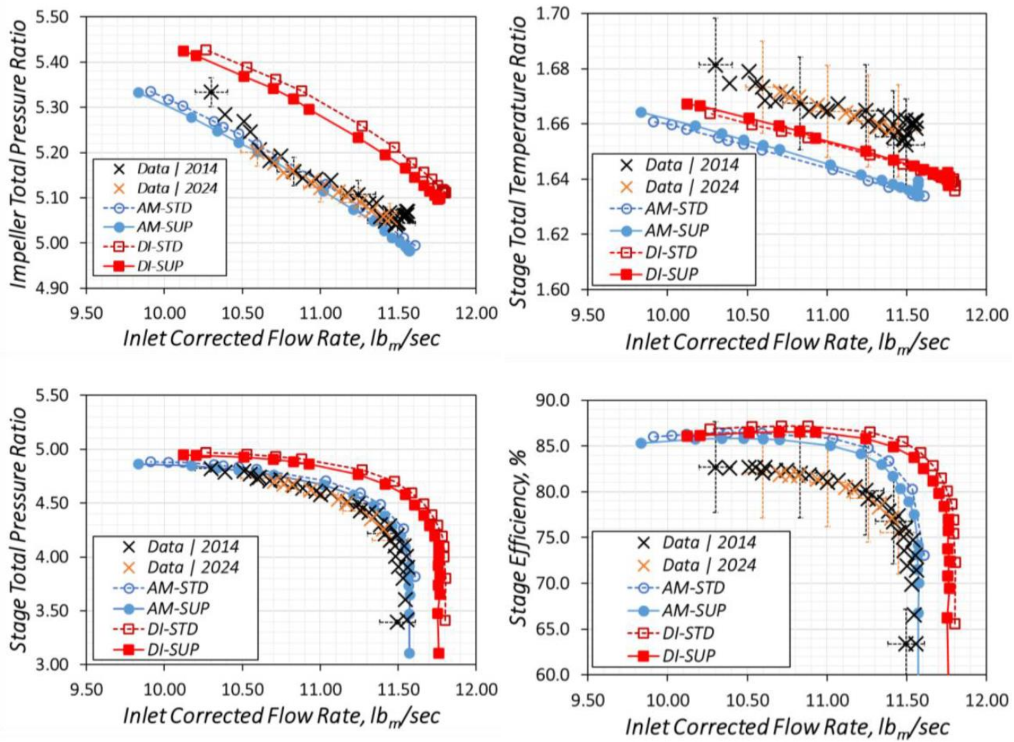
- Solver: Code Leo
  - GPU accelerated
  - Cell vertex scheme
  - Explicit time-marching
  - Finite volume
- Turbulence model: wilcox kw98
- Hub and tip boundary layer: 7%
- Turbulence intensity: 1%
- Turbulence length scale: 0.01 in
- Steady Stall Prediction:
  - Steady simulations were run to within 0.1% backpressure change from numerical stall
- Unsteady Stall Prediction
  - Unsteady simulations were run to within 0.05 lbm/s exit corrected flow change of stall
  - 10 revolutions
- Computational Times
  - Steady | 5 Nvidia L40 GPUs
    - 2 min 27 sec for 8,000 iterations
  - Unsteady | 8 Nvidia L40 GPUs
    - 2 hrs 7 min per revolution
      - 4,500 timesteps/ revolution
      - 300 timesteps per main/splitter blade pair
      - 0.00061 ml-sec timestep size

# Standard Day Steady Simulations




- At standard day inlet conditions the As-Manufactured (AM-STD) simulations show an improved prediction than Design-Intent (DI-STD)
- Comparison of present DI-STD speedline to pre-test results from 2009 show good repeatability for same geometry
  - Choke point is higher for 2009 simulations but could be caused by mesh resolution or similar factors

# Impact of Suppressed Conditions




- Measurements were taken under suppressed inlet conditions
- Design report found that reynolds effects from suppressed inlet conditions were of a magnitude that warranted being taken into account in model
- Present results confirmed previous findings of reynolds effects impacts

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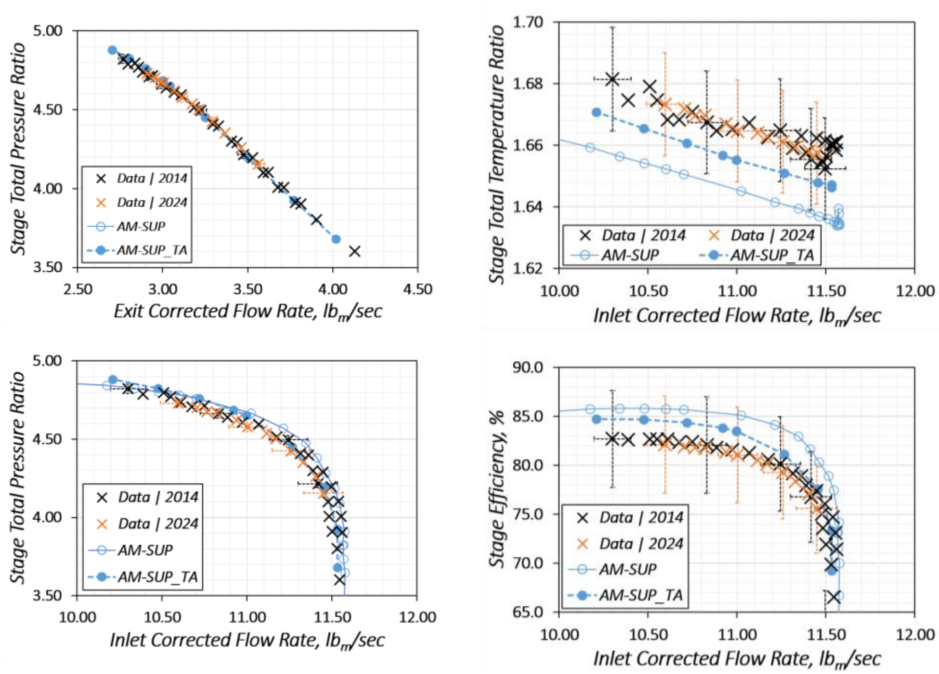
# Unsteady Impacts: 1D Performance




- Unsteady results showed excellent agreement in choke flow rate, stage pressure rise and stall margin
- Unsteady total temperature rise was 0.009 points lower for AM-SUP_TA
  - Corresponds to a difference in exit temperature around 4.5 °R
- Difference in TTR resulted in an adiabatic stage efficiency difference of 2.4% relative to data

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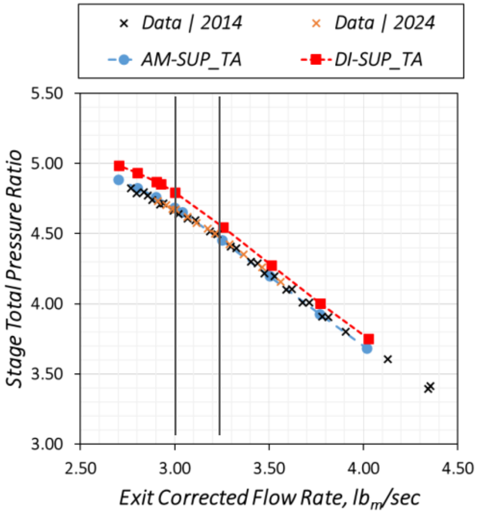
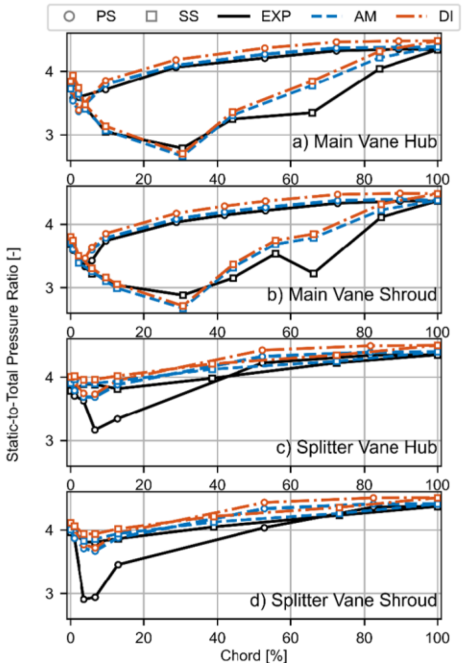
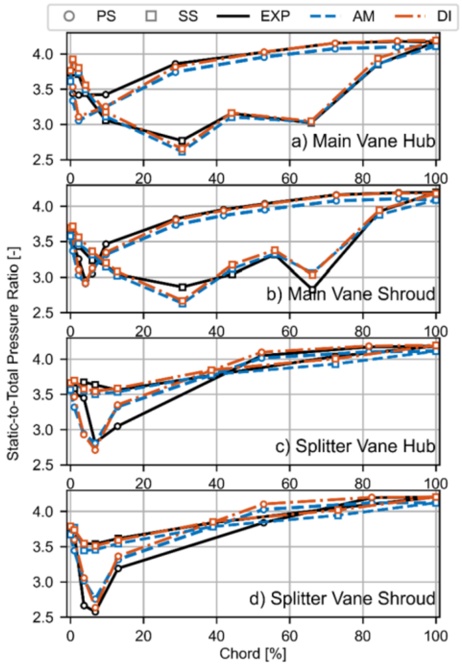
# Unsteady Impacts: Loading




$W_{c,ex}$=3.00 lbm/sec
$W_{c,in}$=11.00 lbm/sec




$W_{c,ex}$=3.25 lbm/sec
$W_{c,in}$=11.26 lbm/sec

- Data measurements are at 11 lbm/sec
- Point slightly towards choke predicts loading well
- Design point simulation fails to predict the drop in pressure rise on the suction side

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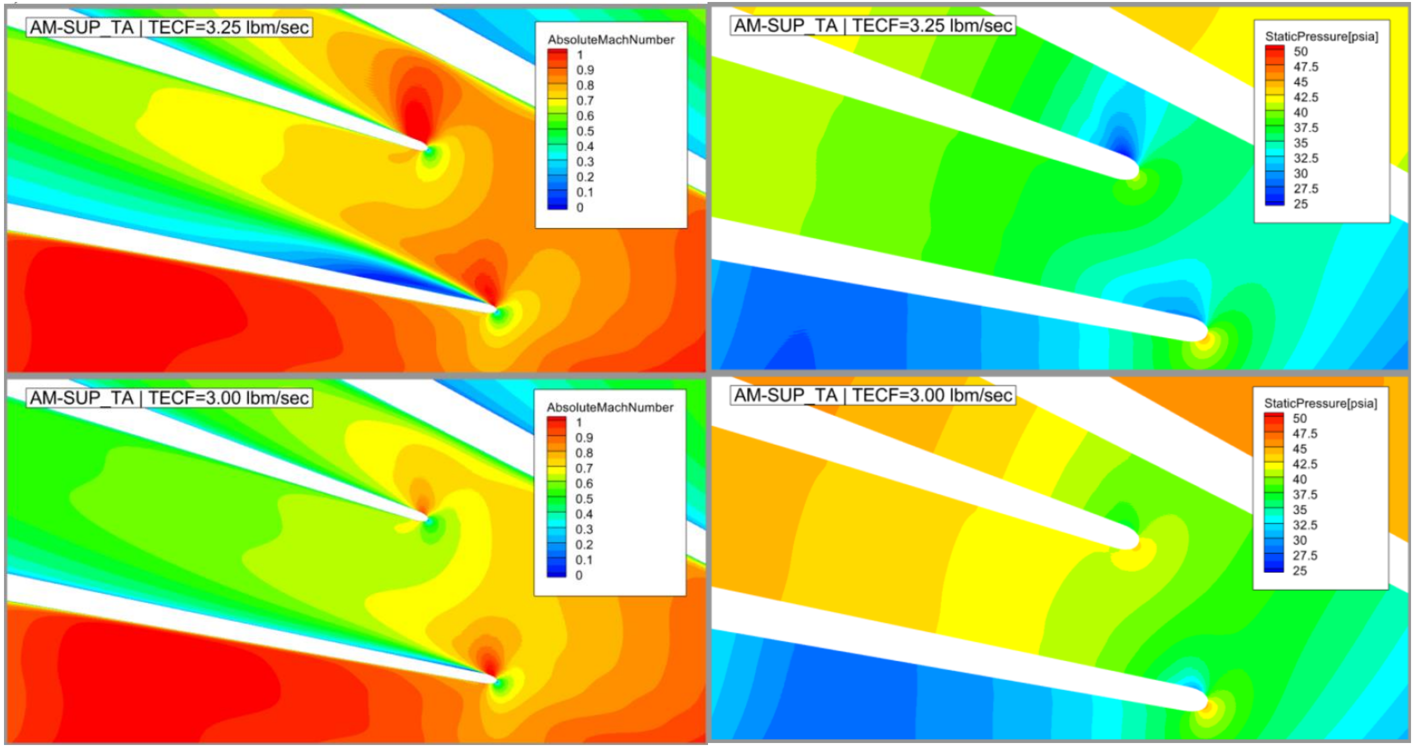
# Unsteady Impacts: Loading



# Conclusions

- The NASA HECC vaned diffuser was re-evaluated following the discovery of the geometric differences between Design-Intent and As-Manufactured
  - Further geometric differences were found and presented in this work
  - Experimental data showed the repeatability of the measurements
  - Numerical simulations provided a new baseline showing that the geometry differences rather than modeling choices accounted for the large difference in prediction and measured performance

# Further Opportunities with HECC

- LDV data acquisition – the stage is prepped for turbulence measurements in the vaned diffuser
- The effect of heat transfer remains difficult to quantify - the plastic and metal inlets offer an opportunity to evaluate this effect
- How would the Design-Intent stage perform?
- Open shroud access facilitates numerous augmentations for advanced surge suppression technologies

The HECC Data Archive is available, but currently offline and in the process of migrating to data.nasa.gov. Please contact the Archive's point of contact, Tammy Nguyen-Huynh, at tam.t.nguyen-huynh@nasa.gov with any questions or for the latest version of the archive.