Cooling Strategies for Vane Leading Edges in a Syngas Environment Including Effects of Deposition and Turbulence

UTSR Workshop – Aerodynamics/Heat Transfer Breakout

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Motivation and Conceptual Approach

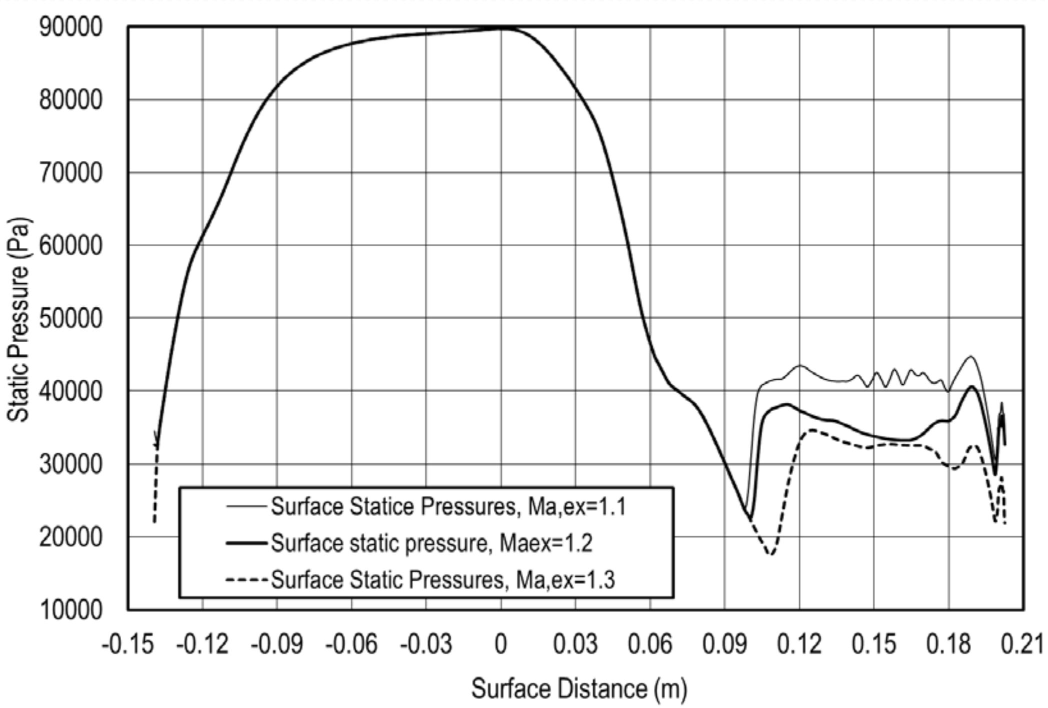
- This research was motivated by the potential of IGCC gas turbines to experience deposition which could possibly lead to clogging of coolant holes.
- This research investigated the influence of large leading edge diameters to gage the potential to reduce leading edge heat transfer to levels which allow the use of internal cooling methods to replace less efficient showerhead cooling and its potential to clog.
- Since land based gas turbines for IGCC cycles run at high Reynolds numbers and often see very high inlet turbulence levels from combustion systems an improved understanding was required for stagnation region heat transfer mechanisms.
- Stagnation regions require high levels of cooling over a relatively broad region so internal cooling systems which provide a sustainable level of high cooling are needed.
- Research was also needed to investigate the influence of large leading edge regions and high turbulence on deposition rates.
- This project also investigated the influence of full coverage film cooling on offering protection both from deposition and for thermal protection of downstream surfaces.

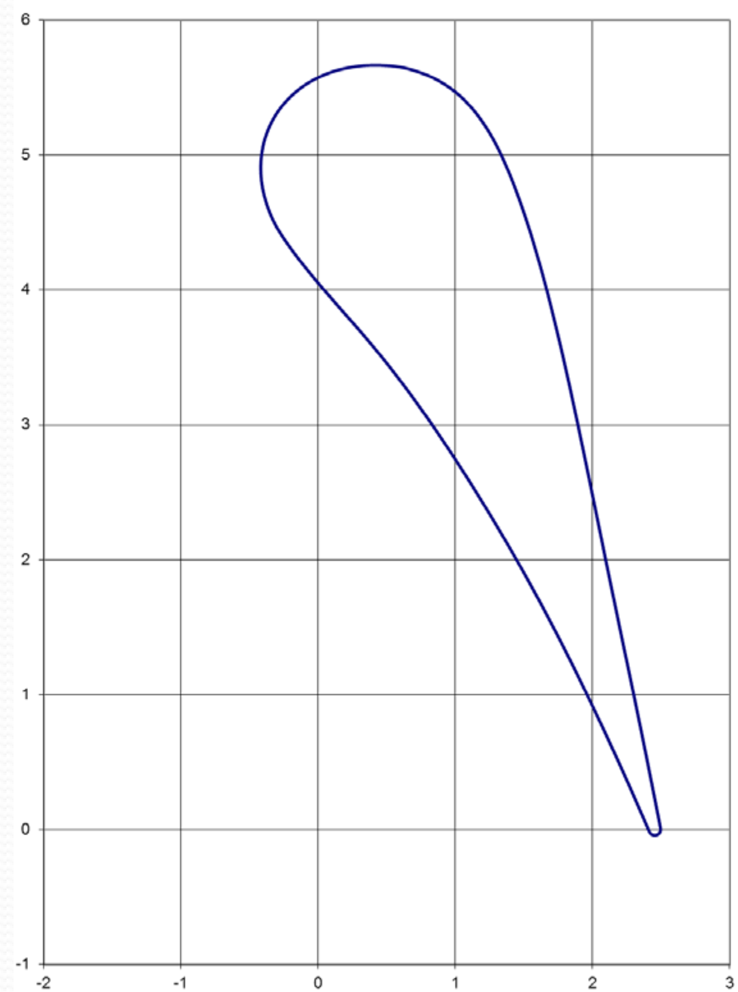
Research at UND investigated leading edge heat transfer rates over a range of turbulence levels to very high values and looked at large leading edge regions at high Reynolds numbers.

Research at UND also investigated incremental impingement a method cooling leading edge regions internally.

UND also investigated the effectiveness of full coverage film cooling subjected to high turbulence levels and acceleration.

Research at OSU investigated deposition rates for the influence of both leading edge diameter and turbulence. Research at OSU also focused on the potential for full coverage film cooling to protect downstream pressure surfaces from deposition buildup.



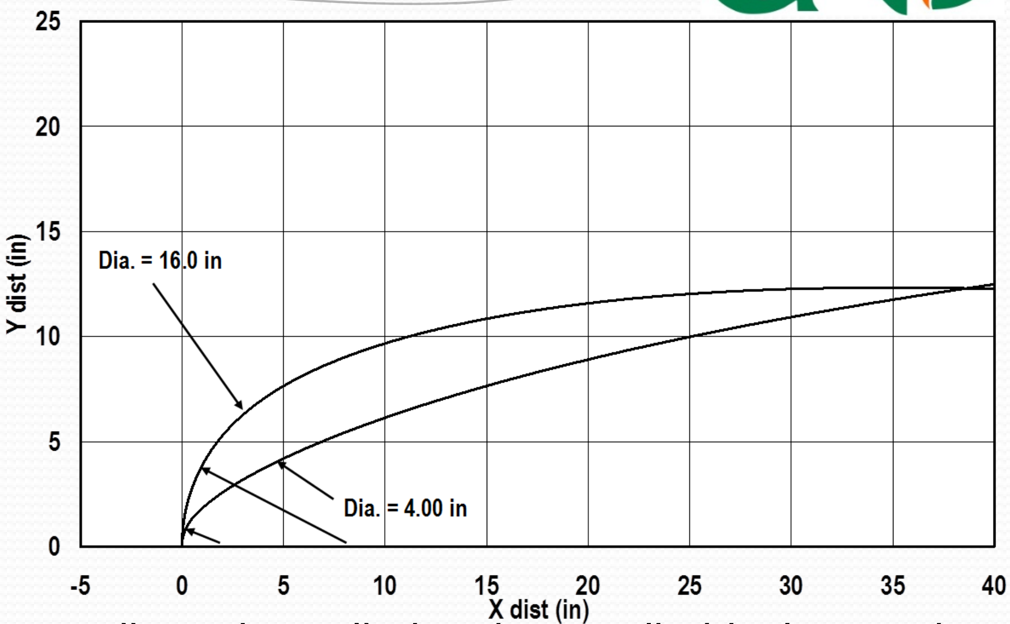


Overview of Experimental Tasks at UND

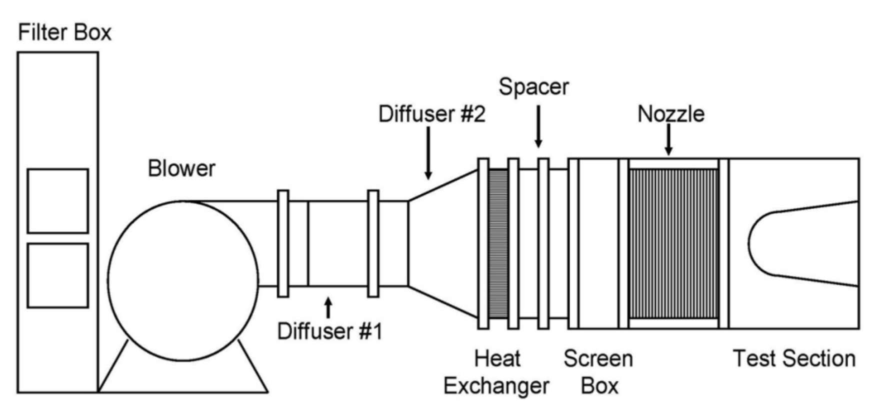
- Extended the parameter range for stagnation region heat transfer
  - Initially used 6 turbulence conditions
  - Later added a very high turbulence condition from a new generator (2 iterations)
- Documented the response of a range of turbulence conditions approaching large leading edges.
- Measured boundary layers near leading edge regions developing under the influence of a range of turbulence conditions.
- Developed internal cooling methods for leading edge regions to eliminate showerhead cooling.
- Investigated full coverage slot and shaped hole film cooling in the accelerating regions downstream from stagnation regions over a range of turbulence conditions.

Heat transfer and film cooling measurements using UND's big cylinder rig.

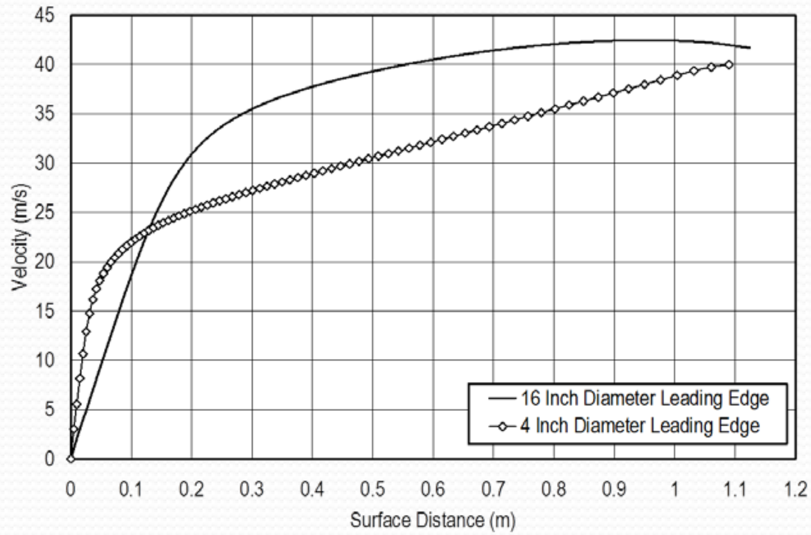
UND's approach to investigate leading edge heat transfer and downstream film cooling was to develop two leading edge cylinders with a constant radius stagnation regions and an accelerating flow downstream. Leading edge regions of 10.16 cm and 40.64 cm diameters were developed. The downstream afterbodies were designed to provide a continued acceleration.



Leading edge cylinders have cylindrical LE regions

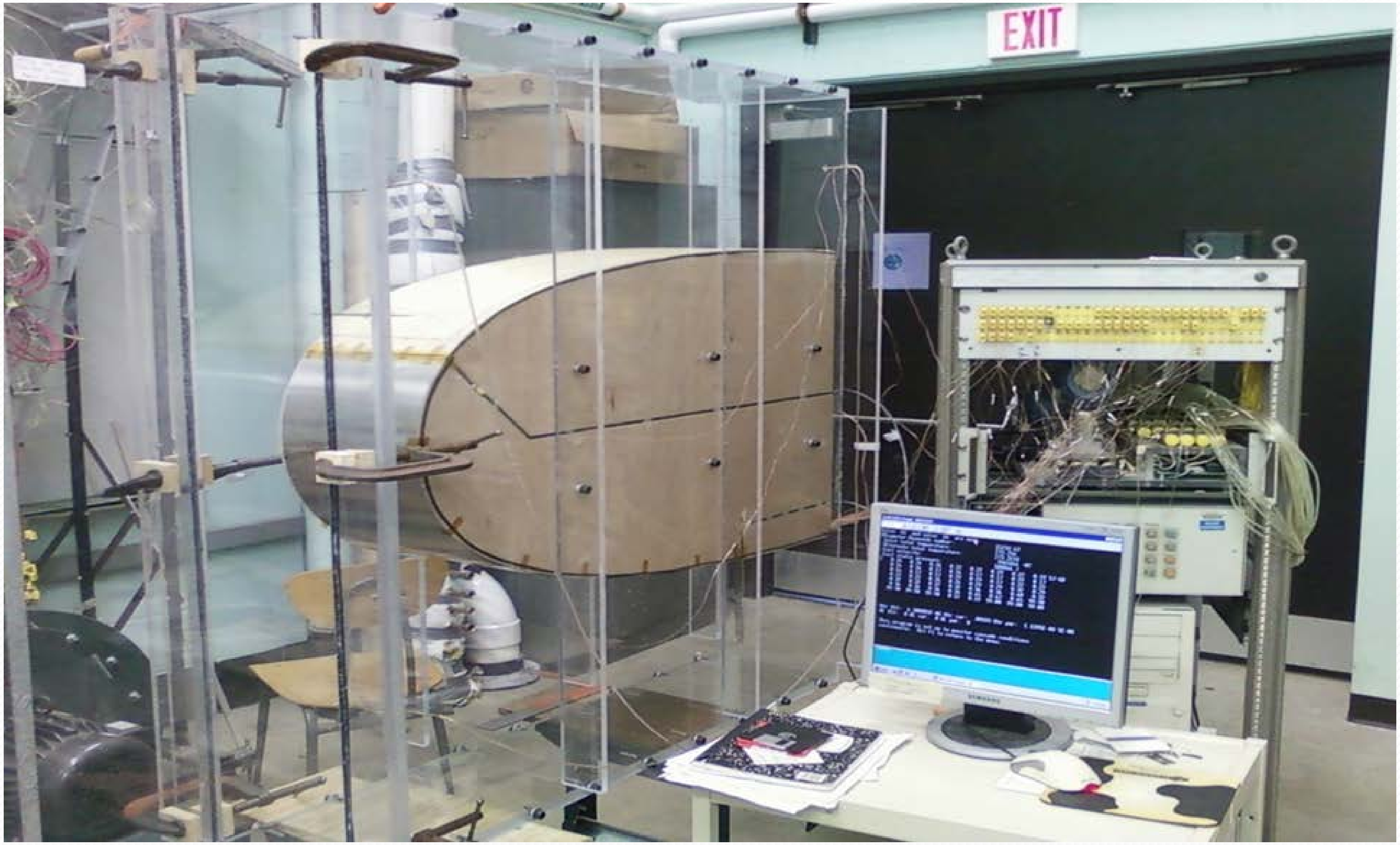


UND's large scale turbine vane cascade wind tunnel is used with large cylinder test section.

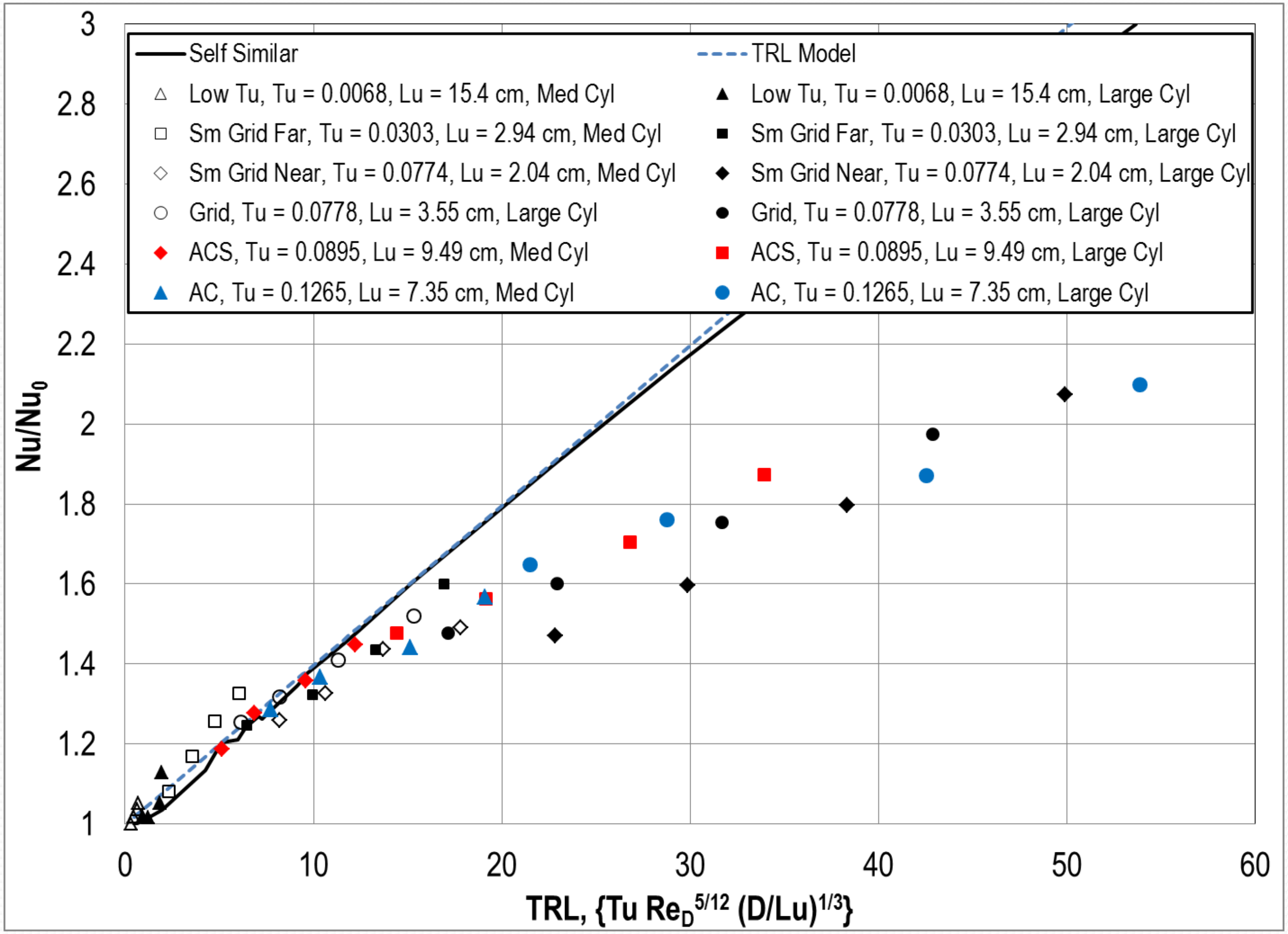


Afterbodies shaped to provide accelerating flow

Photo of large cylindrical leading edge test surface installed in wind tunnel test section



Normalized stagnation region Nusselt number versus TRL parameter for medium and large cylindrical leading edges

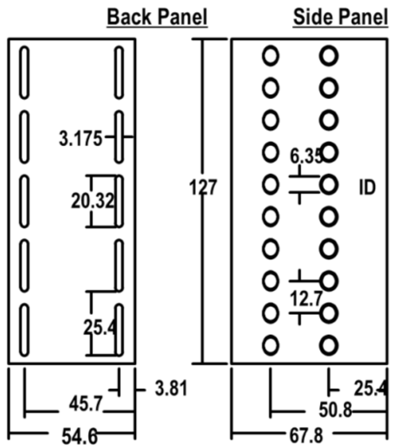


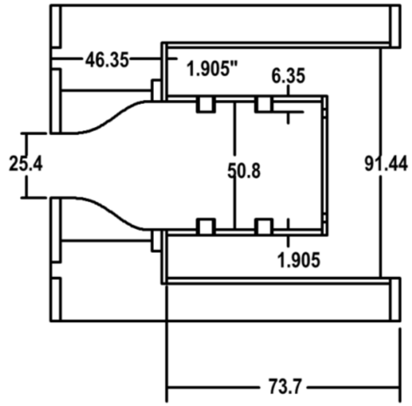
Presented at Turbo Expo 2011,Vancouver, B.C., Canada
10 June 2011, 8:30 am

F. Ames, UND

A range of turbulence conditions were generated for the heat transfer and film cooling studies. These conditions included three aero-combustor turbulence conditions.

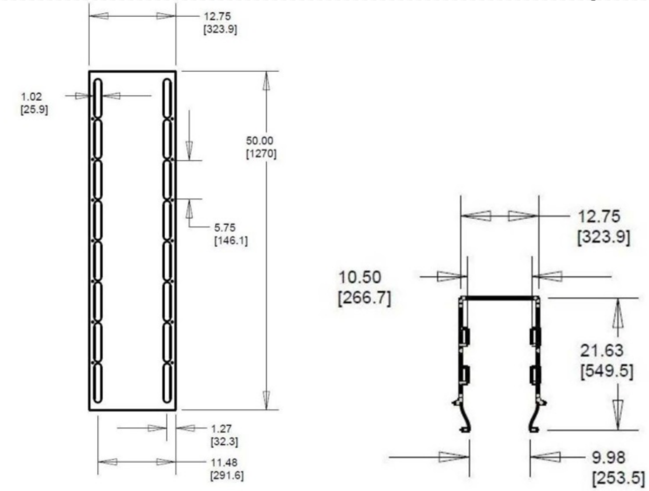
Old aero-combustor turbulence has a 2 to 1 contraction nozzle. First “very high” turbulence aero-combustor had 1 to 1 contraction. Current version has 1.25 to 1 contraction and 7.6 cm decay



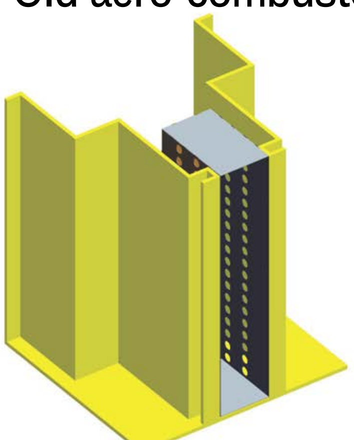


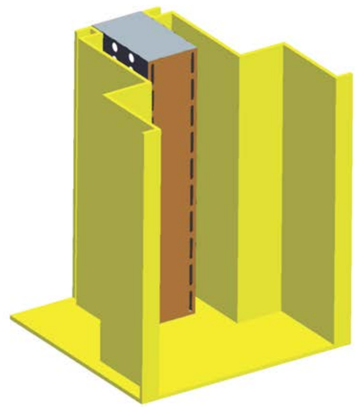
All dimensions are in cm

Cross-Sectional View



Old aero-combustor Tu = 13%, Lu = 7 cm

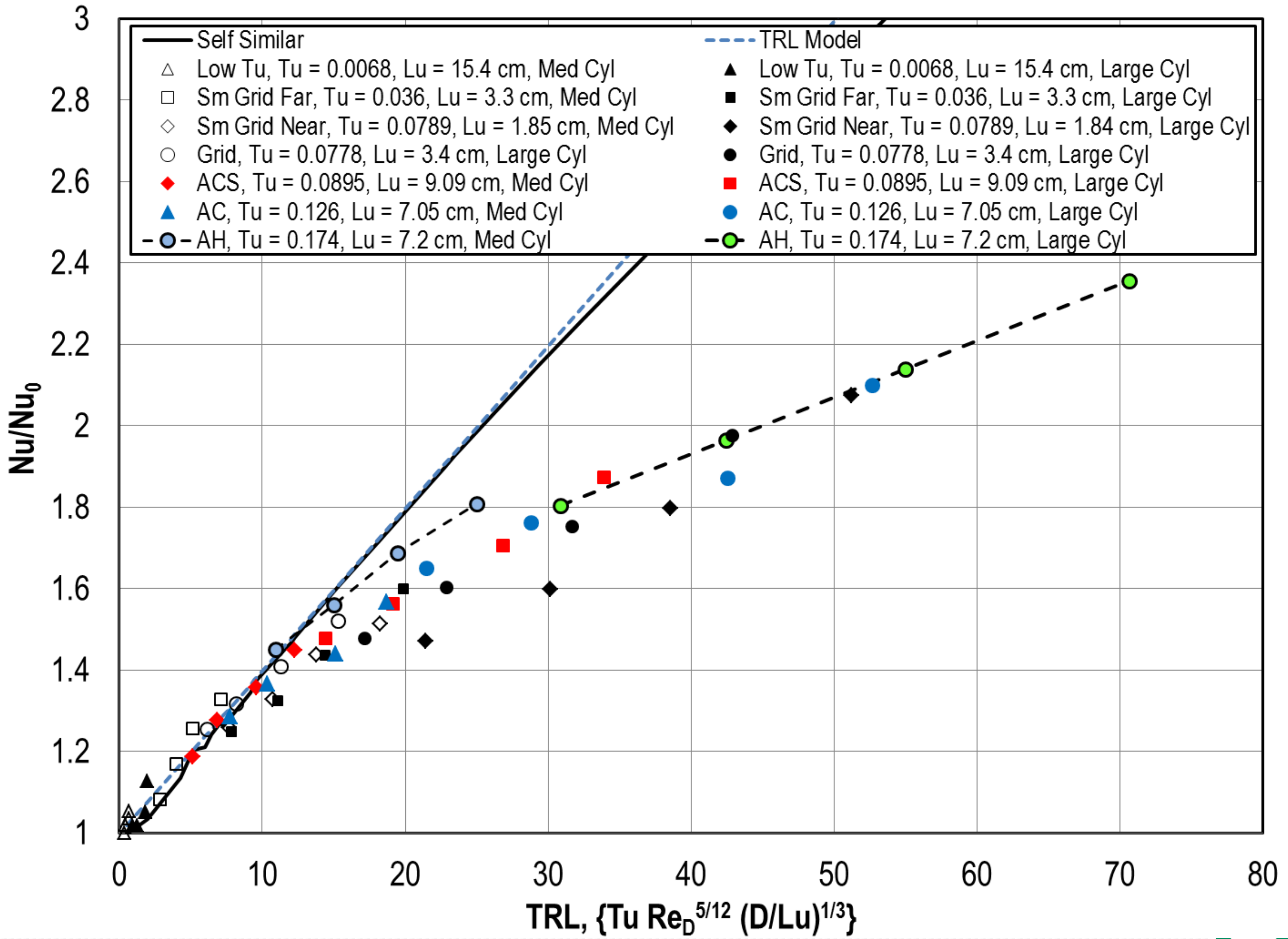




First “very high” turbulence aero-combustor had poor exit velocity dist. Added grid in short spool.

	U_{ave} (m/s)	Tu	L_x (cm)	Lu (cm)	ε (m^2/s^3)
AC	9.11	0.130	3.52	6.36	42.1
	18.11	0.126	3.58	7.35	253.4
ACS	9.17	0.092	4.61	8.81	12.06
	17.6	0.090	4.44	9.49	68.63
GR	9.94	0.079	2.04	3.35	23.4
	18.95	0.081	2.35	3.53	163.4
SG1	9.12	0.078	1.61	1.85	29.4
	17.87	0.079	1.12	1.97	216.0
SG2	9.08	0.035	1.73	3.23	1.49
	17.61	0.035	2.13	2.85	12.1
LT	9.65	0.0076	5.02	154.5	0.0004
	18.71	0.0061	3.58	15.5	0.0144
AH	9.72	0.174	3.915	7.219	101.3
	19.34	0.172	4.004	7.688	715.9

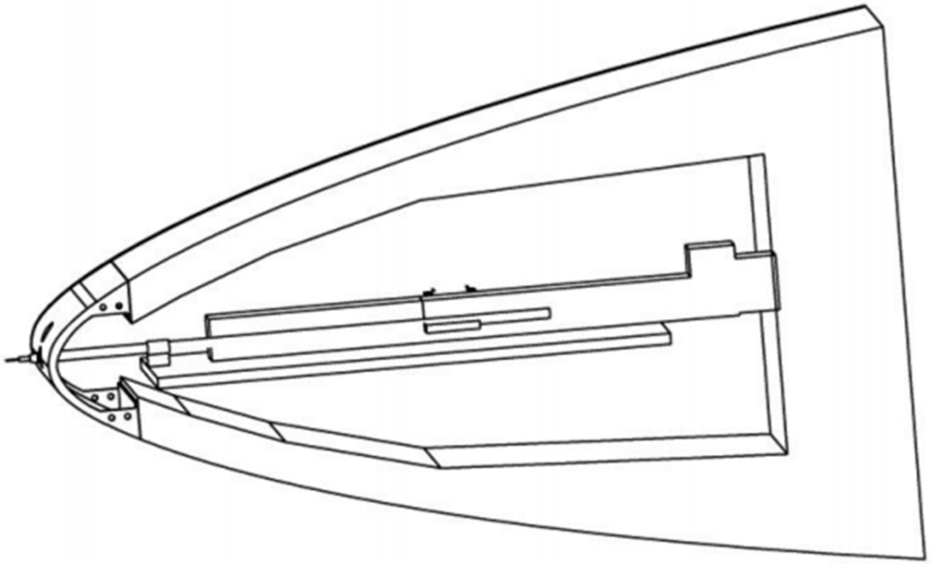
Normalized stagnation region Nusselt number versus TRL extending the parameter range with new aero-combustor (AH)



Turbulence response measurements in the vicinity of the stagnation region and boundary layer measurements

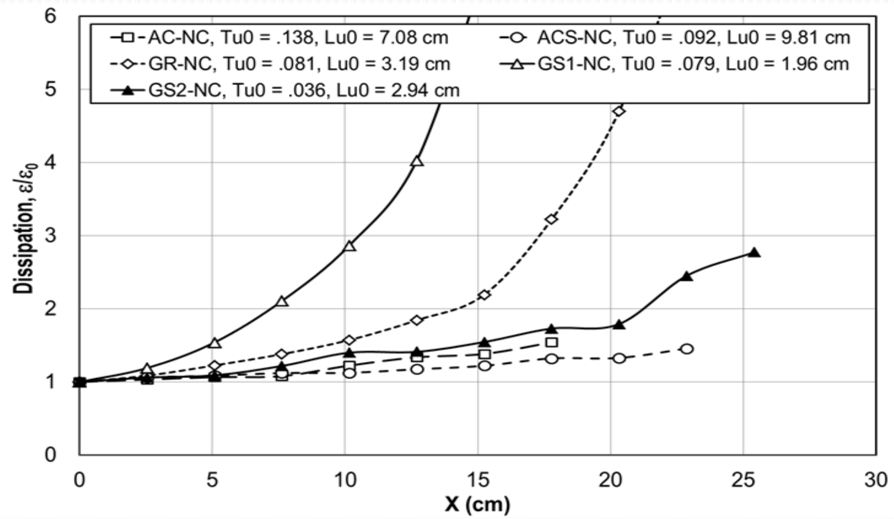
The intensification of turbulence in the vicinity of a stagnation region has previously been documented. However, turbulence seems to be unaffected along the pressure surface of a vane where the strain rate is smaller. Recent heat transfer measurements have suggested that turbulence may not be significantly intensified in the presence of large stagnation regions, which are becoming a more popular design for first vanes. Current work was focused on documenting the response of turbulence to large leading edge regions. We have also integrated a traversing system into our large cylinders to investigate boundary layers.

Turbulence decay measurements began without the cylinder in place.

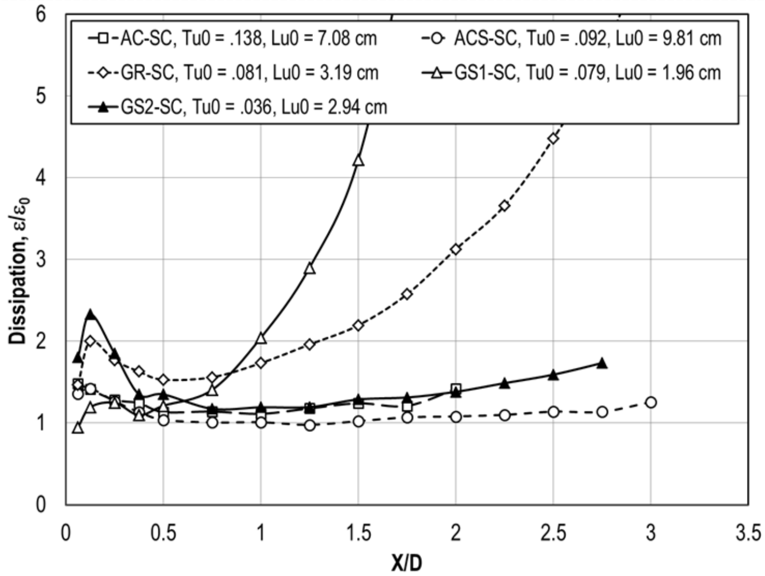


Leading edge cylinders were designed to incorporate boundary layer and approach turbulence measurements

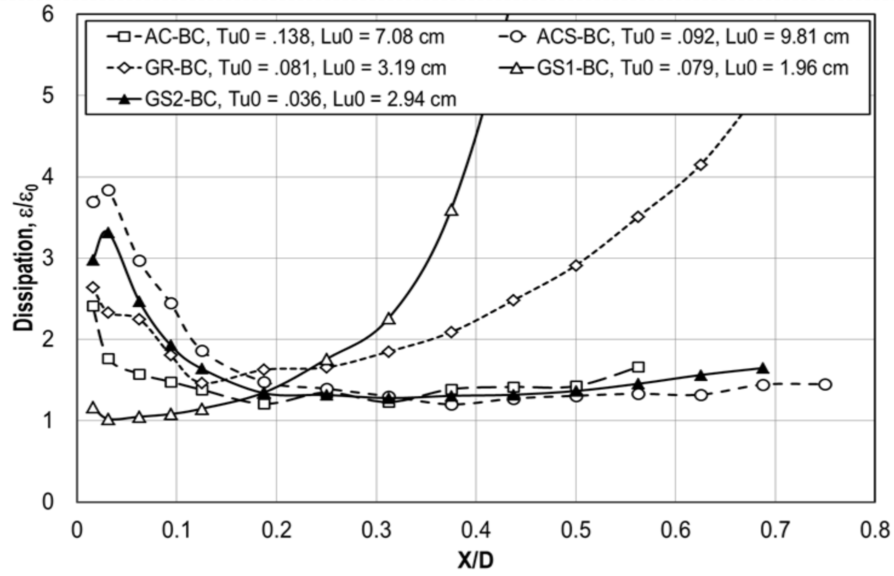
Streamwise distribution of normalized dissipation, $\varepsilon / \varepsilon_0$, in approach flow



No cylinder

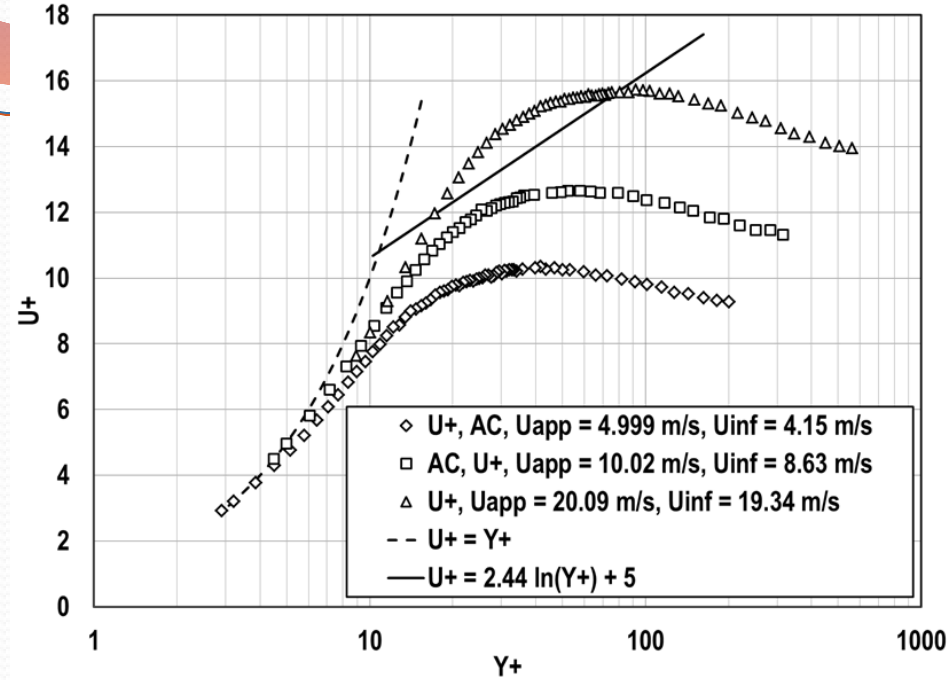


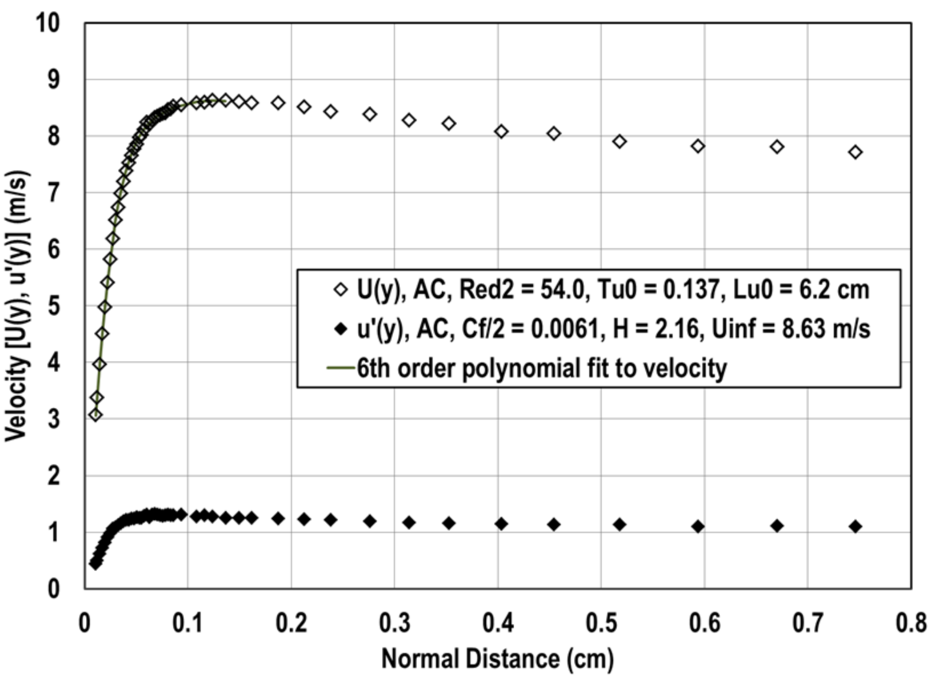
4” diameter leading edge

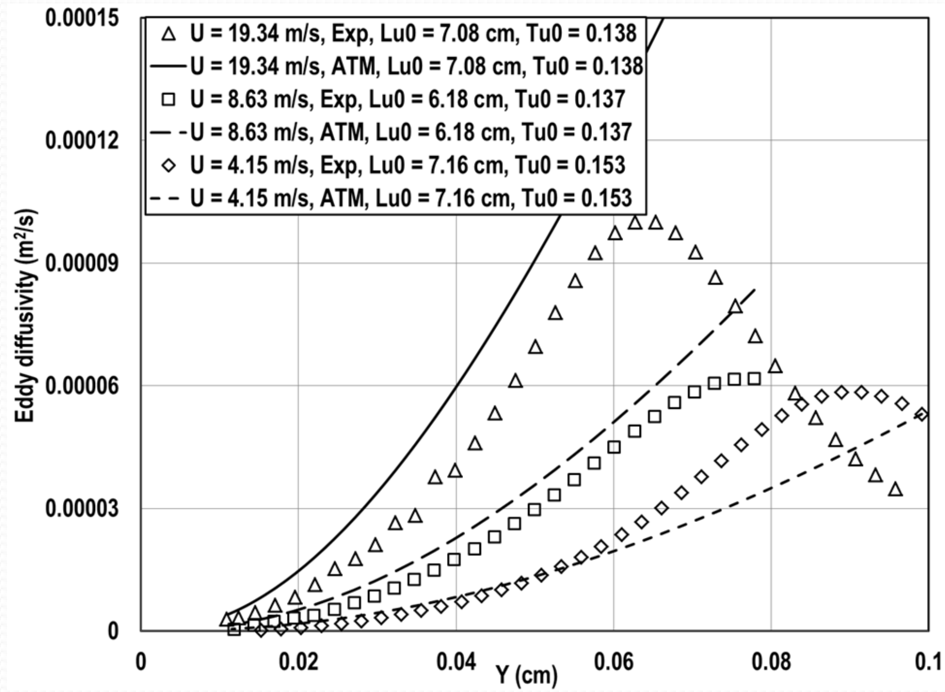


16” diameter leading edge

Boundary layers developing at 30° from the stagnation region on the large, 0.4064 m diameter leading edge test surface are quite thin.
Plotting these boundary layers in traditional u+ vs y+ coordinates provides confidence in the shear stress estimate.
Using the estimated shear stress distribution we can subtract out the viscous shear and estimate the apparent turbulent shear. We can estimate the eddy diffusivity by dividing by the local velocity gradient. To improve the accuracy of this estimate, the boundary layer is fit to a polynomial.

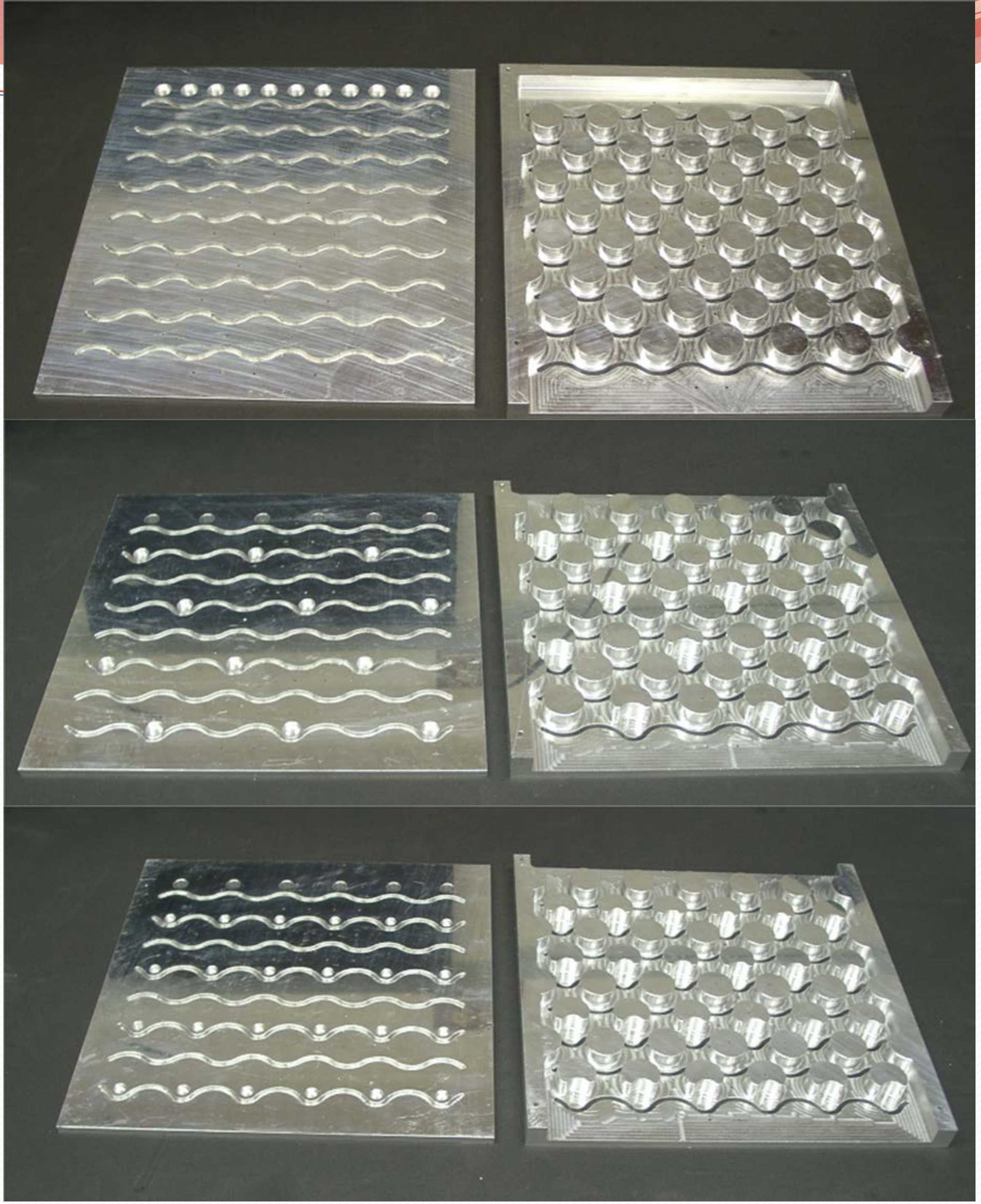






Internal Cooling Methods

The three cooling geometries included a baseline high solidity array with an inlet that used a row of impingements jets. The incremental cooling arrays introduced about 1/3 of the air from holes between the first row of pedestals and then incrementally injected air along the array behind rows 2, 4, 6, & 8. The impingement jets are integrated behind the pedestals in a cavity

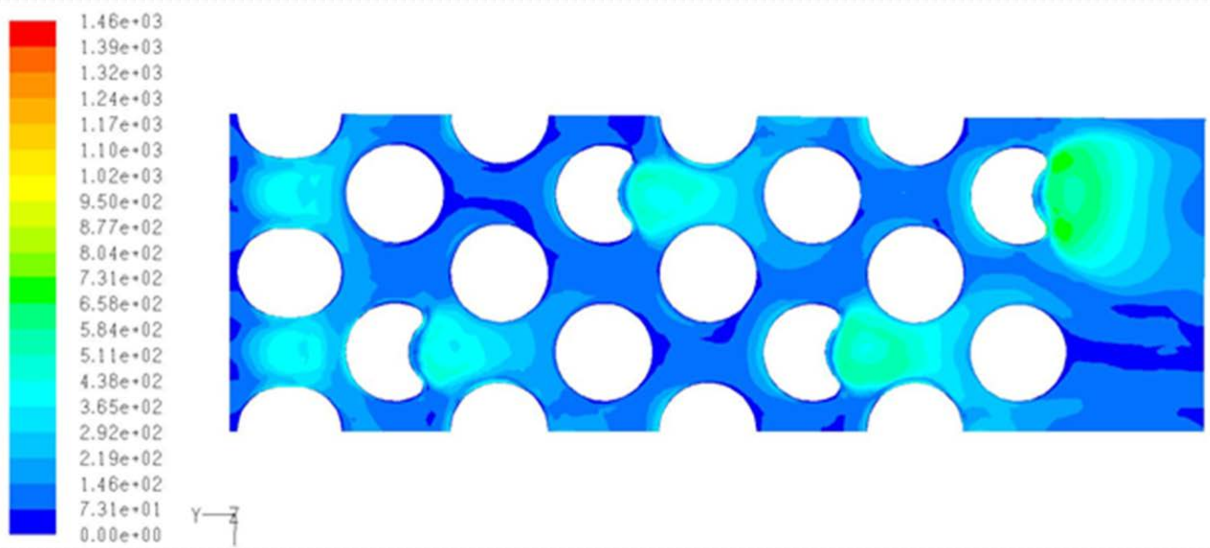


ternal Cooling Methods

Impingement hole is placed in cutout region behind pedestals.

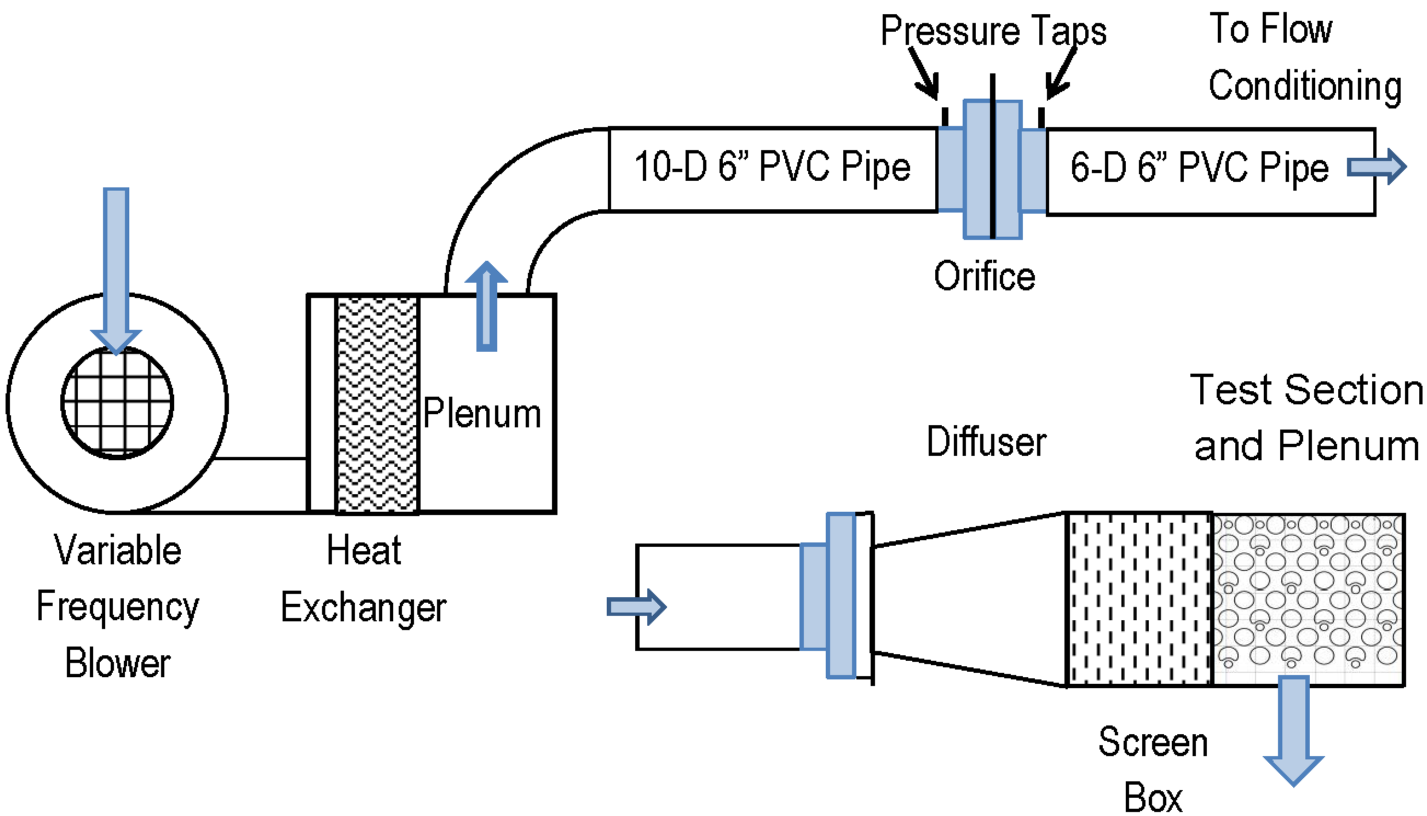
Cutout region protects the jets from deflection and allows the impingement flow to reach hot side surface improving heat transfer.

CFD modeling of incremental impingement inside of arrays indicated that the integration of impingement holes behind large pedestals produced a very effective impingement jet. As pressure drop increased along the array impingement strength increased significantly.



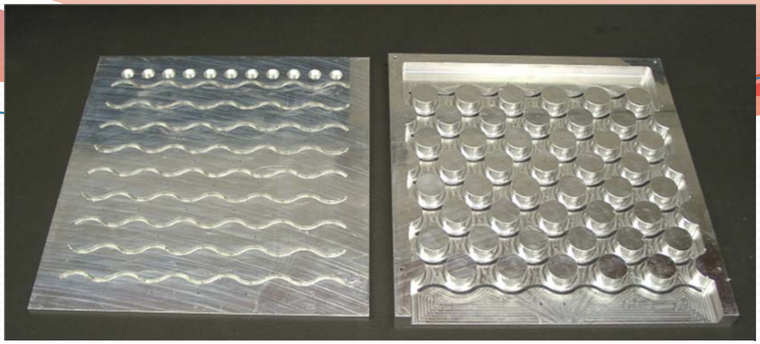
Internal Cooling Methods

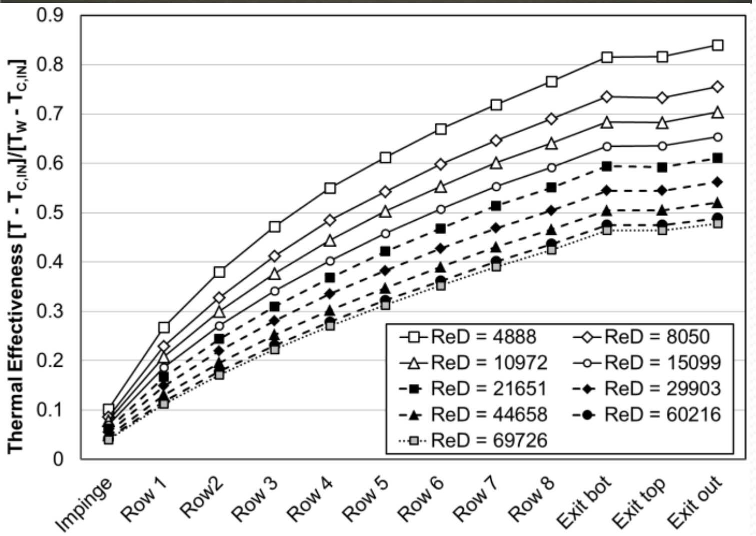
This schematic shows the internal cooling, flow and heat transfer rig used for testing the conventional high solidity pin fin array and the two candidate incremental replenishment cooling geometries. This internal cooling rig includes a high pressure blower with variable frequency drive, a plenum with heat exchanger, an orifice tube, a downstream diffuser section and a flow conditioning section flow or screen box.

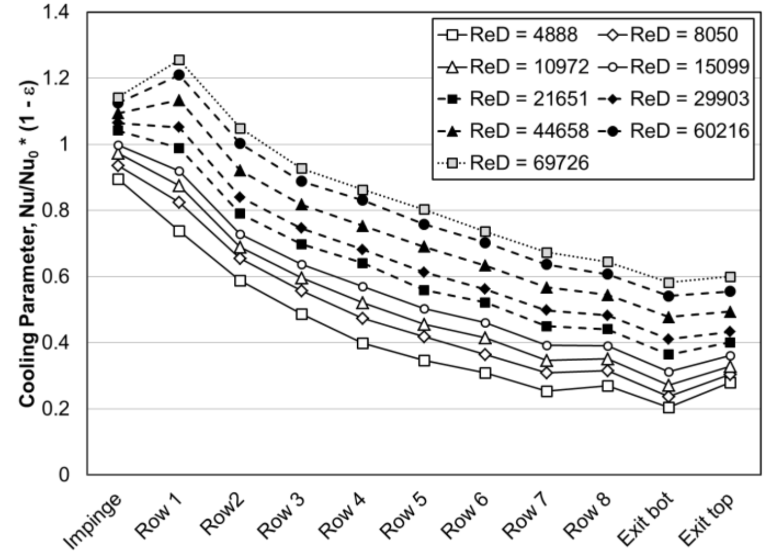


Internal Cooling Methods

- In conventional high solidity arrays, cooling air temperatures rise rapidly resulting in a reduced ability to cool component surfaces adequately.
- In the configuration above air is injected into a cooling channel through a row of impingement holes.
- The thermal effectiveness increases quickly row by row, with a result particularly difficult at lower Reynolds number.
- The resulting potential to cool can be estimated based on a cooling parameter $(1-\varepsilon)\ Nu/Nu_0$
- This cooling parameter quickly drops to unusable values.

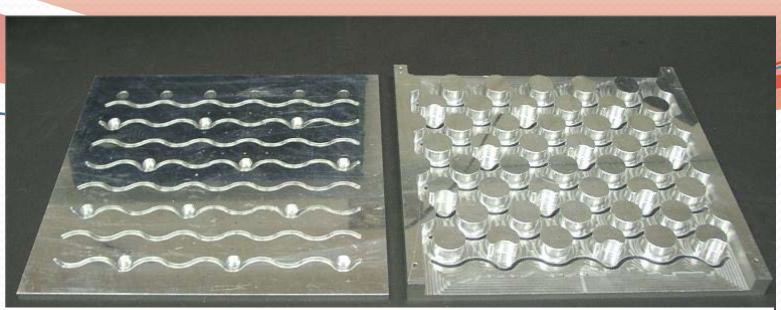


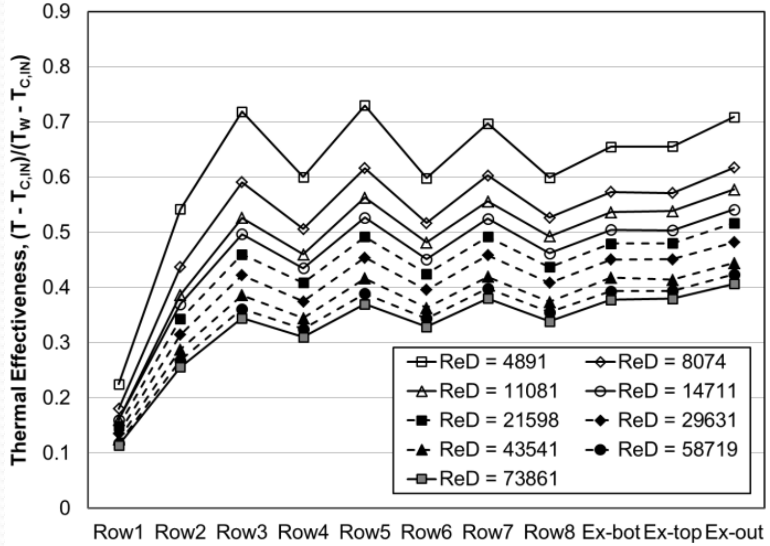


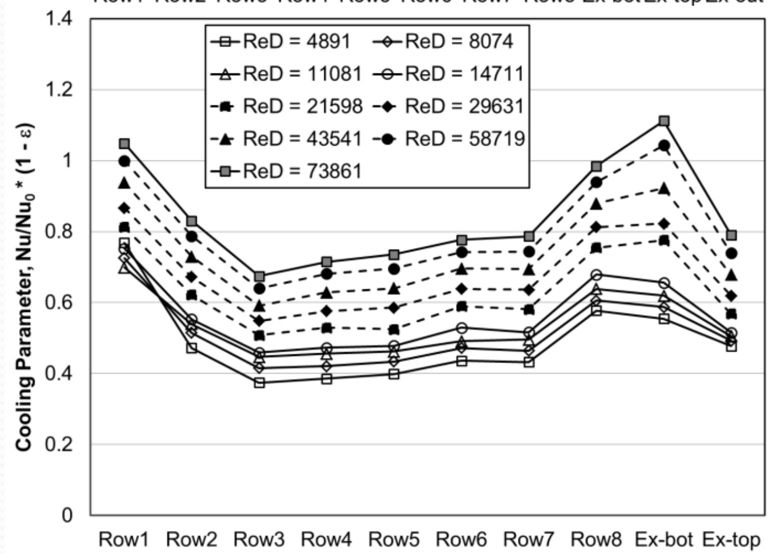


Incremental impingement

- Incremental impingement overcomes the streamwise increase in air temperature by adding air using impingement holes.
- In typical impingement arrays cross-flow deflects jets and insulates the surface.
- Incremental impingement overcomes crossflow by hiding jets in recesses behind pedestals.
- Based on leading edge heat load balances this approach should be very effective in the stagnation region.
- Holes can be sized to adjust cooling as needed along the array.

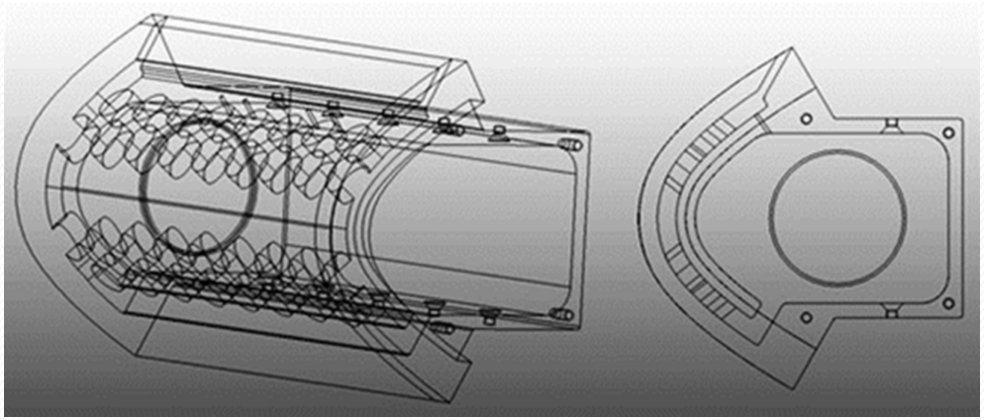


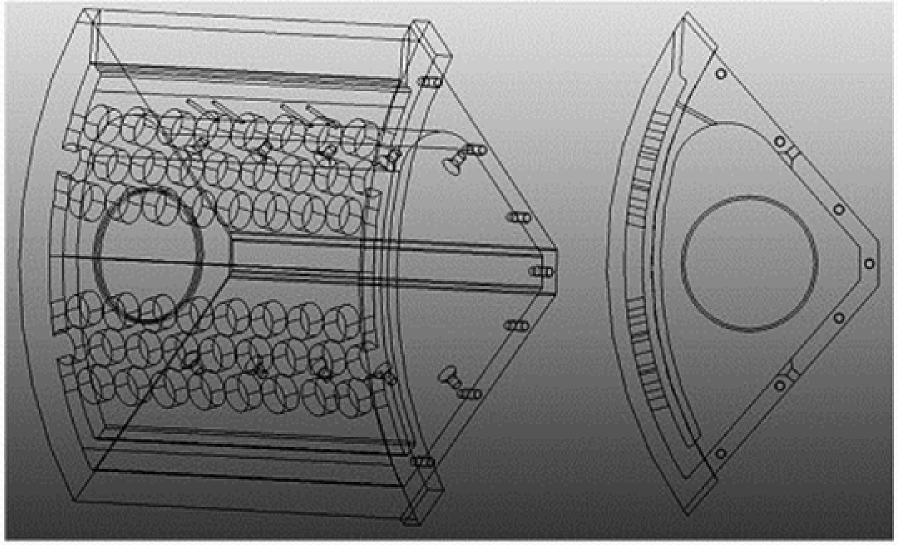


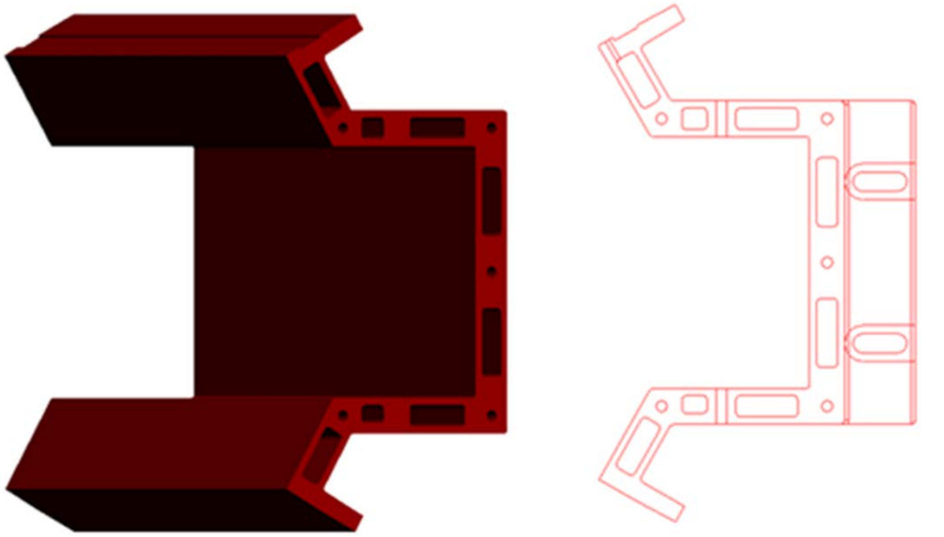


Schematic of slot film cooling inserts for larger (0.4064 m) and smaller cylindrical leading edge test section with bracket for smaller insert.

Slot film cooling measurements were acquired on both the larger and smaller cylindrical leading edge test surfaces. These 30° slots each had realistic internal geometries with high solidity pins. Measurements were made of the slot exit temperature, the static pressure on the bracket, as well as the local surface temperature. The bracket also integrated the heat transfer foil bus bar and G10 surface.

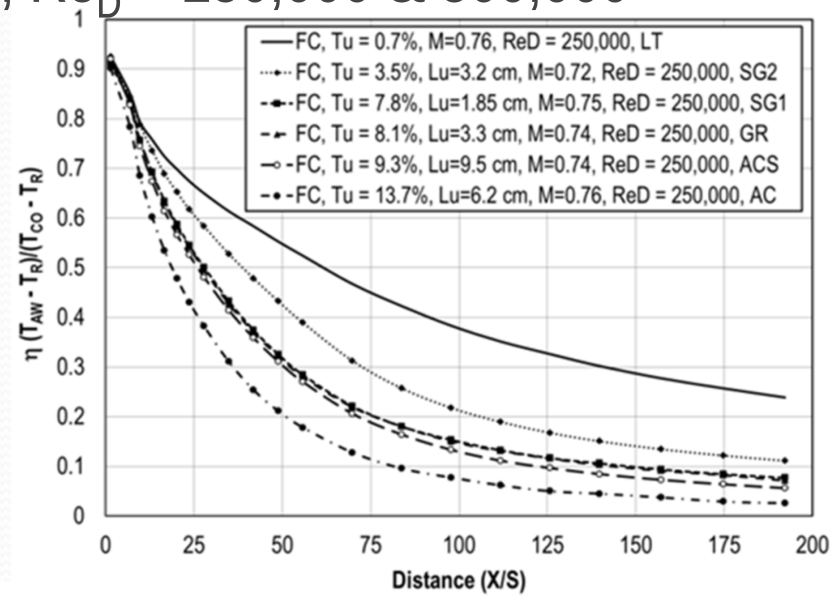


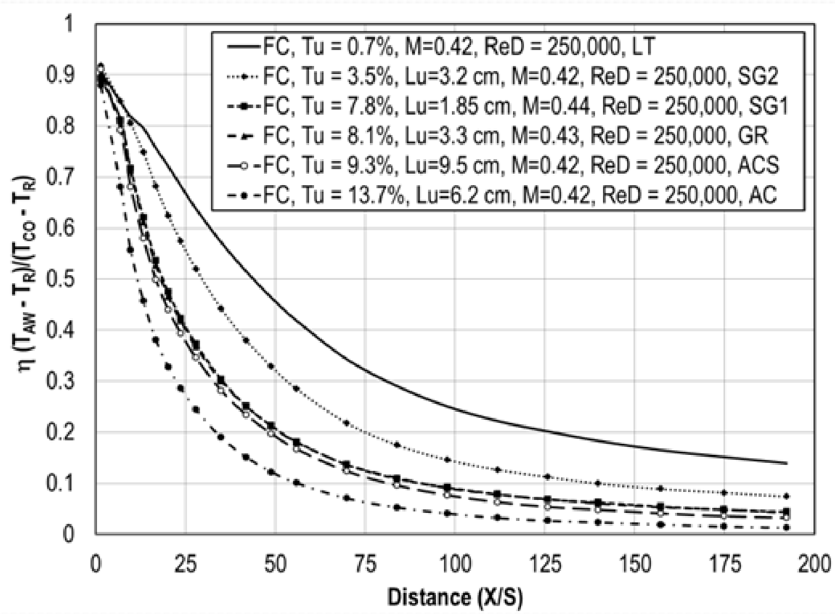


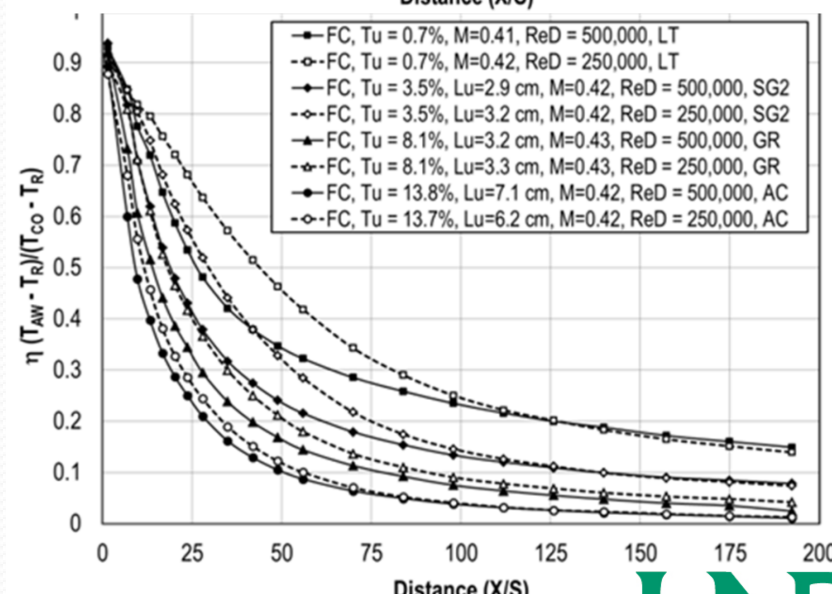


Adiabatic film cooling effectiveness, M = 0.42, M = 0.74 variable turbulence condition, larger cylinder, Re_D = 250,000 & 500,000

A comparison at the same blowing ratio with varying turbulence shows its dramatic influence.
Figures show comparisons at M = 0.42 & M = 0.75
Increasing the blowing ratio from 0.42 to 0.75 raised effectiveness levels in all cases.
A comparison of film cooling at higher and lower Reynolds number suggests that the state of the boundary layer has a significant influence on film effectiveness which reduces with turbulence.

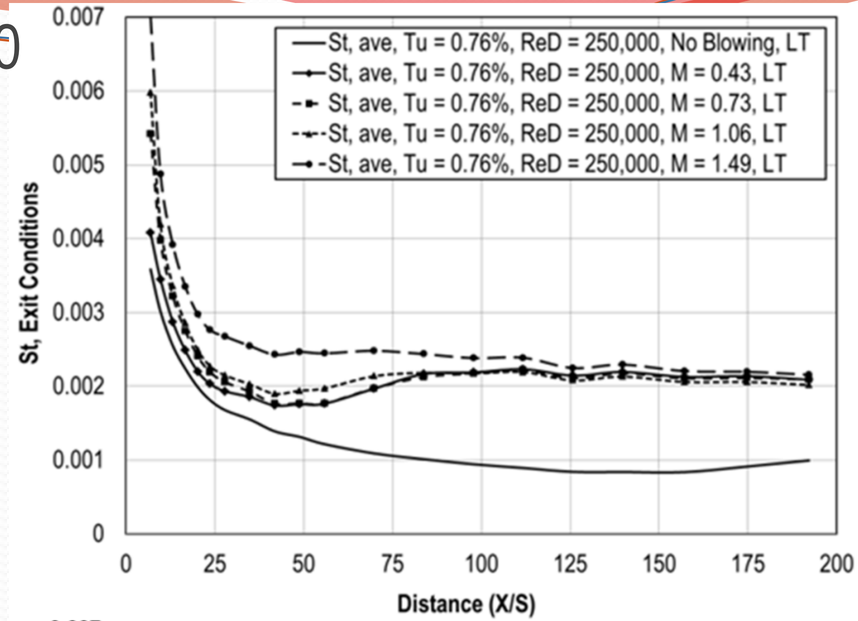


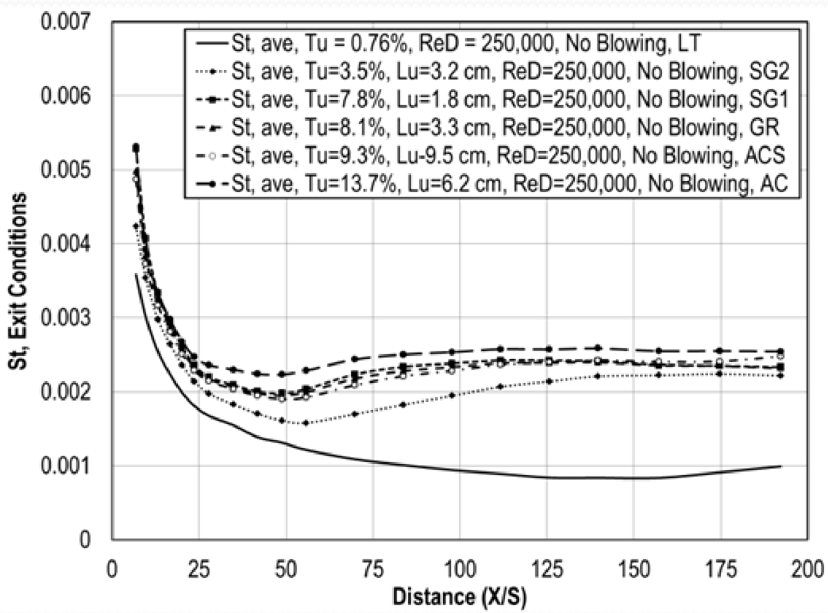


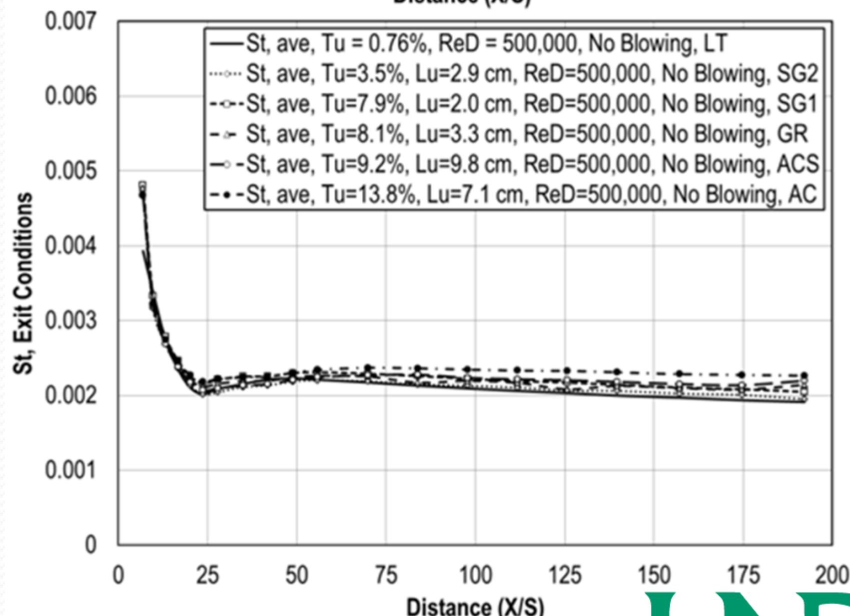


Stanton number distributions, M = 0.0, variable turbulence, low turbulence, variable blowing, Re_D = 500,000, M = 0.0

At the lower Reynolds number and no blowing, all turbulence conditions are transitional except the low turbulence case which is laminar.
As blowing increases the flow becomes transitional and transition moves upstream.
Increased blowing also increases the initial St.
At the high Reynolds number boundary layers transition shortly downstream from the coolant discharge location.

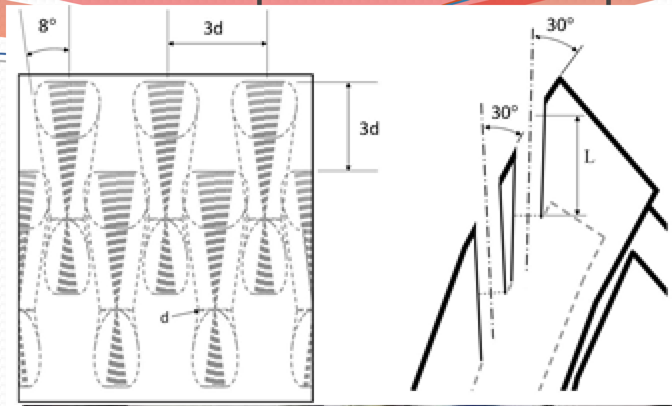


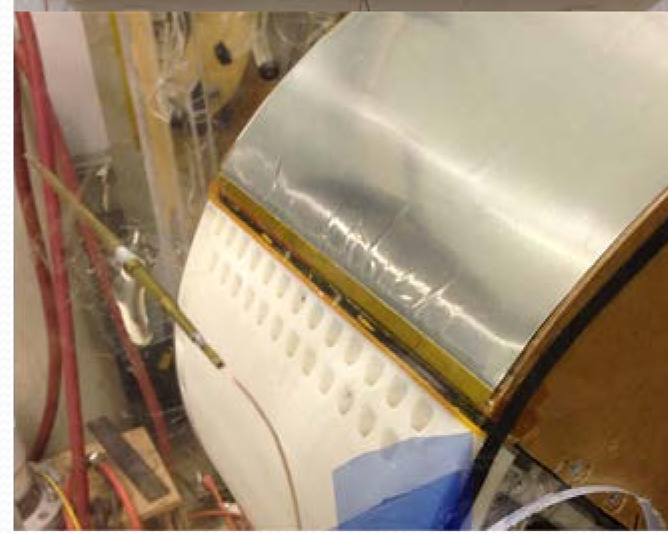


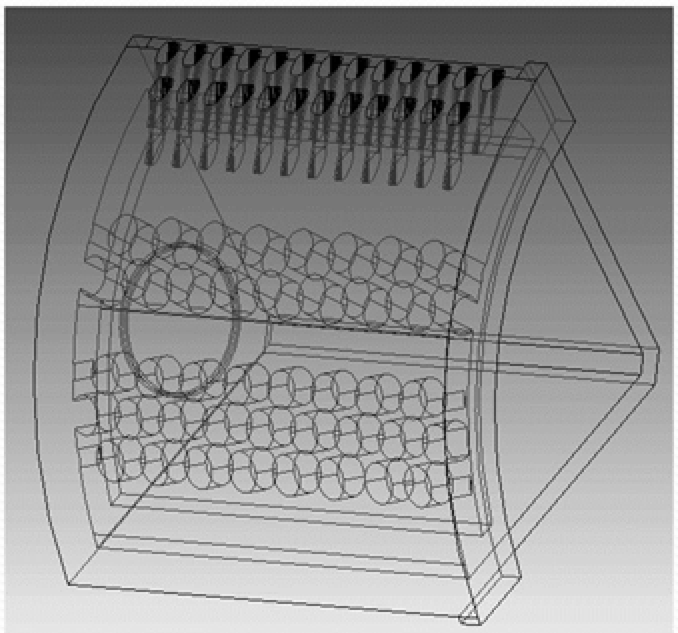


Shaped hole film cooling measurements involved the development of a shaped hole film cooling insert for the large leading edge.

A wire frame of the shaped hole insert shows a relevant internal geometry similar to the large slot insert.
The full coverage shaped holes have a 30° injection angle with the surface and an 8° lateral diffusion.
The hole spacing is 3d in both the pitchwise and streamwise directions producing a full coverage geometry.
The area ratio at the point the hole centerline intersects the surface is about 2.1 to 1.







Preparations for shaped hole film cooling measurements involved adding a heat exchanger, adding a mixer, and adding a flow straightener to the apparatus.

During the acquisition of shaped hole film cooling at high Reynolds number control problems and a temperature stratification were experienced in the wind tunnel flow facility.

A heat exchanger was added to the exit of the film cooling blower prior to the A/C unit.

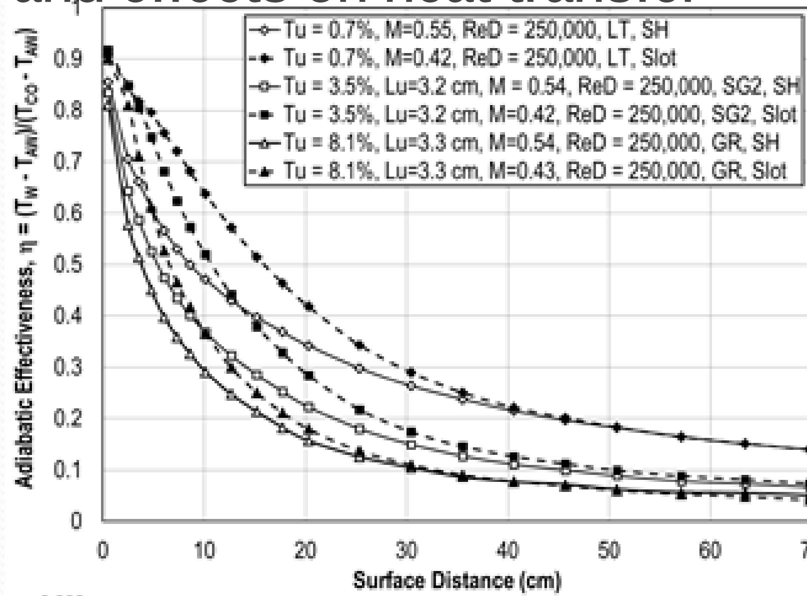
A flow mixer and flow straightener were added to the tunnel downstream from the heat exchanger.

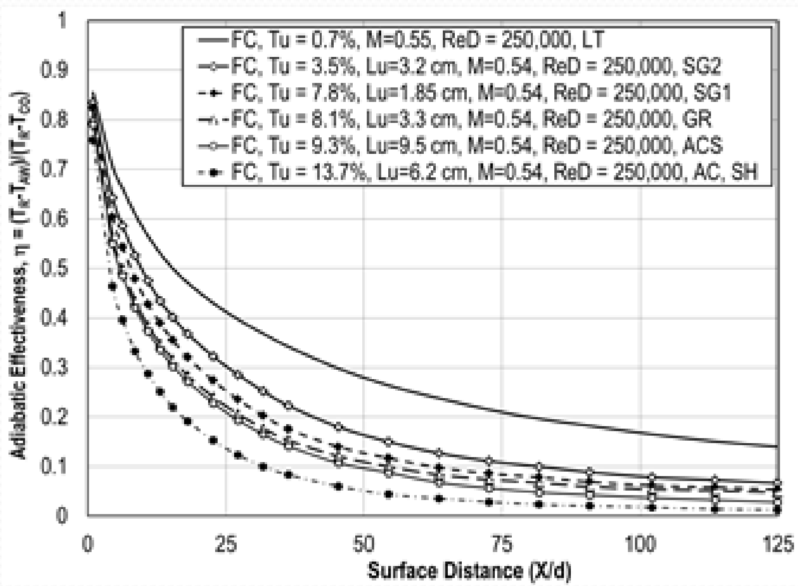
Adiabatic film cooling effectiveness, M = 0.54 variable turbulence condition, shaped holes versus slot, and effects on heat transfer

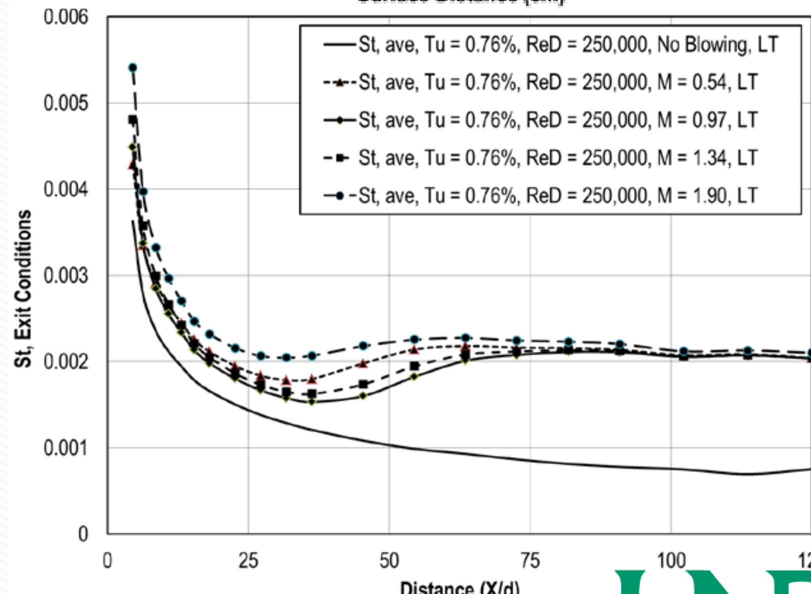
A comparison at the same blowing ratio, varying turbulence, shows a large effect on shaped holes.

A comparison between shaped holes and the slot at the same coolant mass flow rate indicates significant differences upstream but similar levels downstream.

A look at the influence of blowing on downstream heat transfer shows that increased blowing moves the location of transition upstream. Also, shaped holes are no worse than slots on heat transfer.

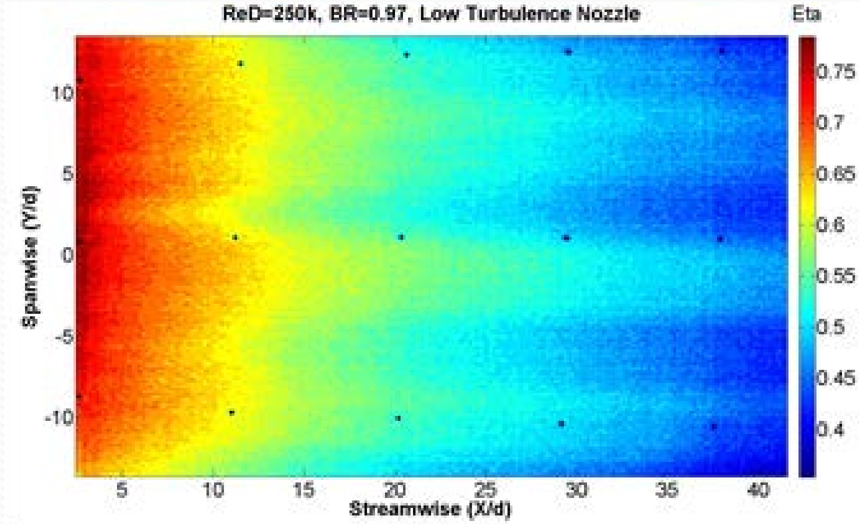


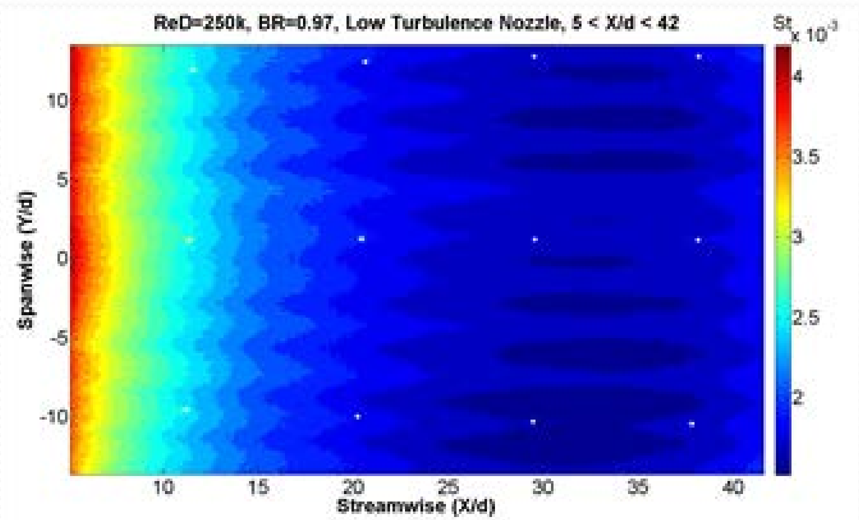


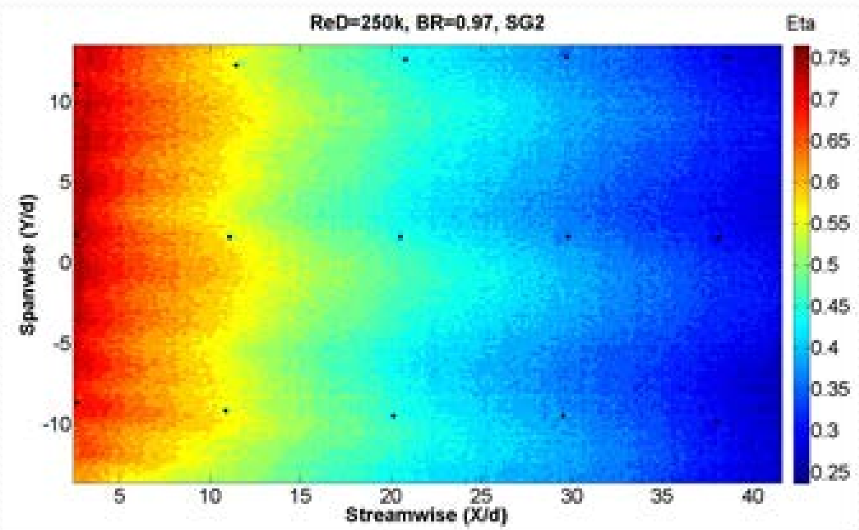


Adiabatic film cooling effectiveness effects on heat transfer, low turbulence, M = 0.97, plus comparison of LT and SG2 turbulence

A full surface visualization of surface Stanton No. shows the influence of the discrete SH injection.
A full surface visualization of film cooling from the shaped holes shows a degree of jet grouping at low turbulence.
At the small grid far turbulence level (SG2, Tu = 3.5%) has the influence of providing enhanced spanwise mixing and more rapid film cooling decay compared with the low turbulence condition.

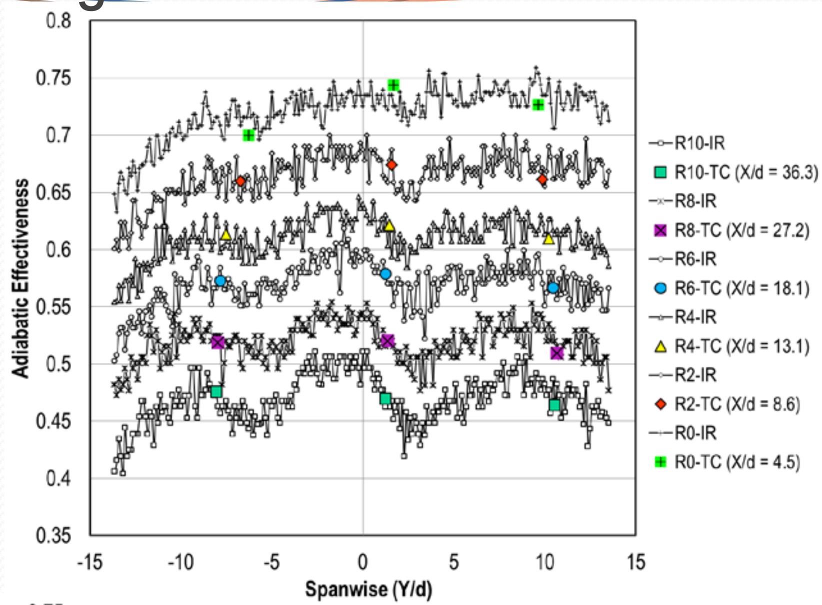


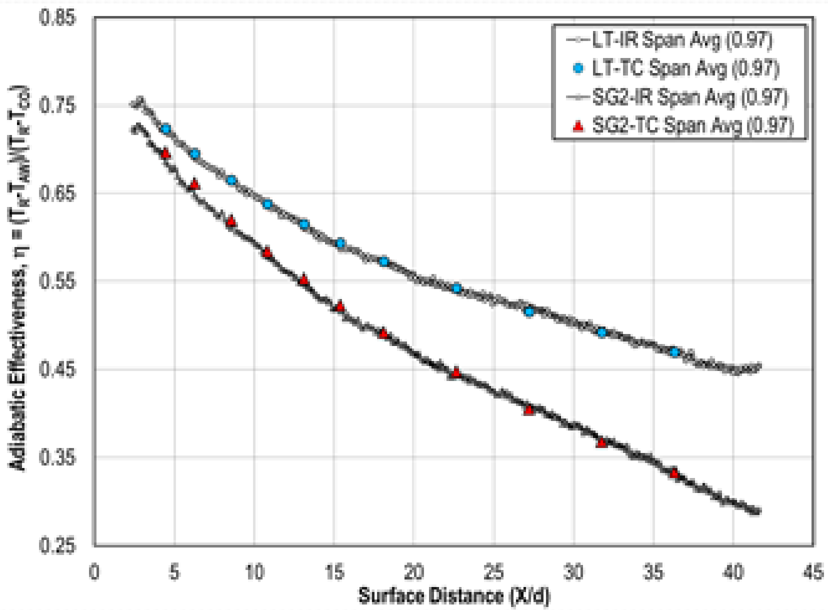


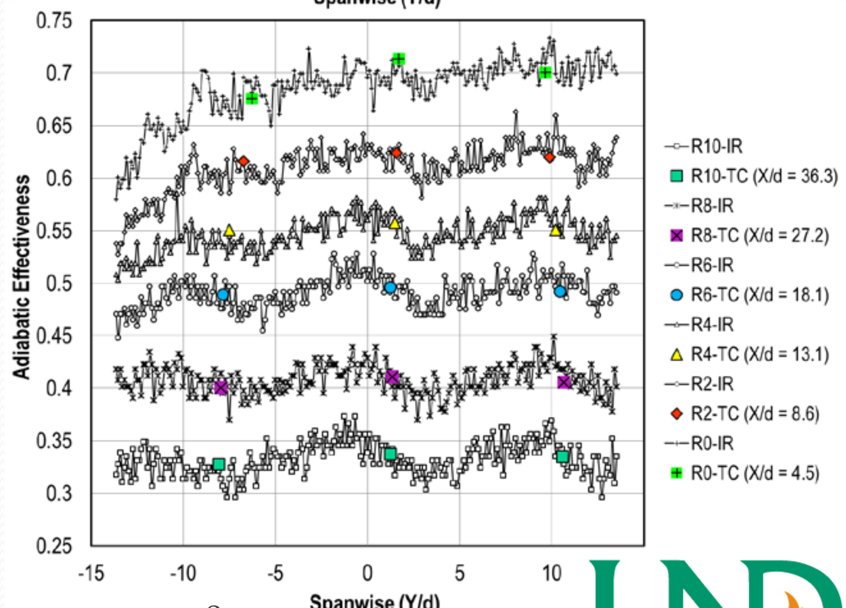


Full surface visualizations allow a comparison with TC data to assess the spanwise variation , M = 0.97, comparing LT and SG2 turbulence

A comparison between span averaged full surface visualization and thermocouple data is very close. The full surface visualization allows an assessment of spanwise variability of the measurements which can be used to assess the uncertainty of the thermocouple measurements. Spanwise variability significantly decreases with even a moderate level of turbulence such as the small grid far in comparison with the LT condition.







Summary and Conclusion for Tasks at UND

- The parameter range for stagnation region heat transfer has been extended over 7 turbulence conditions & 4 Re_D, for 2 surfaces
- The response of a range of turbulence conditions approaching large leading edges was documented showing significant amplification.
- Measurements of boundary layers has also been made on the large leading edge region subjected to a range of turbulence conditions.
- An internal cooling method for vane leading edge regions has been developed to eliminate showerhead cooling and improve film cooling.
- Full coverage slot and shaped hole film cooling measurements have been made in the accelerating regions downstream from stagnation regions across a wide range of turbulence conditions and two Reynolds numbers. The data demonstrate the large influence of turbulence on film cooling dissipation and the potential benefit of slot and full coverage film cooling in the accelerating region of a vane.