THERMALLY EFFECTIVE AND EFFICIENT COOLING TECHNOLOGIES FOR ADVANCED GAS TURBINES

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PRESENTATION OVERVIEW

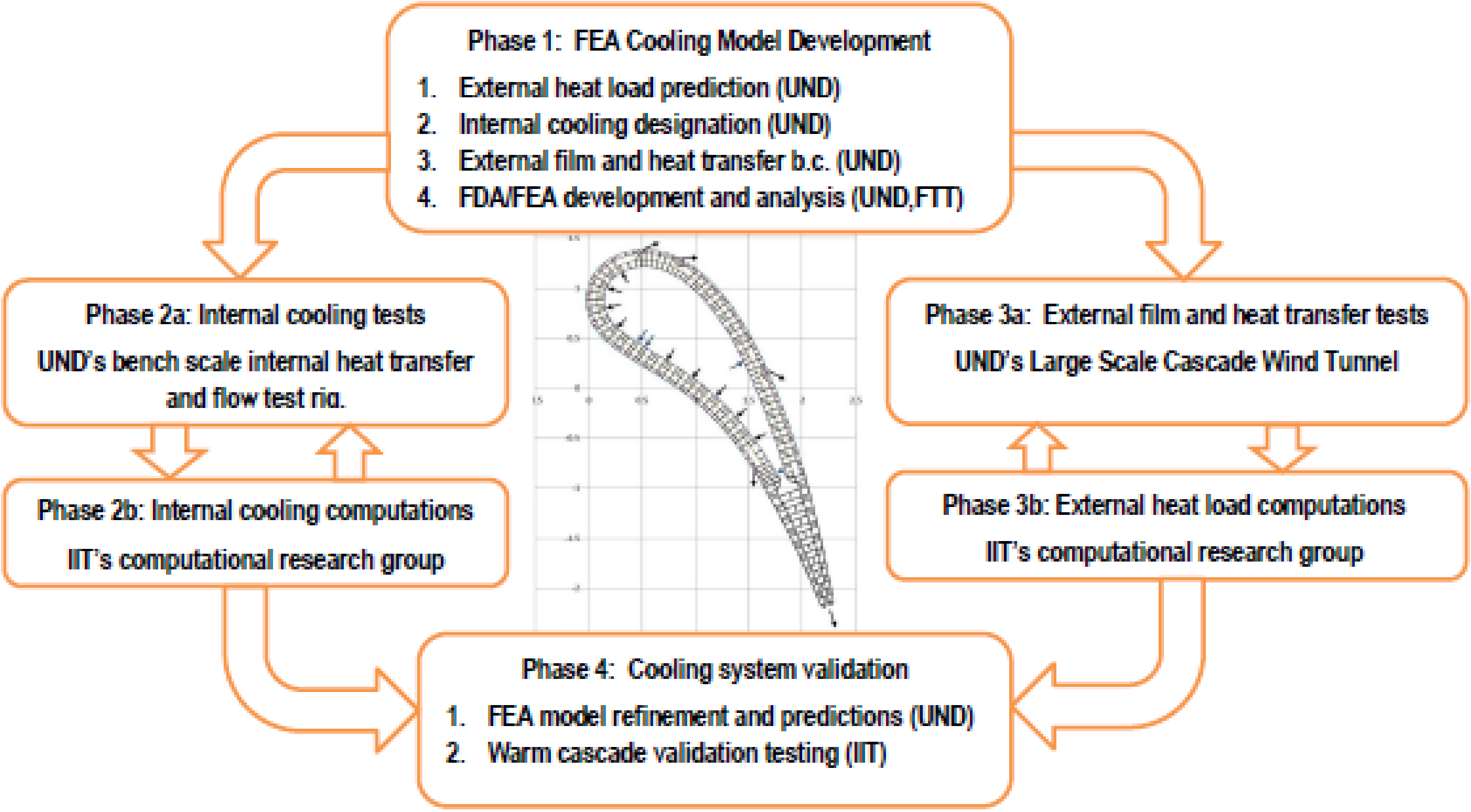
- Conceptual approach
- Four phases the present program
- FEA analysis is used to drive the development of internal cooling methods based on external boundary conditions
- Recently acquired heat transfer data
- Preparations for film cooling measurements in our low speed cascade test section.
- Internal cooling methods development: Bench scale rig.
- Computational methods: Clarifying physics of film cooling and internal cooling & serving to refine model boundary conditions.
- Warm cascade testing was planned for cooling system evaluation and validation based on comparing the results with an enhanced FEA vane model – *will not be completed under current grant*.

CONCEPTUAL APPROACH

- Component cooling methods need to provide highly effective, efficient, locally prescribed, and reliable cooling systems.
- Ideal internal cooling methods
  - Achieve good levels of internal effectiveness
  - Discharge spent cooling air onto surfaces in optimum films.
- Leading edge regions can be cooled internally:
  - Achieving a high level of overall effectiveness
  - Eliminating the disruption of shower-head films and the potential for clogging
  - Improving downstream film cooling levels.
- The efficiency and effectiveness of downstream cooling levels can be improved by better matching of internal cooling concept with external films (counter cooling).
- Covered trailing edge designs offer the best thermal protection:
  - There is no clear evidence of higher losses compared to pressure side cutbacks.

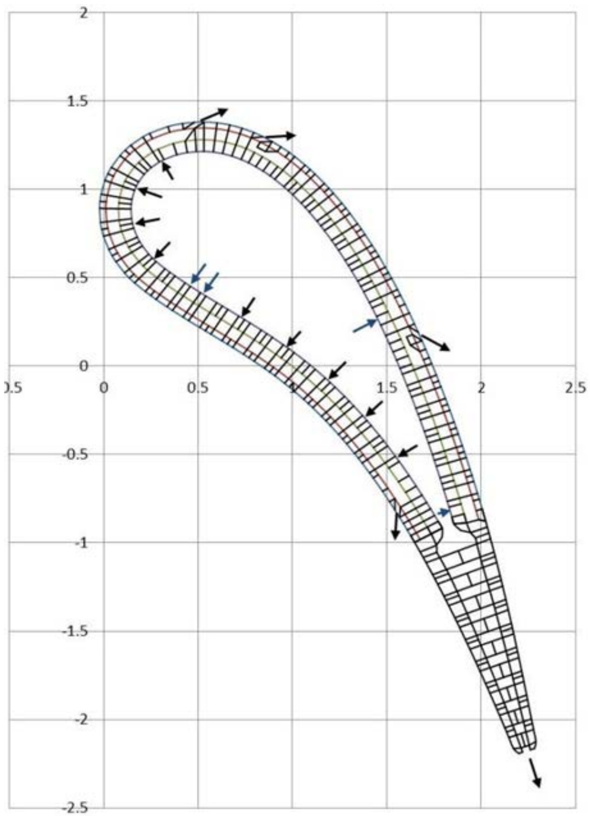
FOUR PHASE PROGRAM

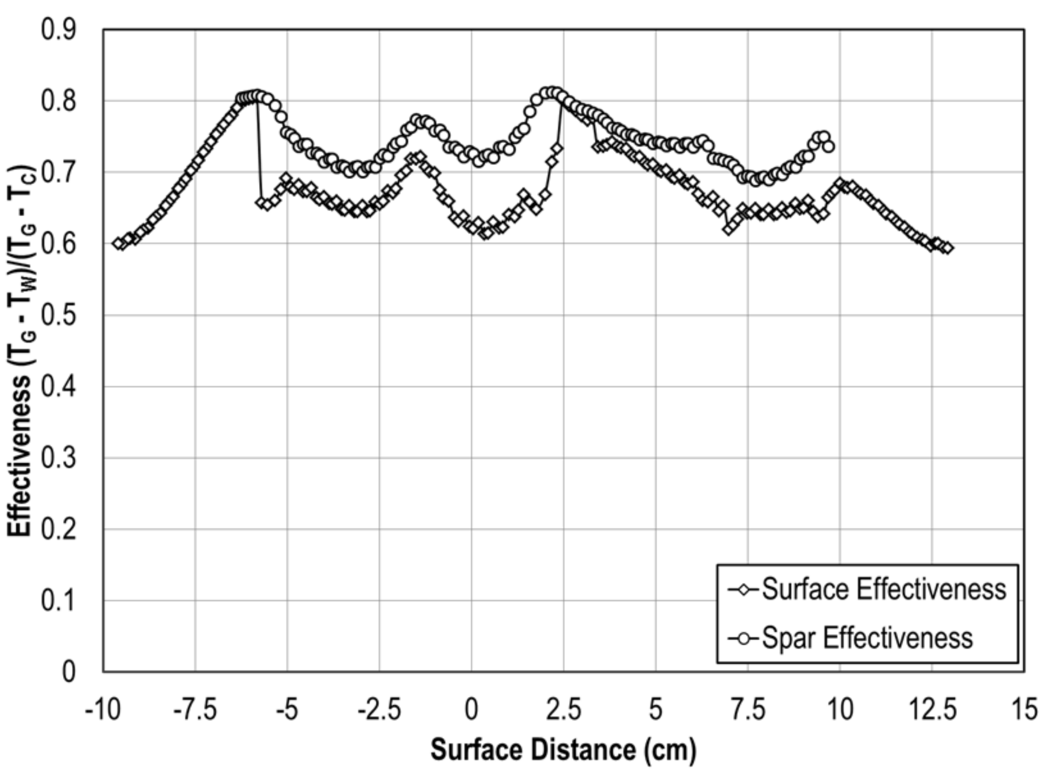
DETAILED RESEARCH PLAN



FINITE DIFFERENCE ANALYSIS

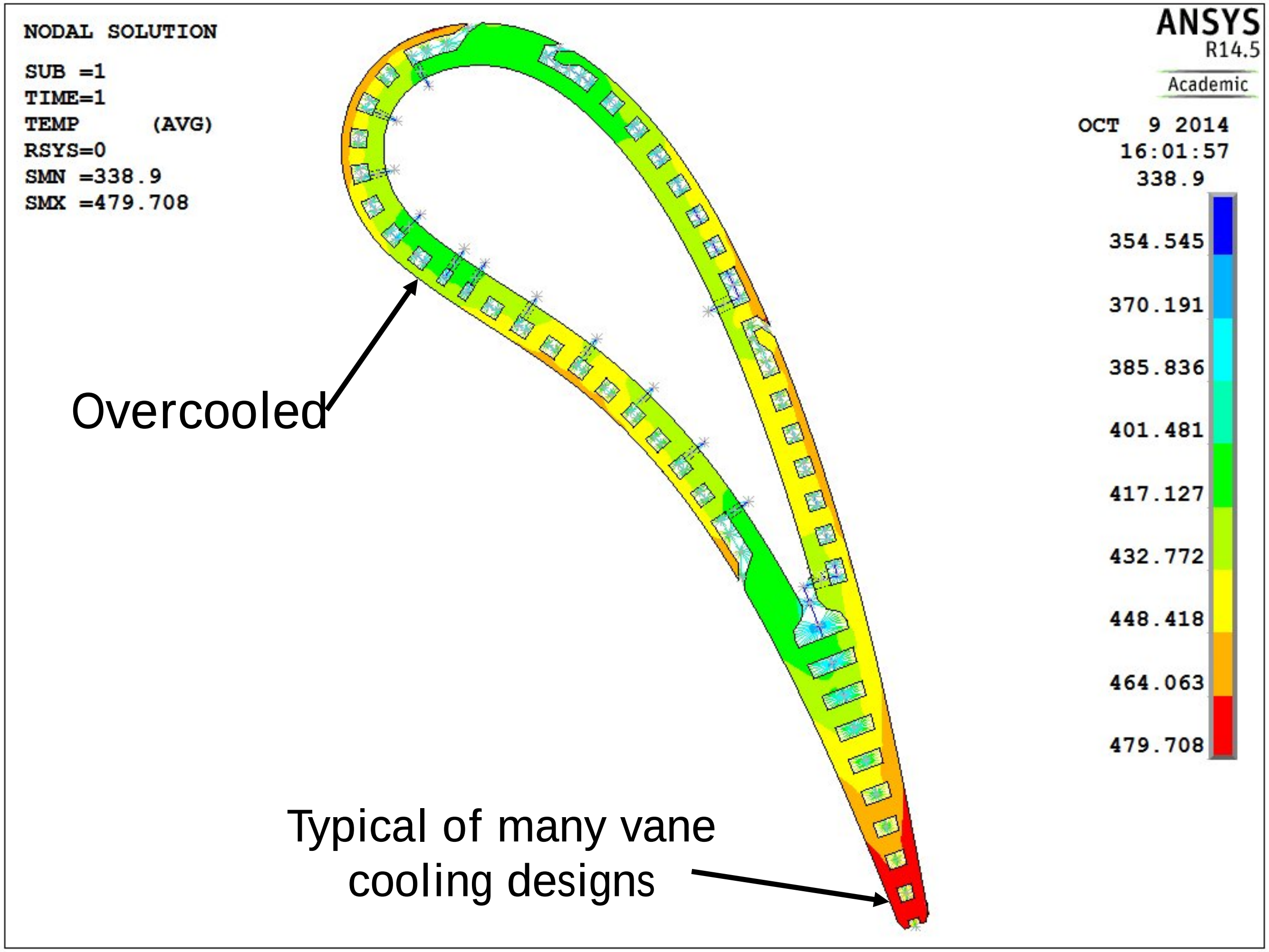
- Finite difference analysis provides a means to match external heat loads with appropriate cooling design and coolant flows.
- Results of analysis suggest regions of overcooling and regions where cooling is more challenging.
- The present objective is to demonstrate the successful integration of three cooling technologies into a cooling design.





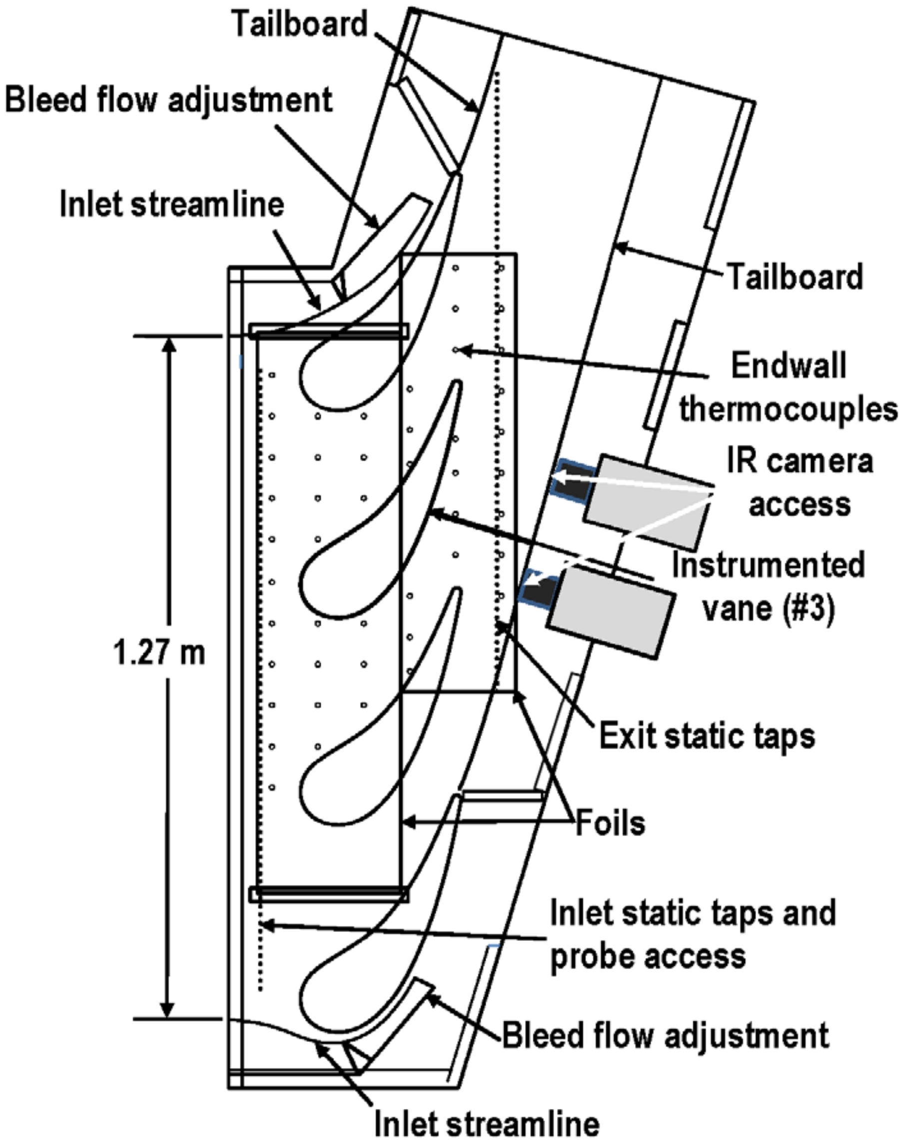
FINITE ELEMENT ANALYSIS ANSYS

The boundary conditions developed for the FDA were imported into a 2D FEA in ANSYS. The FDA and FEA analyses point to areas were cooling levels can be optimized.



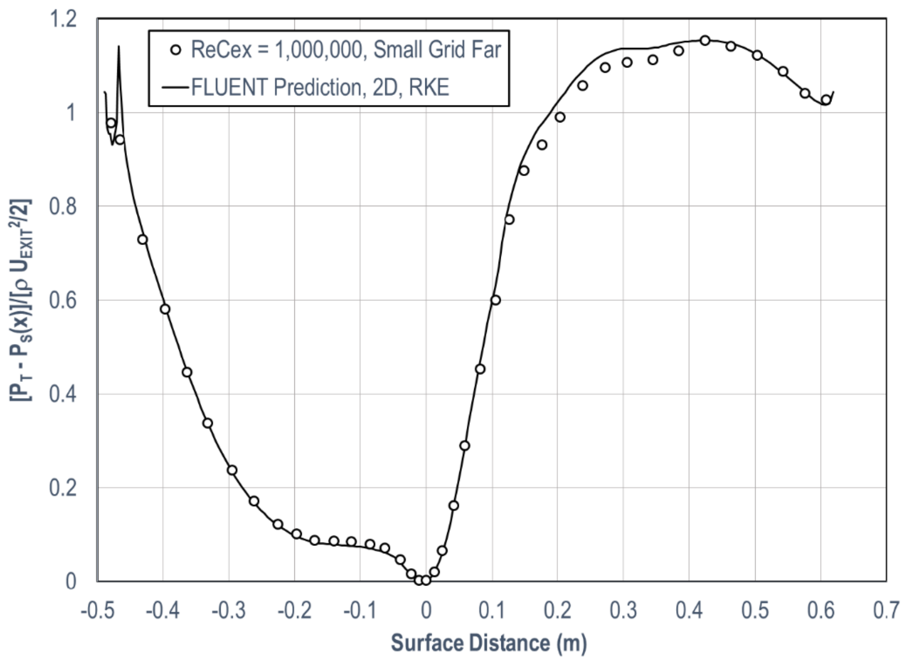
Large Scale Low Speed Cascade Testing

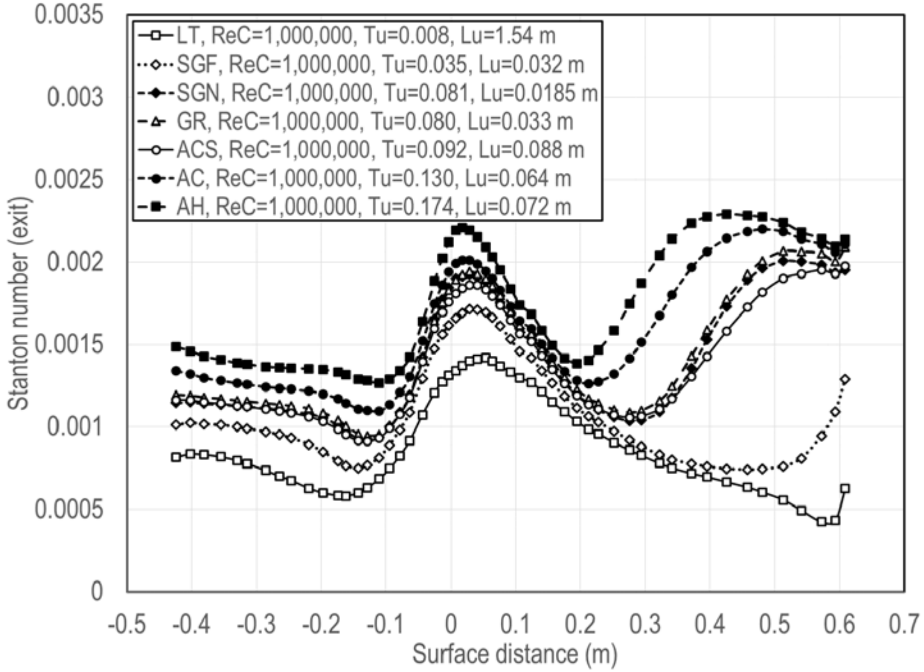
- UND's large scale cascade has been used to evaluate midspan and suction surface heat transfer distributions over a relevant range in turbulence conditions.
- Soon it will be used to evaluate film cooling effectiveness and the influence of film cooling on heat transfer.
- UND/IIT will use these data to help refine the heat transfer and film cooling boundary conditions for the warm cascade test vane analysis.



MIDSPAN HEAT TRANSFER DISTRIBUTIONS

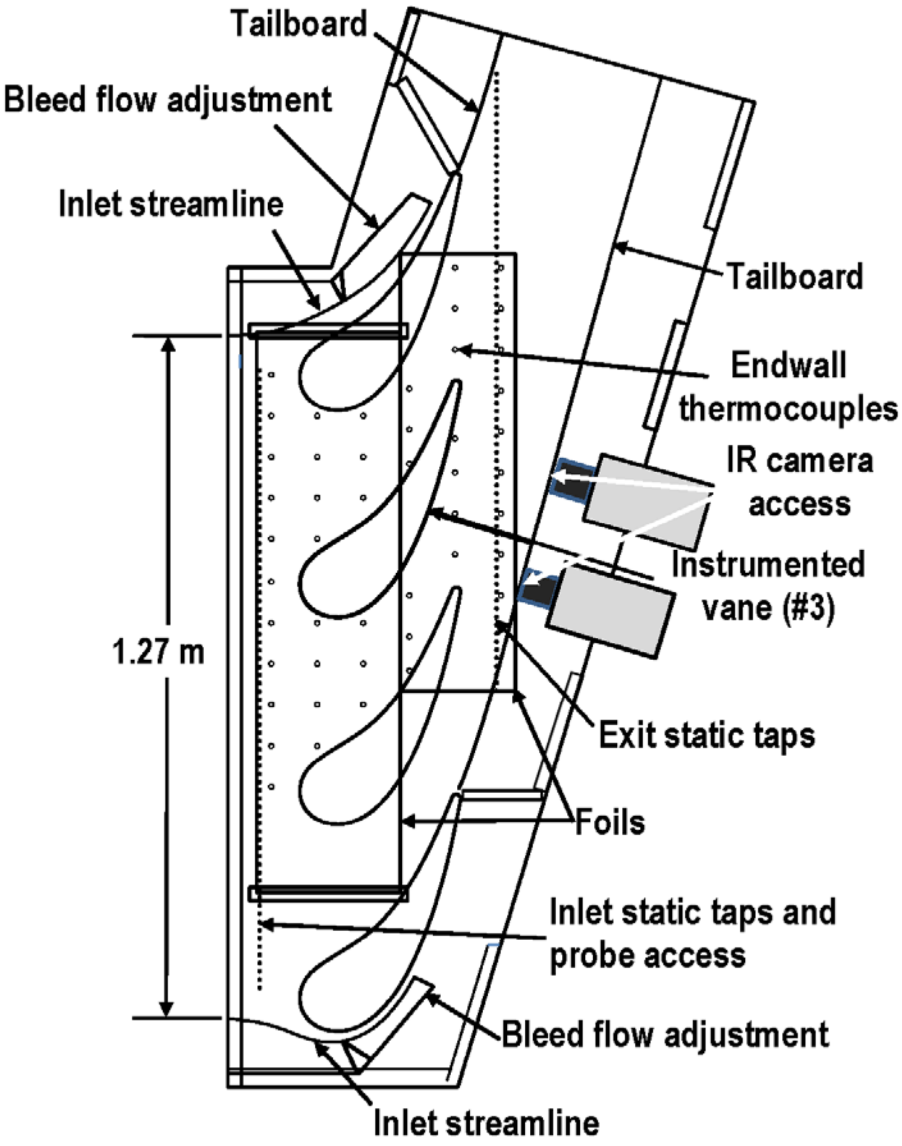
- The vane was designed with a large leading edge and an aft loaded pressure distribution. The minimum pressure is at about 70% surface.
- The larger leading edge reduces the heat load and the aft loading pushes transition downstream.
- Midspan and suction surface heat transfer distributions were acquired over Reynolds numbers from 500,000 to 2,000,000.
- The six elevated turbulence levels show significant incremental augmentation for levels ranging from 3.5% to 17.4%.





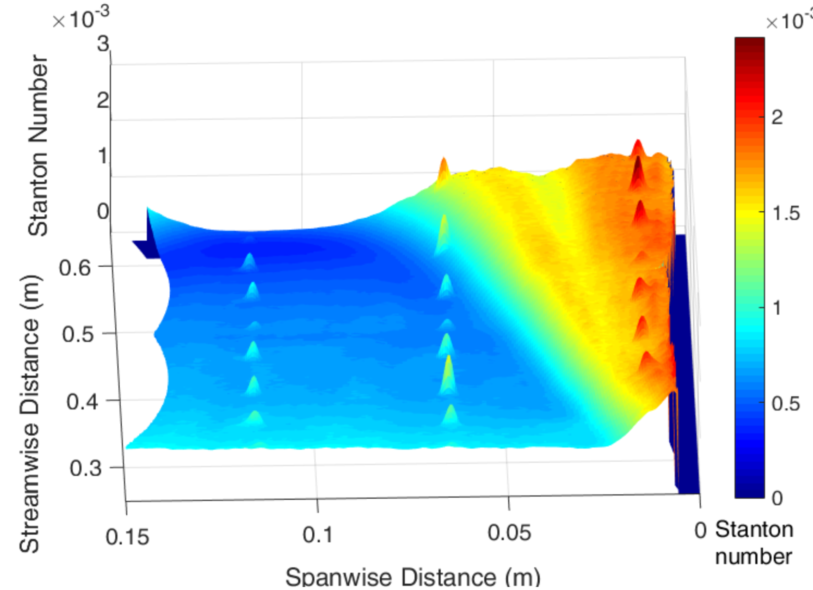
Full surface vane suction surface heat transfer

- UND's large scale cascade provides thermal camera access to the suction surface through a tailboard which integrates zinc selenide windows.
- For full surface heat transfer measurements the vane is painted black and reflective dots are painted on the surface to provide physical reference points.
- Infrared images in the 8 to 13 μm range are acquired for the heated and unheated conditions.
- Midspan temperatures acquired at the same time as IR images are used for in situ calibration.

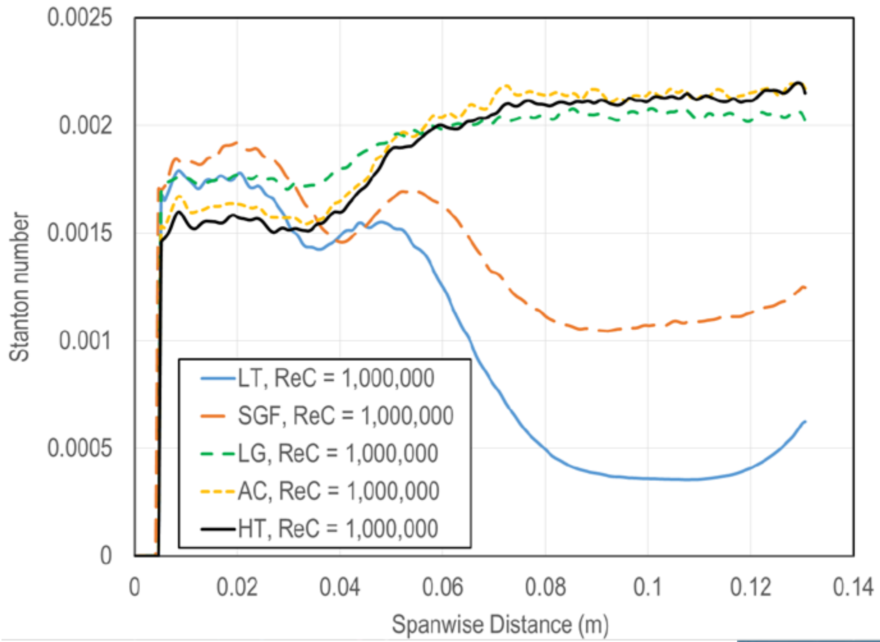


SUCTION SURFACE HEAT TRANSFER DISTRIBUTIONS

- At a low turbulence level the contrast between the laminar midspan and the turbulent secondary flow is readily visible.
- Spanwise distributions of Stanton No. show a large variation in the midspan area with turbulence but a much smaller difference in the region affected by secondary flows.
- The dip in Stanton number at a span of around 1.6 inches for the LT and SGF cases may indicate the separation line of the passage vortex (no film cooling).
- The data acquired at the higher turbulence levels show higher heat transfer in the midspan area.
- The evidence of discrete vorticity is much less dominate at the higher turbulence levels due to aggressive mixing and unsteadiness.



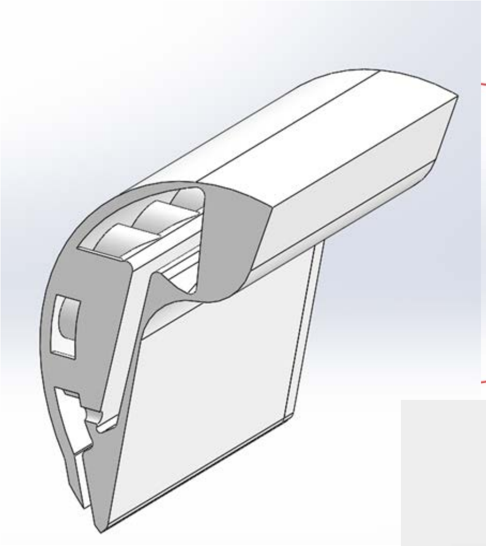
Low turbulence (LT) suction surface, ReC = 1M

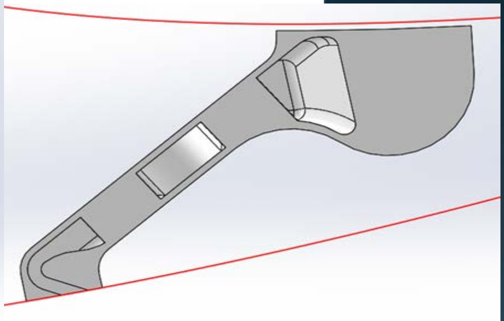


Showing the influence of turbulence level on the spanwise distribution of heat transfer.

VANE FILM COOLING AND HEAT TRANSFER DISTRIBUTIONS

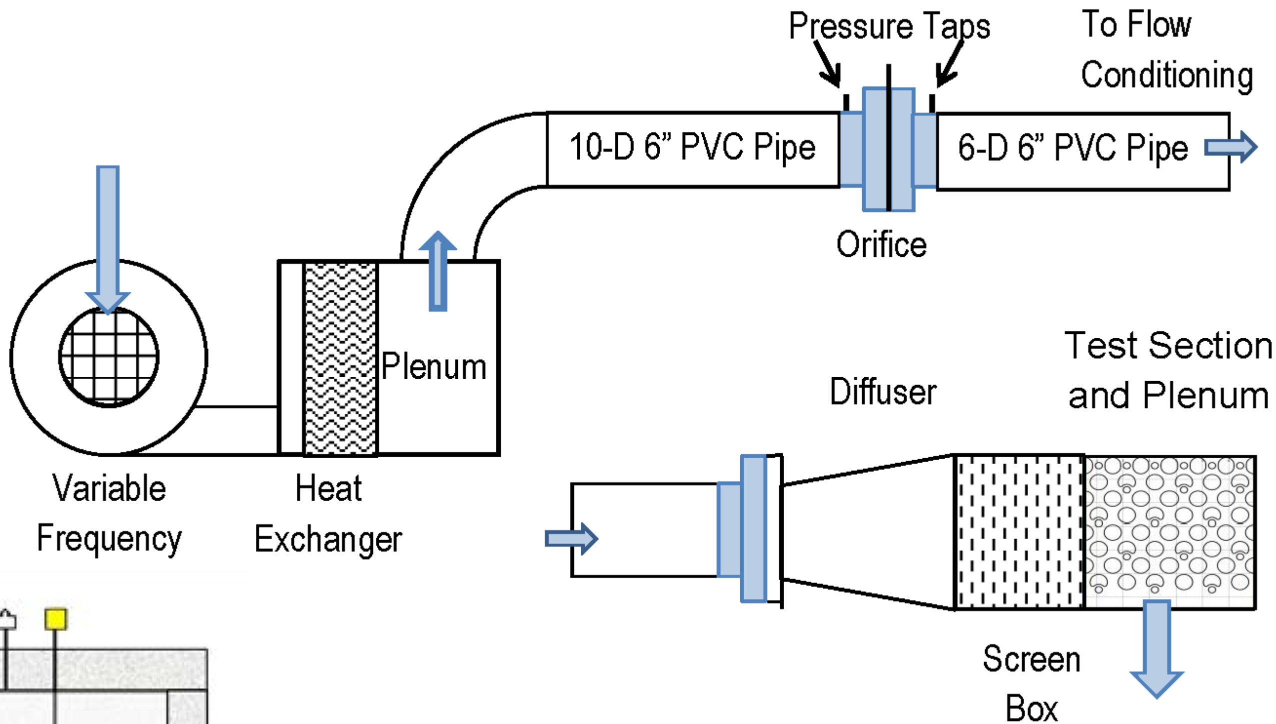
- Suction surface heat transfer distributions are complete.
- Preparations are being made to fabricate a heat transfer vane which integrates film cooling plenums.
- A solid model of two of the suction surface film cooling plenums are shown.
- The plenums integrated into the profile of the vane shows the flow geometry.
- The three suction surface plenums dropped into the vane shape are shown on the right and preparations are ongoing to cast the two film cooling vanes.

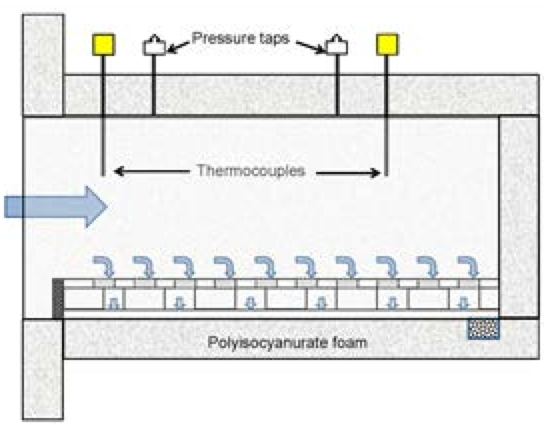




INTERNAL COOLING INVESTIGATION

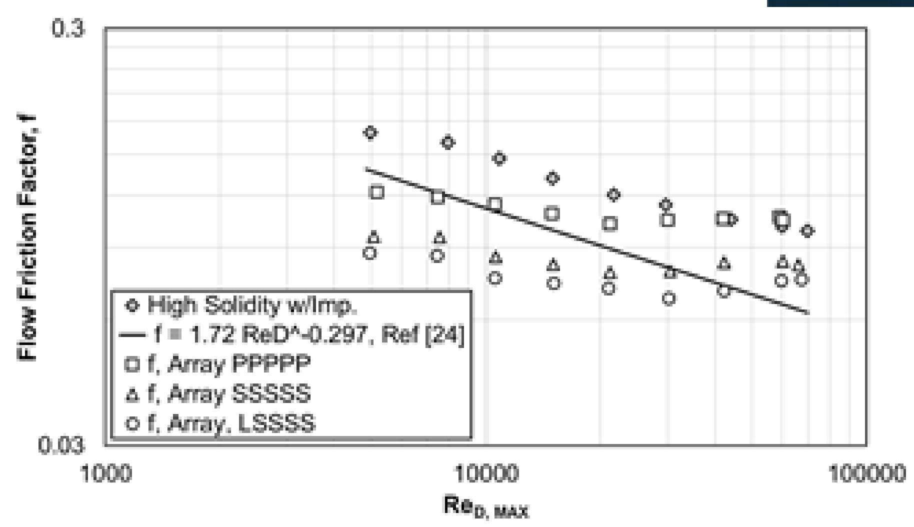
This bench scale internal cooling, flow and heat transfer rig, has been used for investigating configurations of incremental impingement and testing converging high solidity arrays for the trailing edge. The internal cooling rig includes a high pressure blower driven with a variable frequency drive, a plenum with heat exchanger, an orifice tube, a downstream diffuser section and a flow conditioning section flow or screen box.

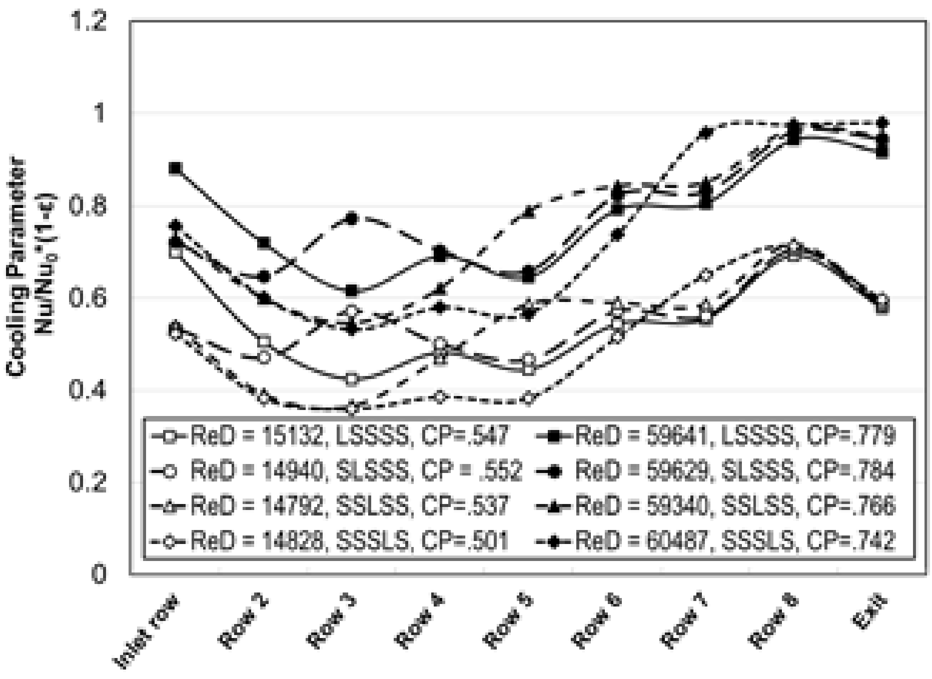




INCREMENTAL IMPINGEMENT WITH VARIABLE HOLE SIZES

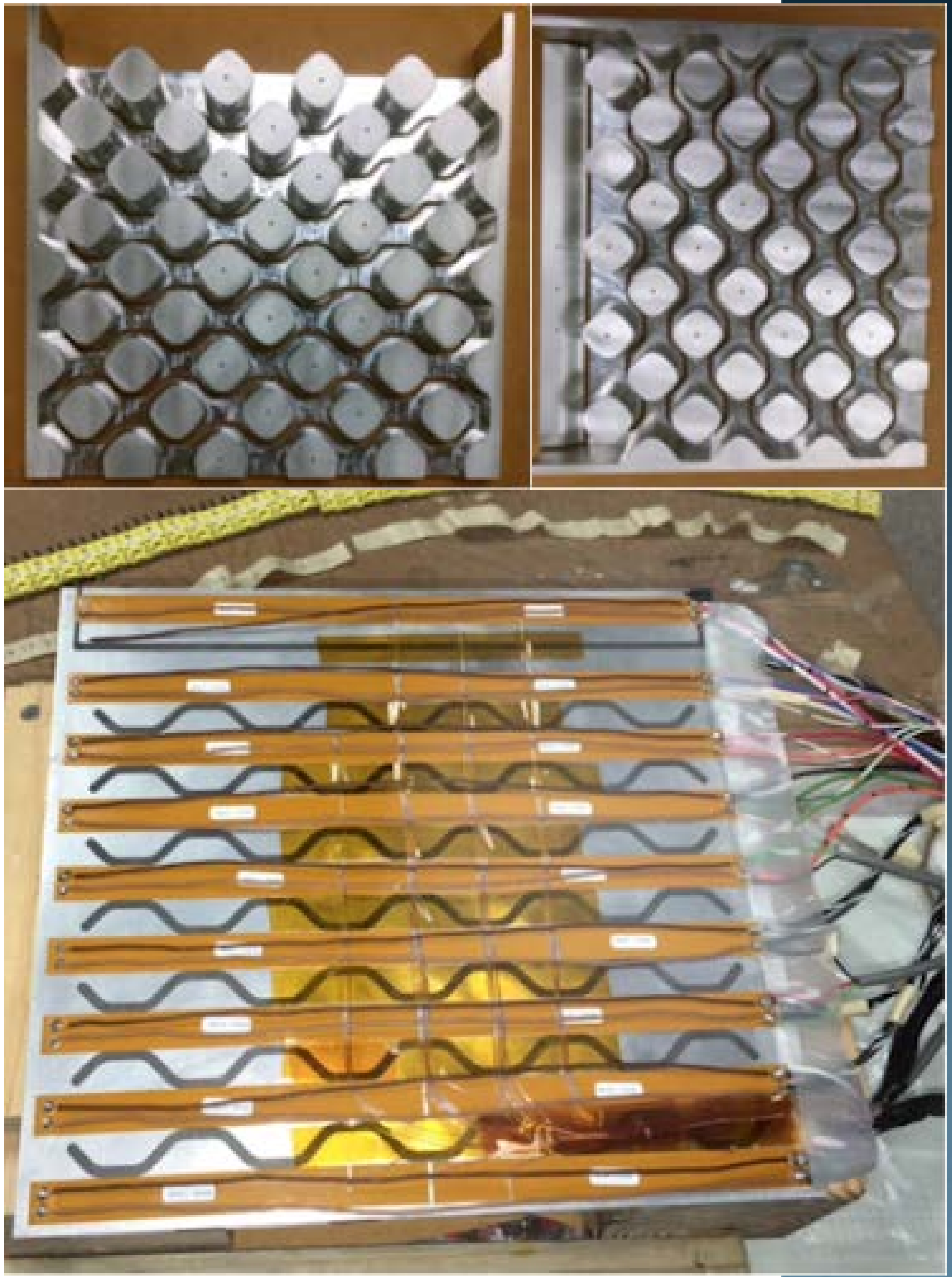
- All petit hole sizes raised the flow friction factor. However, pressure drop can be managed by varying impingement hole area. Pressure drop is much lower than conventional arrays.
- Adding a petite hole size provided significantly more flexibility in addressing variable heat load.
- The current array is designed to put impingement holes behind pedestals in rows 2, 4, 6, and 8 in addition to the first row of pedestals.
- However, in principle a hole can be placed behind any pin in the array .
- Although our current configuration is not ideal to match our current heat load in the leading edge, it is improved.
- The current database should be sufficient to ground the developing analytical tool giving more flexibility.





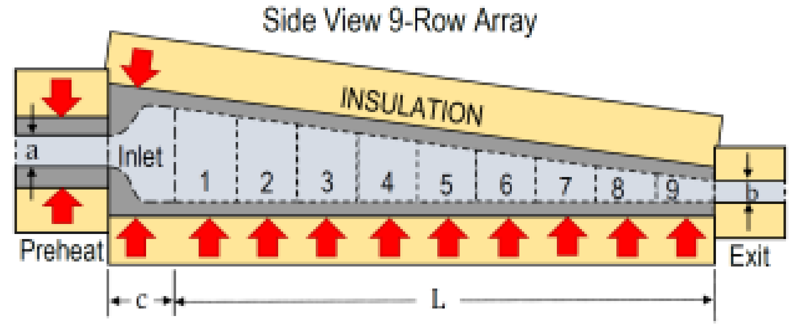
CONVERGING DIAMOND PEDESTAL TRAILING EDGES

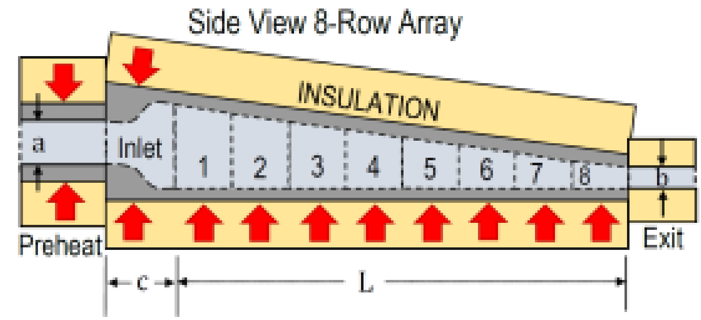
- A converging diamond pedestal array was initially proposed to cool the trailing edge.
- The finite difference and FEA analyses indicated a trailing edge effectiveness which was lower than the initial goal.
- A second array was designed with one fewer rows of pedestals and a trailing edge region opened to allow more flow.
- Both arrays have been tested and the results have both similarities and differences.
- The heat transfer and pressure drop have been compared in terms of a reference Reynolds number based on the 8th row for the 9-row array and the 7th row for the 8-row array.

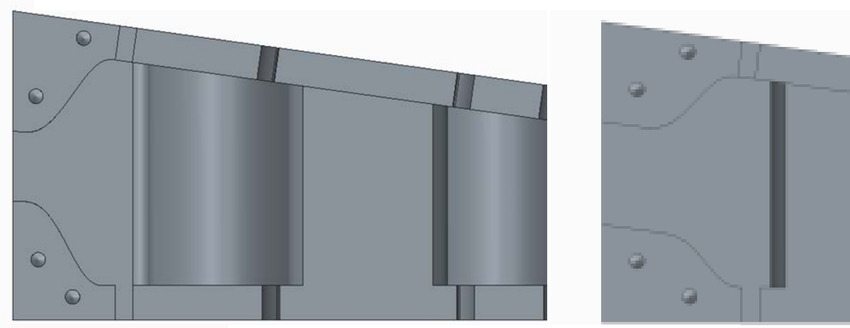


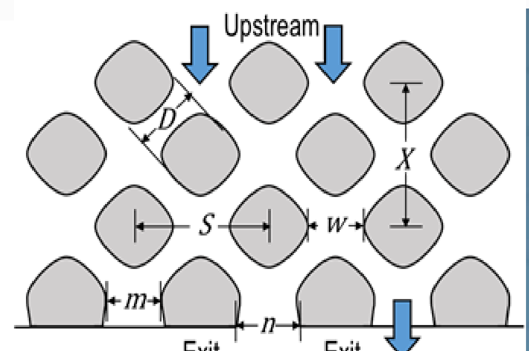
CONVERGING DIAMOND PEDESTAL TRAILING EDGES

- The 9-row array has a narrower inlet than the 8 row array but rows 2 thru 8 of the 9-row are the same as rows 1 thru 7 for the 8-row. Also, see the middle figure.
- The 9th row of the 9-row has the same pedestal pattern shown at lower right.
- The 8th row of the 8-row has an expanded outlet with dimensions m and n larger than the 9-row to keep the area of the last row approximately the same as the 7th row.
- Upstream of the inlet of both arrays a preheater was used to eliminate any unheated starting length affect similar to what Jaswal and Ames saw in row one of their high solidity arrays.
- The Reynolds number ranged from 5000 to 70,000 based on Vmax.



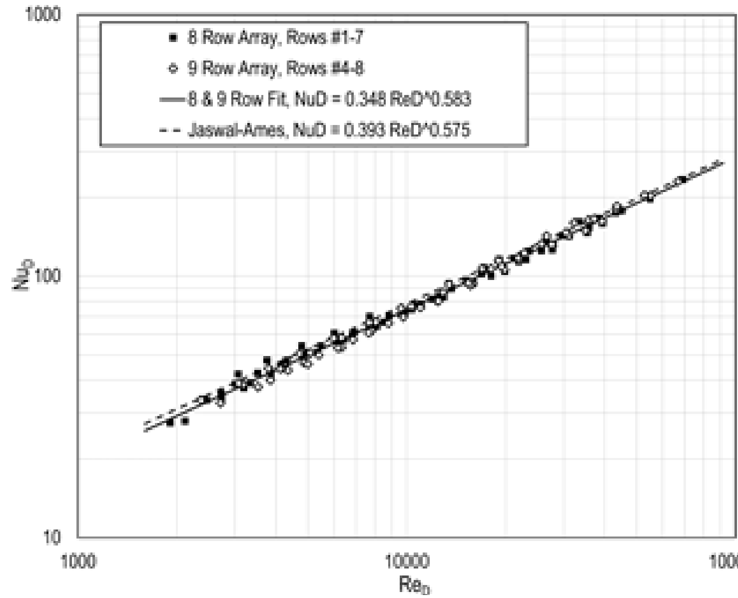


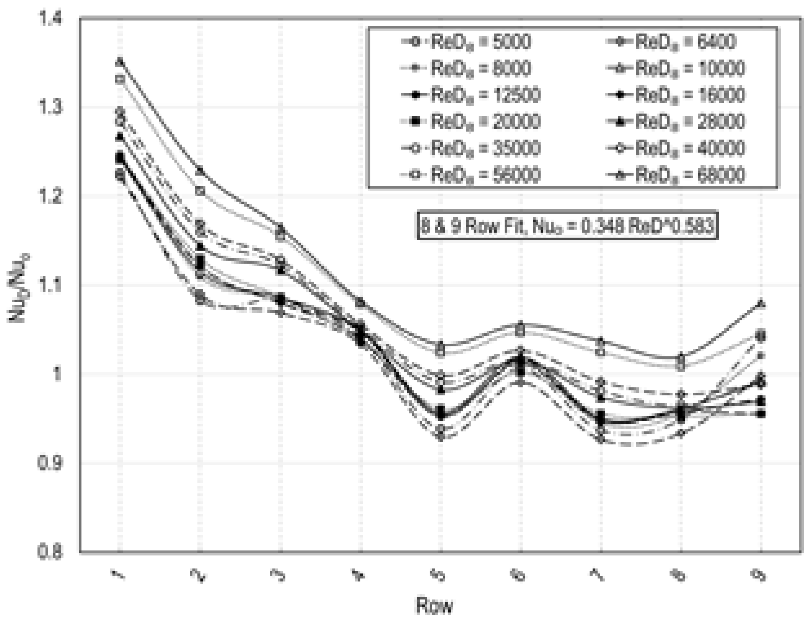


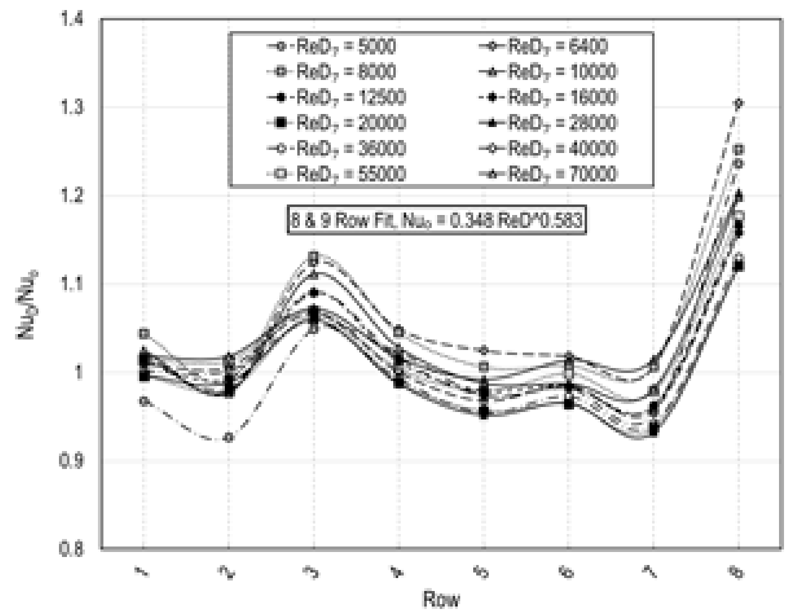


CONVERGING DIAMOND PEDESTAL TRAILING EDGES

- Rows 4 thru 9 of the 9-row array and rows 1-7 of the 8 row array fit a correlation based on local Reynolds number well as shown at the right.
- The 9-row array with its thinner inlet area shows higher initial heat transfer. Perhaps this is due to the higher inlet velocity along with the sudden expansion which may generate high Tu.
- The 8-row array has higher downstream heat transfer which may be due to the expansion.

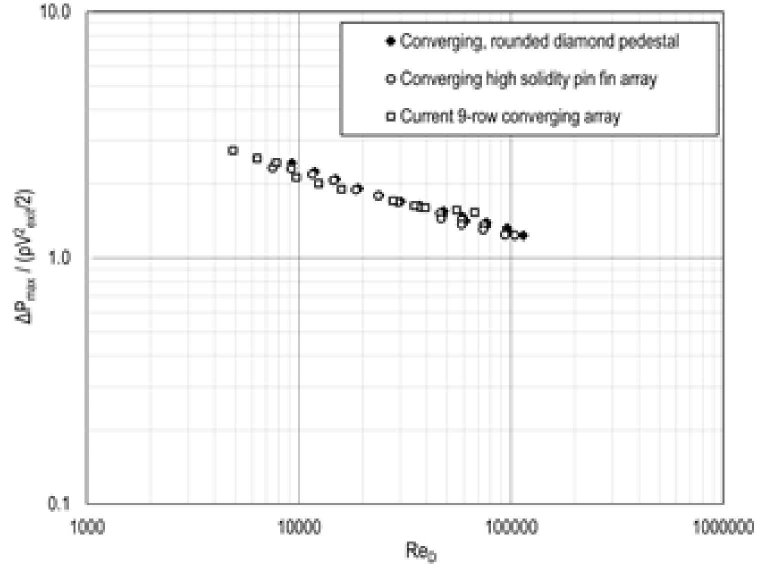


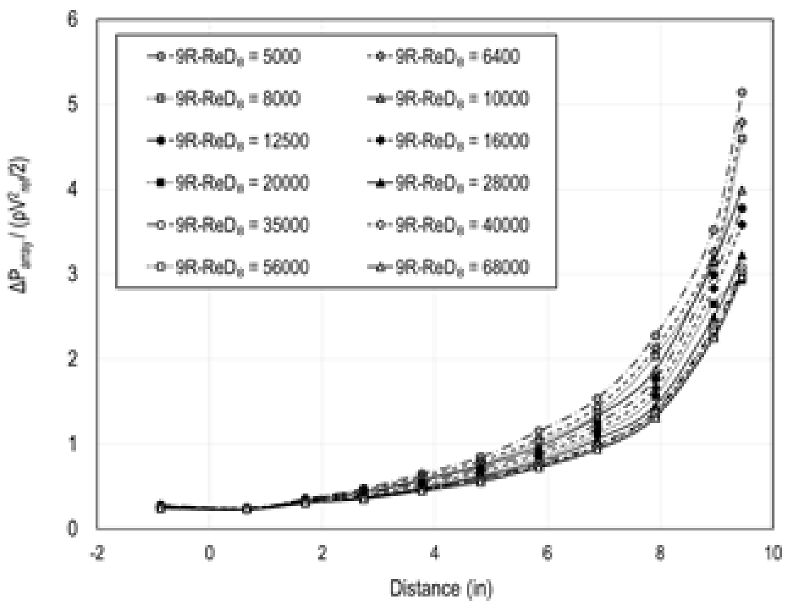


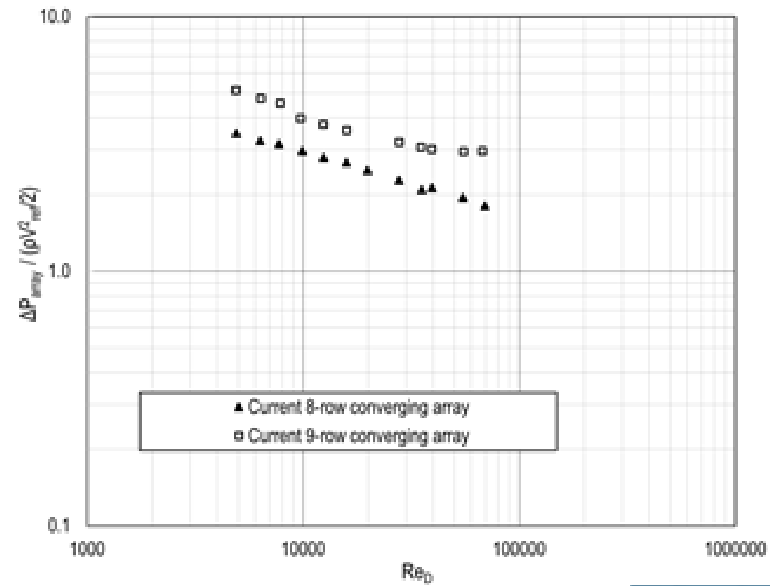


CONVERGING DIAMOND PEDESTAL TRAILING EDGES

- The 9-row pedestal array with its constant convergence has a pressure drop similar to the high solidity pin and pedestal converging arrays of Jaswal and Ames.
- The 9-row array has its largest pressure drop in the last row.
- The 8-row array has about a 31% lower pressure drop at similar similar flow rates suggesting a 17% higher flow at a similar pressure drop.







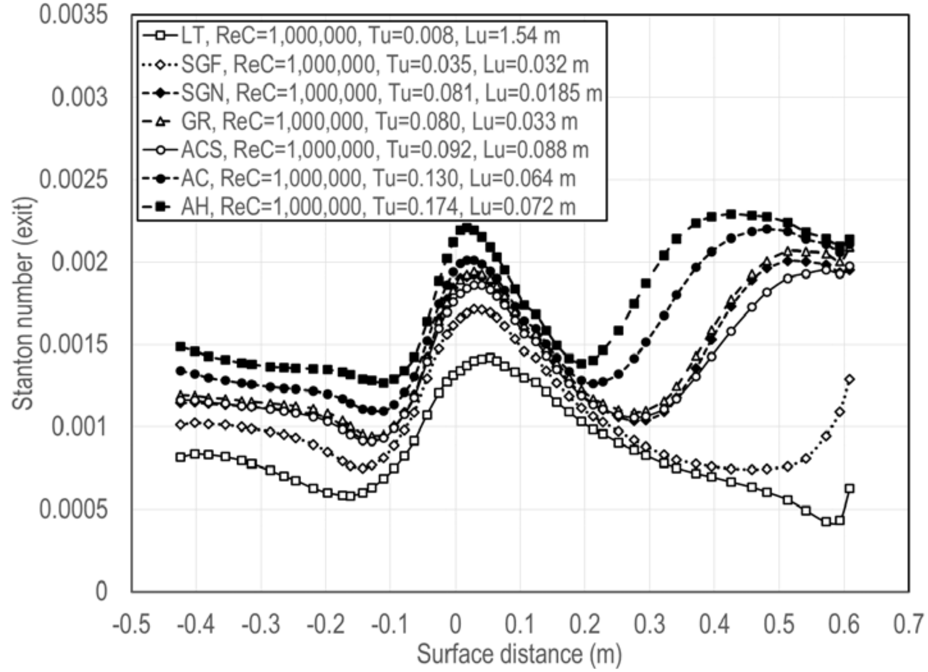
PRESENTATION SUMMARY

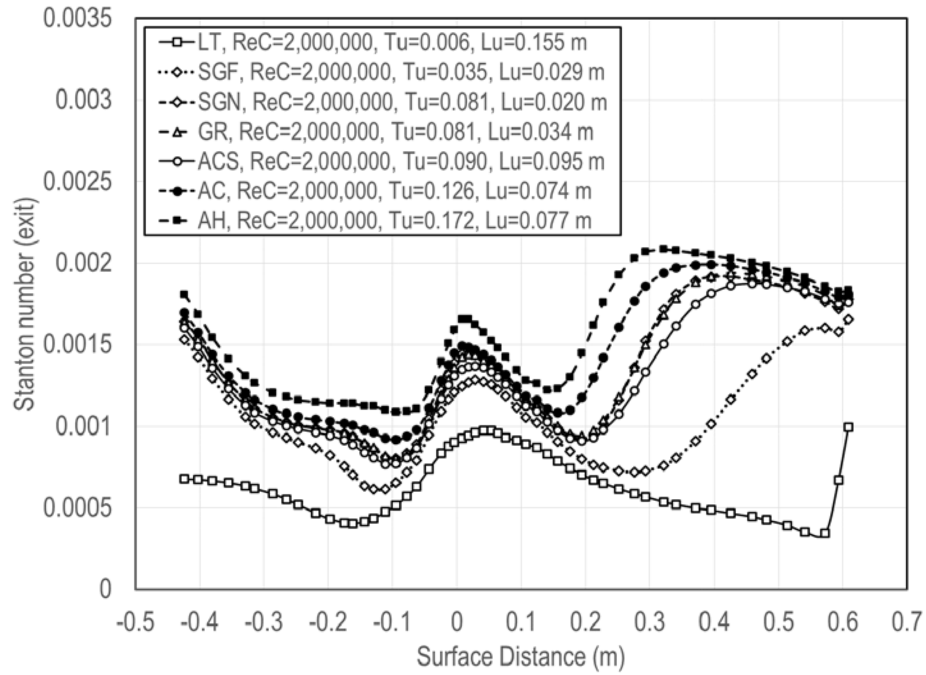
- The present research project combines a four phase experimental and analytical program to advance the readiness of three internal cooling methods.
- External midspan heat transfer distributions and full suction surface heat transfer data have been acquired on the vane showing the impact of turbulence and secondary flows while preparations for film cooling measurements are ongoing. (Even though the contract is over Loren Soma plans to continue working on this as part of his Ph.D. research)
- Twenty nine configurations of variable hole size incremental impingement have been tested providing a highly extended database for computational grounding of predictive methods. Trailing edge cooling measurements have also been acquired
- Internal heat transfer predictions show excellent promise in matching experimental data while helping to clarify the physics of the cooling method.
- External film cooling and heat transfer predictions have been challenging and wall resolved LES has been applied to cope with the complex physics of the film cooling and external heat transfer.
- The final vane cooling configuration includes the new 8-row trailing edge configuration and the incremental impingement geometry will be selected using LES computations. The final results will be integrated into the final vane cooling model.

QUESTIONS?

MIDSPAN HEAT TRANSFER DISTRIBUTIONS

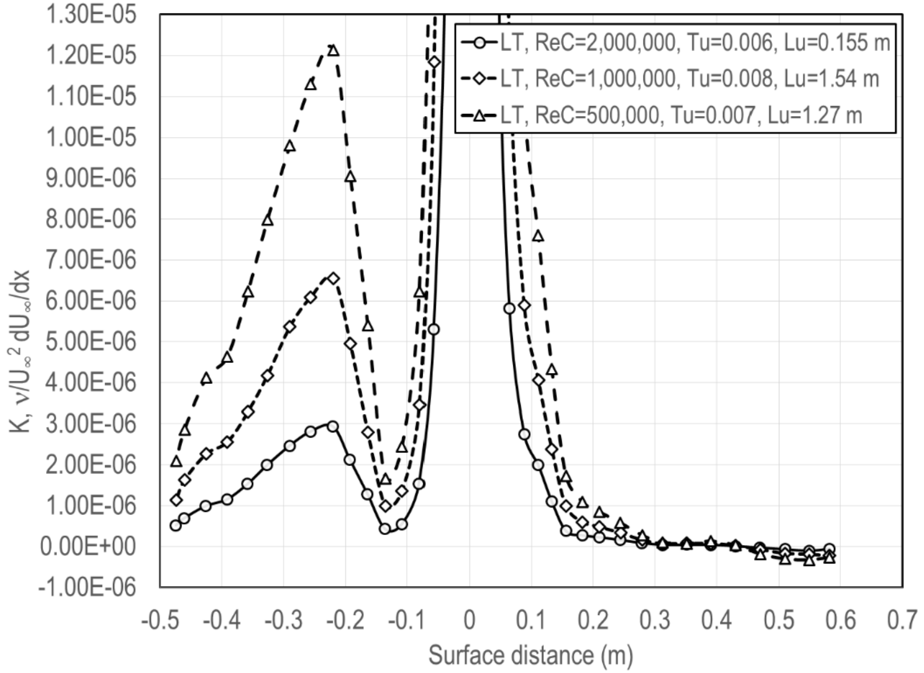
- At the 1,000,000 and 2,000,000 Reynolds number we see the transition moving forward on the suction surface with increasing Reynolds number.
- The relative heat load on the leading edge drops well below the turbulent suction surface at Rec = 2,000,000.
- Transition seems to appear on the downstream pressure surface at the higher turbulence levels at 1,000,000 Reynolds No. and it is present at all higher turbulence levels at 2,000,000
- The six elevated turbulence levels show significant augmentation of laminar heat transfer.

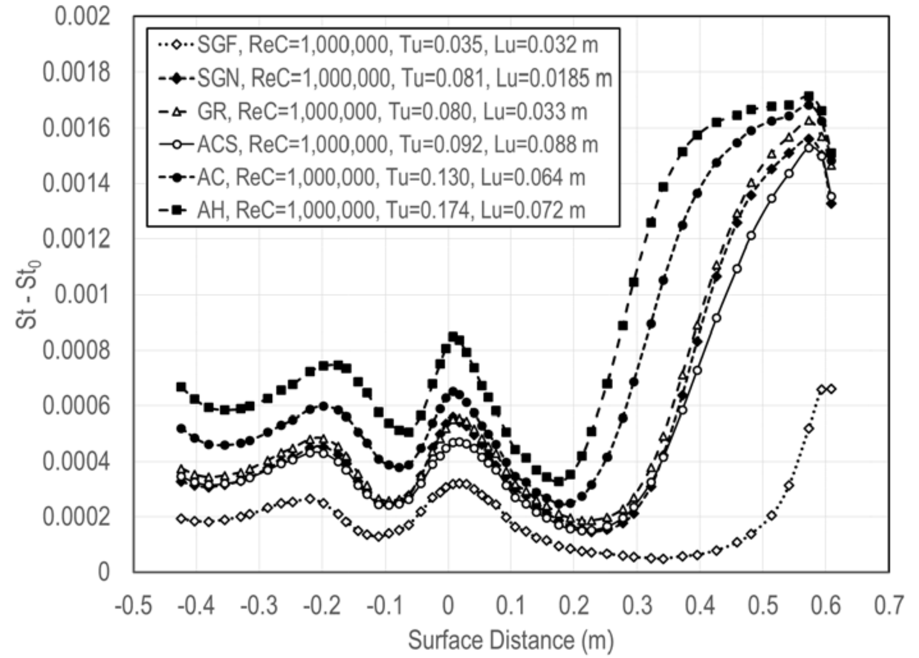




MIDSPAN HEAT TRANSFER DISTRIBUTIONS

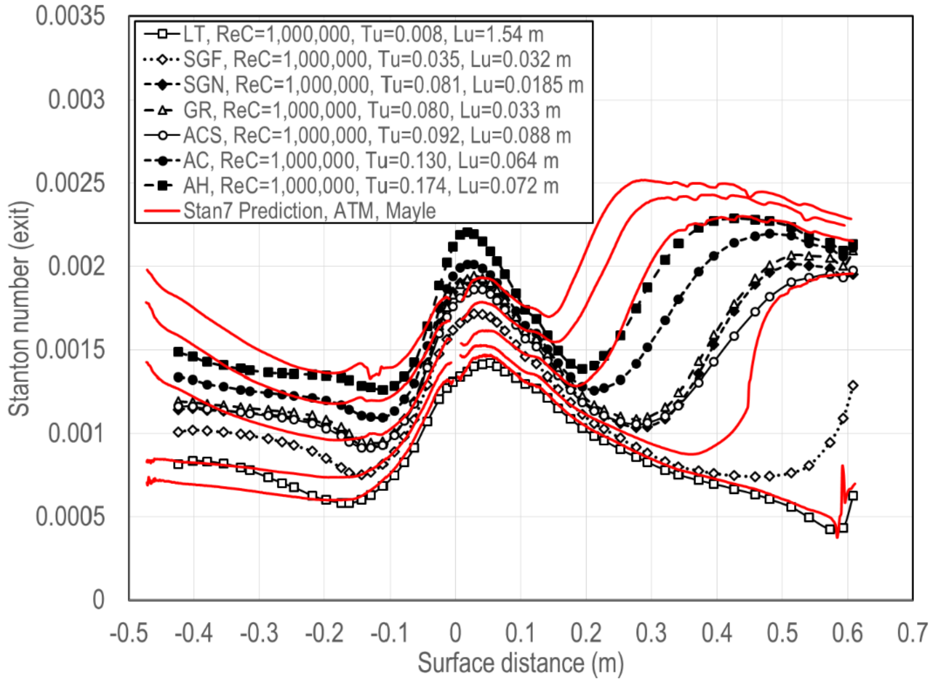
- Streamwise acceleration levels are very high in the stagnation region but drop on the suction surface and the near pressure surface.
- After the initial drop on the pressure surface, high acceleration is reestablished downstream.
- Peak augmentation occurs in the leading edge not including transition.
- Augmentation levels continue to fall on the suction surface prior to transition indicating the influence of convex curvature.
- After the initial drop, augmentation levels rise on the pressure surface while transition criteria is initially met.

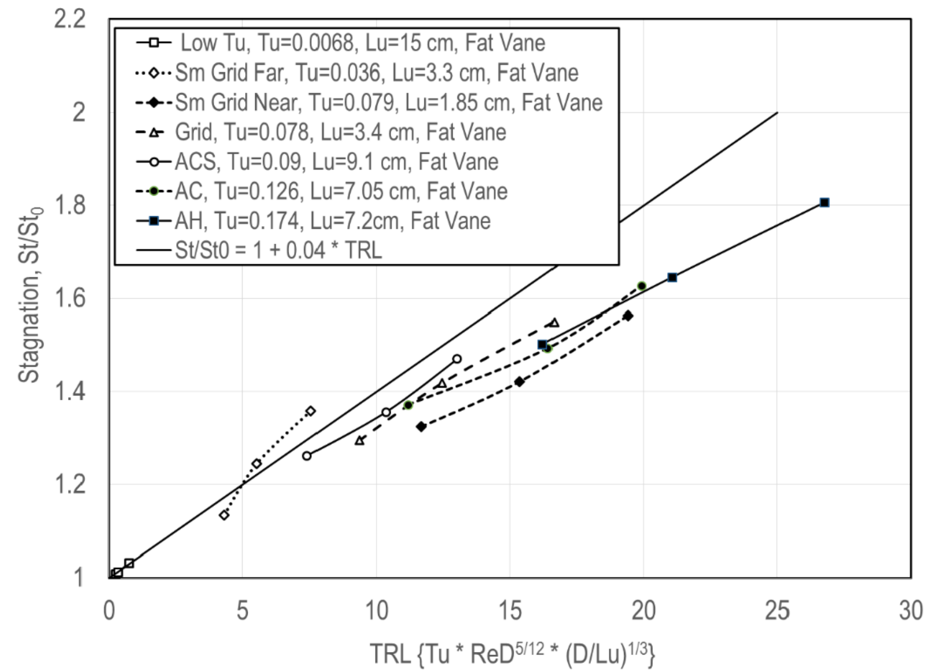




MIDSPAN HEAT TRANSFER DISTRIBUTIONS

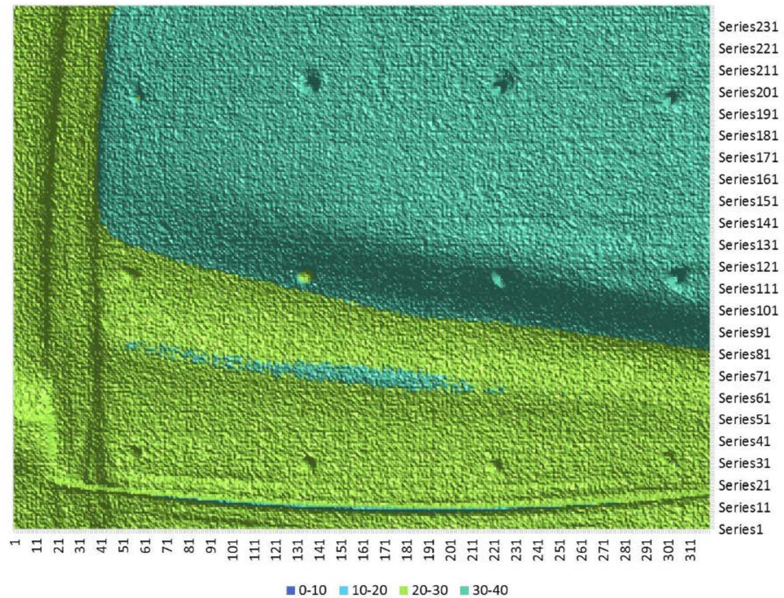
- Boundary layer predictions show reasonable agreement with laminar augmentation except in the leading edge where it is significantly low.
- Transition on the suction surface is predicted early probably due to a delay caused by convex curvature.
- Pressure surface predictions show some difficulty with augmentation and transition.
- Stagnation region augmentation levels drop increasingly below the TRL parameter as the pseudo time scale (Lu/u') decreases. One known influence is the increased relative decay of turbulence with lower Lu/u'.

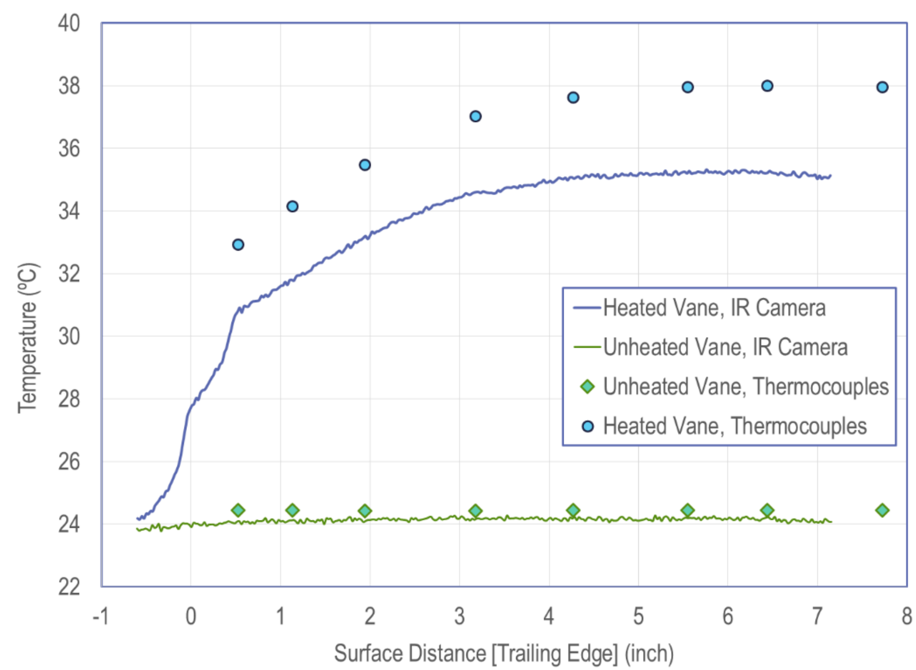




SUCTION SURFACE HEAT TRANSFER DISTRIBUTIONS

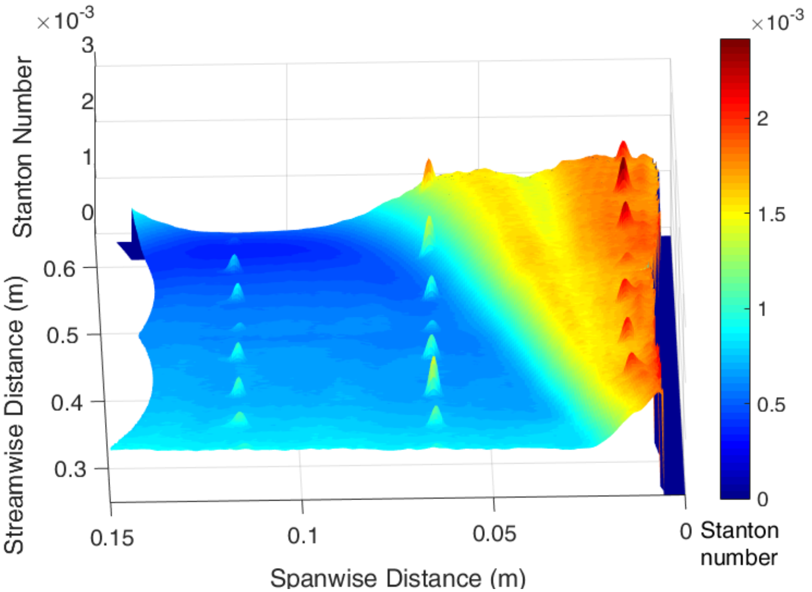
- The raw infrared image shows the start of heating on the left as well as the trailing edge of the vane and the vane/endwall interface.
- The reflective spots visually show on the thermal image providing physical mapping information for the heat transfer distribution.
- Both the image in general and the dots show the fisheye effect of the camera which can be adjusted.
- A comparison of the midspan thermo-couples with the IR temperature values at the same span with and without heating allow for an in situ calibration.



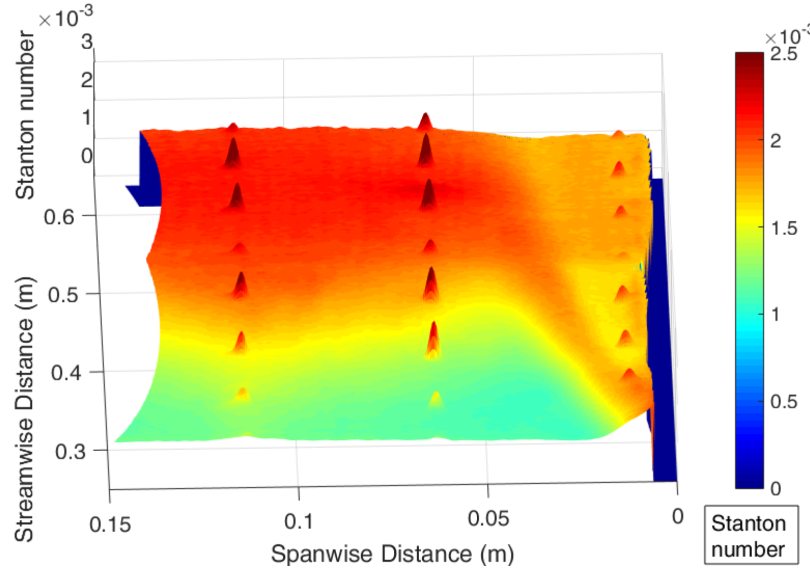


Midline comparison of heated and unheated temperatures, thermocouple vs. IR camera.

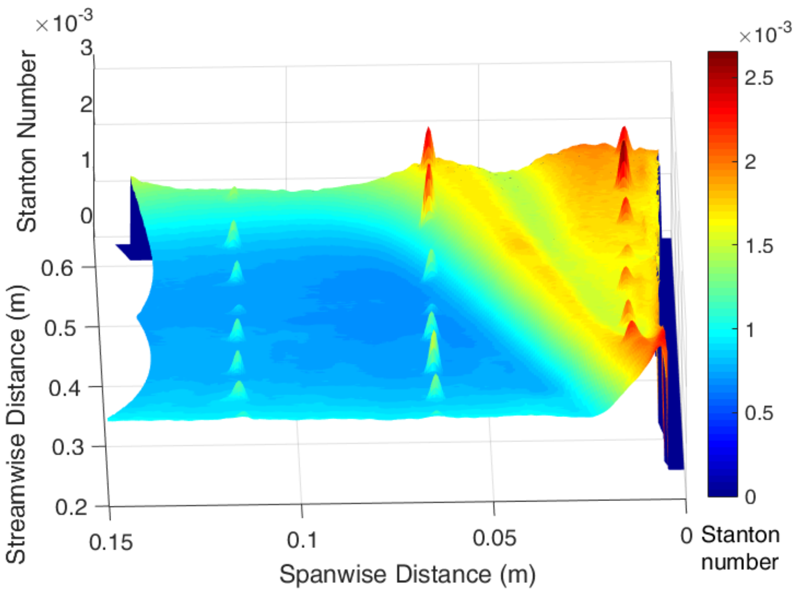
SUCTION SURFACE HEAT TRANSFER DISTRIBUTIONS



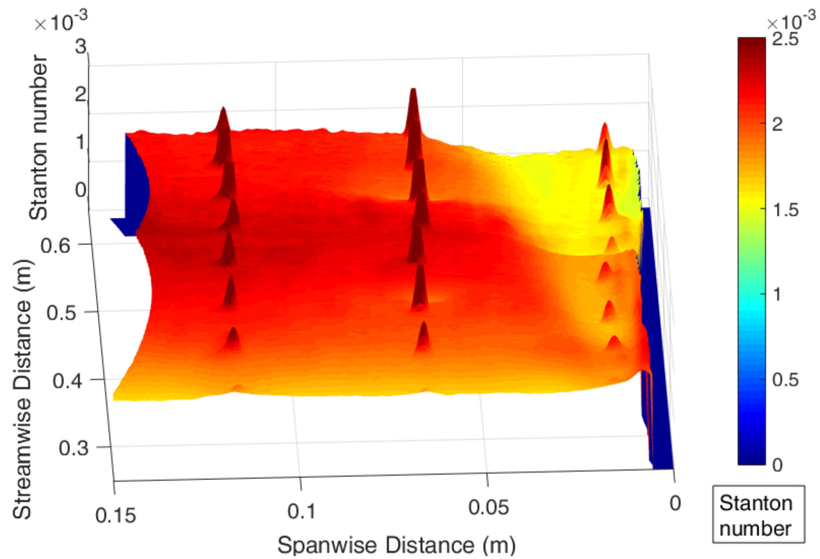
Low turbulence (LT) suction surface, ReC = 1M



Large Grid (LG) suction surface, ReC = 1M



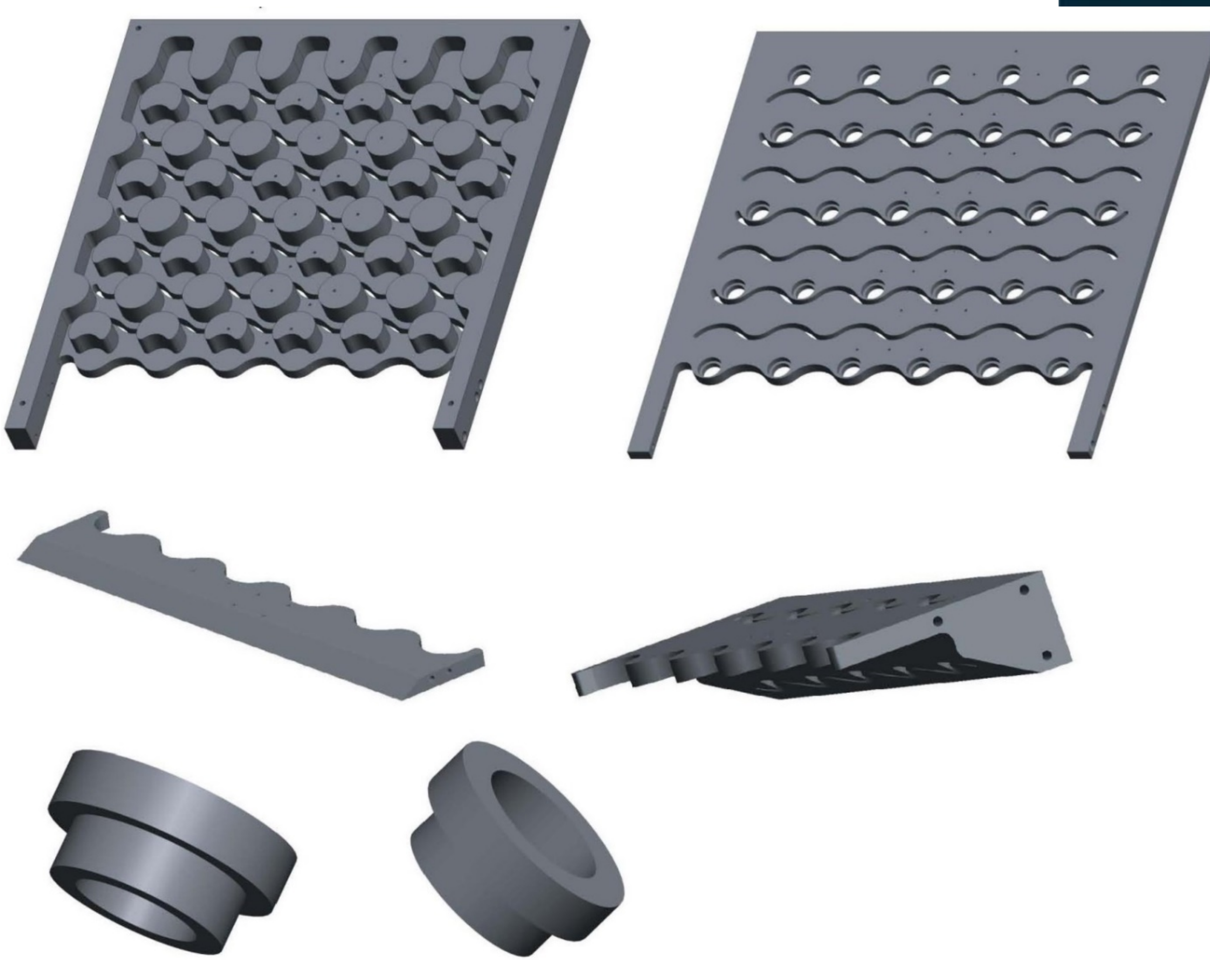
Small Grid Far (SGF) suction surface, ReC = 1M

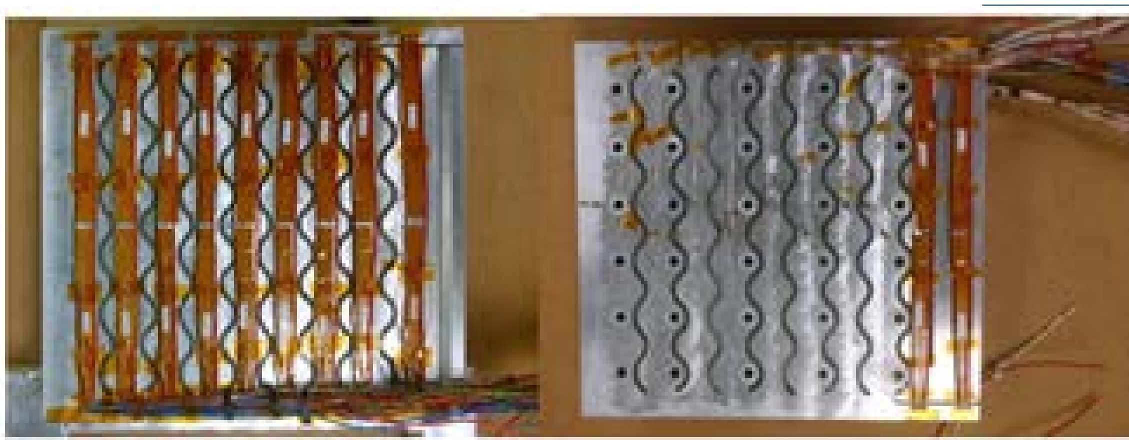


High turbulence (HT) suction surface, ReC = 1M

INCREMENTAL IMPINGEMENT GEOMETRY

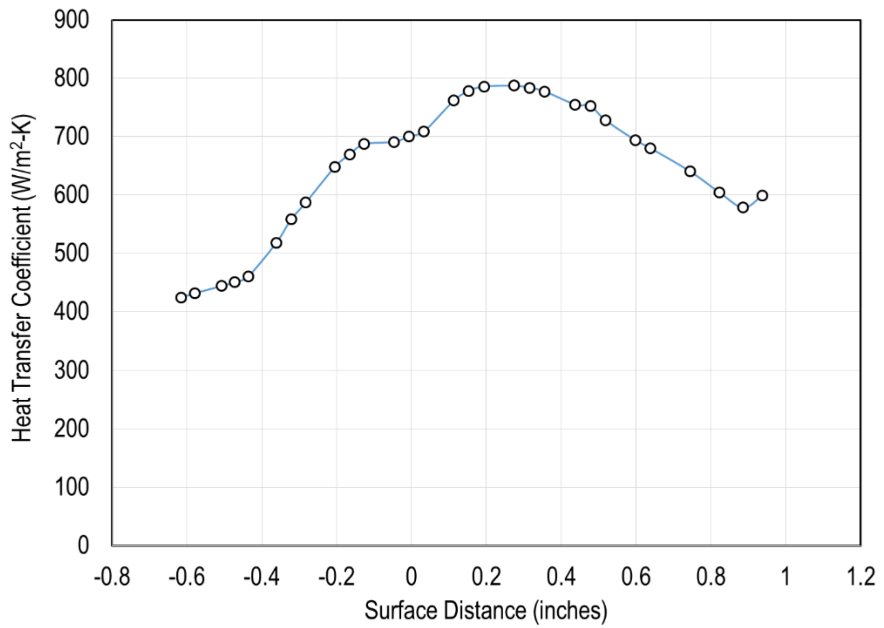
Testing has included relevant inlet and exit geometries along with variable hole size to allow a significant variation of the cooling hole distribution for a given application. Testing has included 29 different hole configurations. The instrumented test surface is shown at the right.



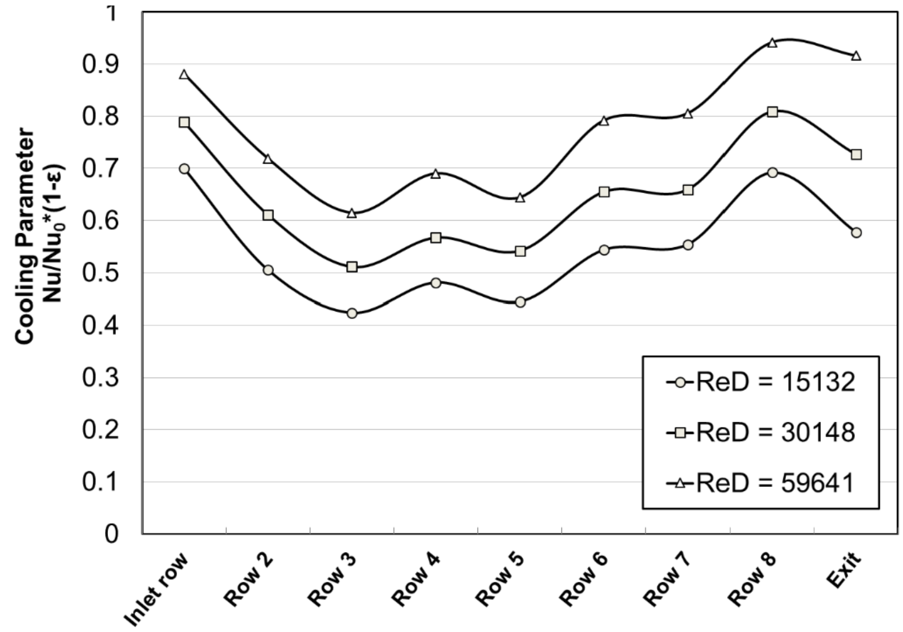


INCREMENTAL IMPINGEMENT WITH VARIABLE HOLE SIZES

- Heat load can vary over the surface of a component, while conventional cooling methods have limited ability to vary locally.
- The heat transfer distribution around the stagnation region for the current vane design is presented in the top figure.
- The cooling parameter data shown below is for the earliest configuration for incremental impingement, LSSSS.
- While this cooling method keeps a high level of cooling across the array it does not match the needed heat load very well.
- Variable hole size incremental impingement is clearly needed.

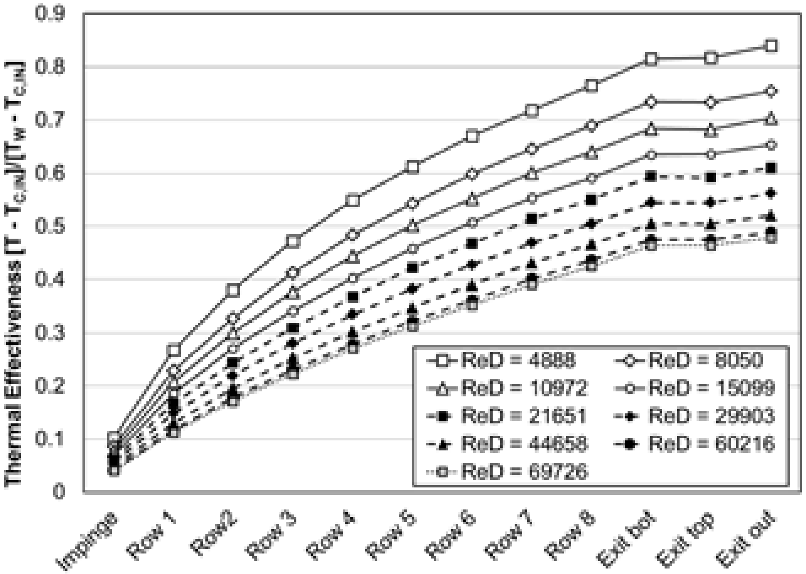


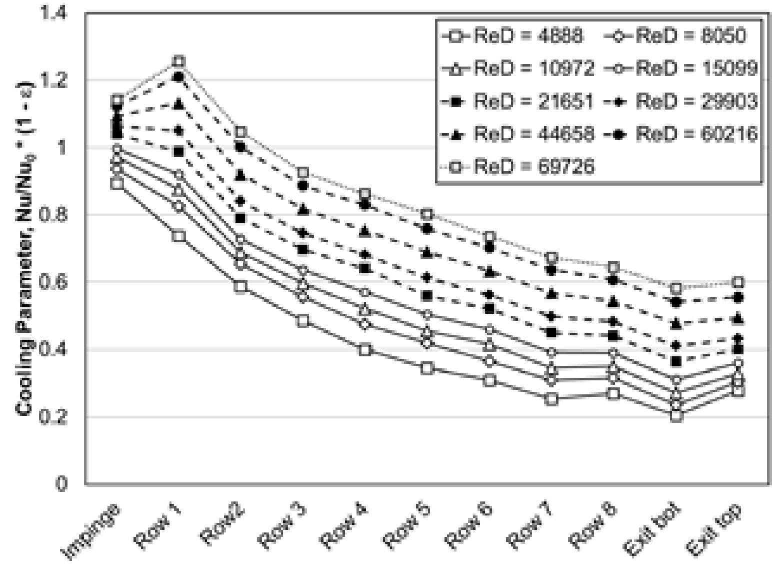
The predicted heat transfer loading distribution for warm cascade vane in the stagnation region and near suction surface.



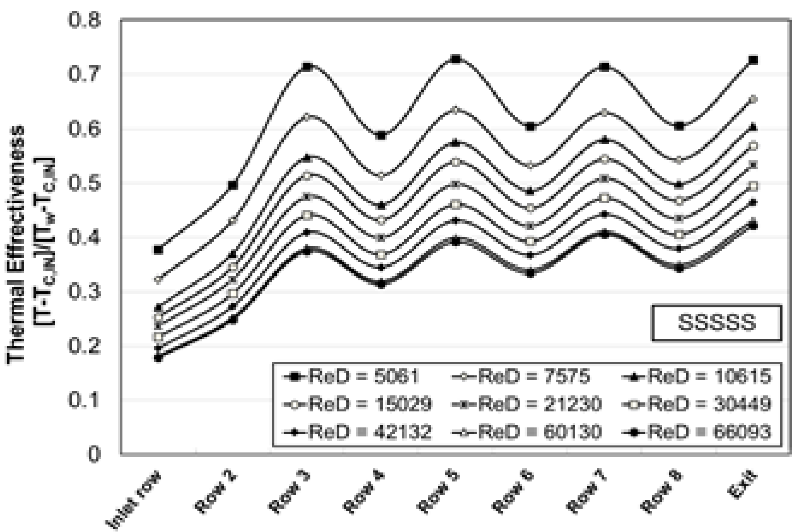
The influence of Reynolds number on cooling parameter, $(1-\varepsilon)^* Nu/Nu_0$, LSSSS.

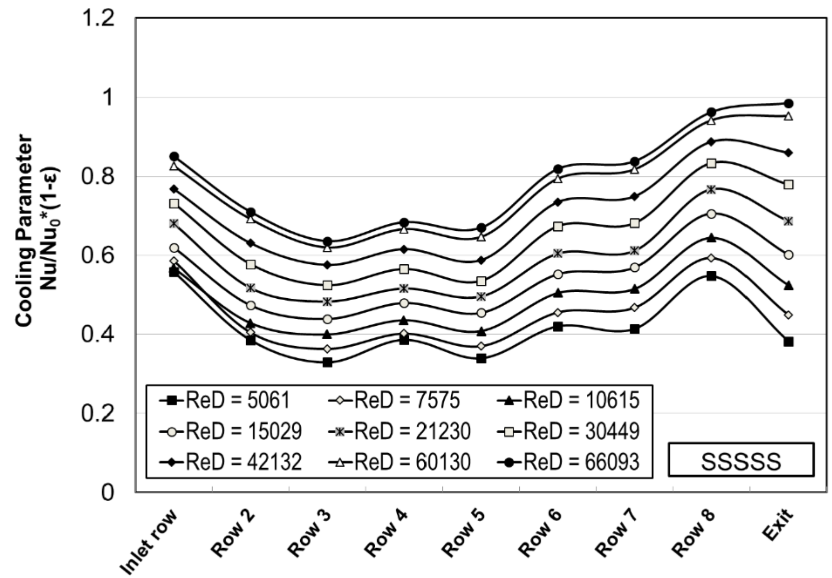
INCREMENTAL IMPINGEMENT VERSUS HIGH SOLIDITY ARRAY





In conventional high solidity arrays initial cooling is high but the ability to cool drops rapidly as cooling air heats up.





Incremental impingement manages air temperatures to keep heat transfer high.

INCREMENTAL IMPINGEMENT WITH VARIABLE HOLE SIZES

- All petit hole sizes raised the flow friction factor. However, pressure drop can be managed by managing impingement hole area. Pressure drop is much lower than conventional arrays.
- Adding a petite hole size provided significantly more flexibility in addressing variable heat load.
- The current array is designed to put impingement holes behind pedestals in rows 2, 4, 6, and 8 in addition to the first row of pedestals.
- However, in principle a hole can be placed behind any pin in the array .
- Although our current configuration is not ideal to match our current heat load in the leading edge, it is improved.
- The current database should be sufficient to ground the developing analytical tool giving more flexibility.