THERMALLY EFFECTIVE AND EFFICIENT COOLING TECHNOLOGIES FOR ADVANCED GAS TURBINES

UTSR Workshop Georgia Tech University

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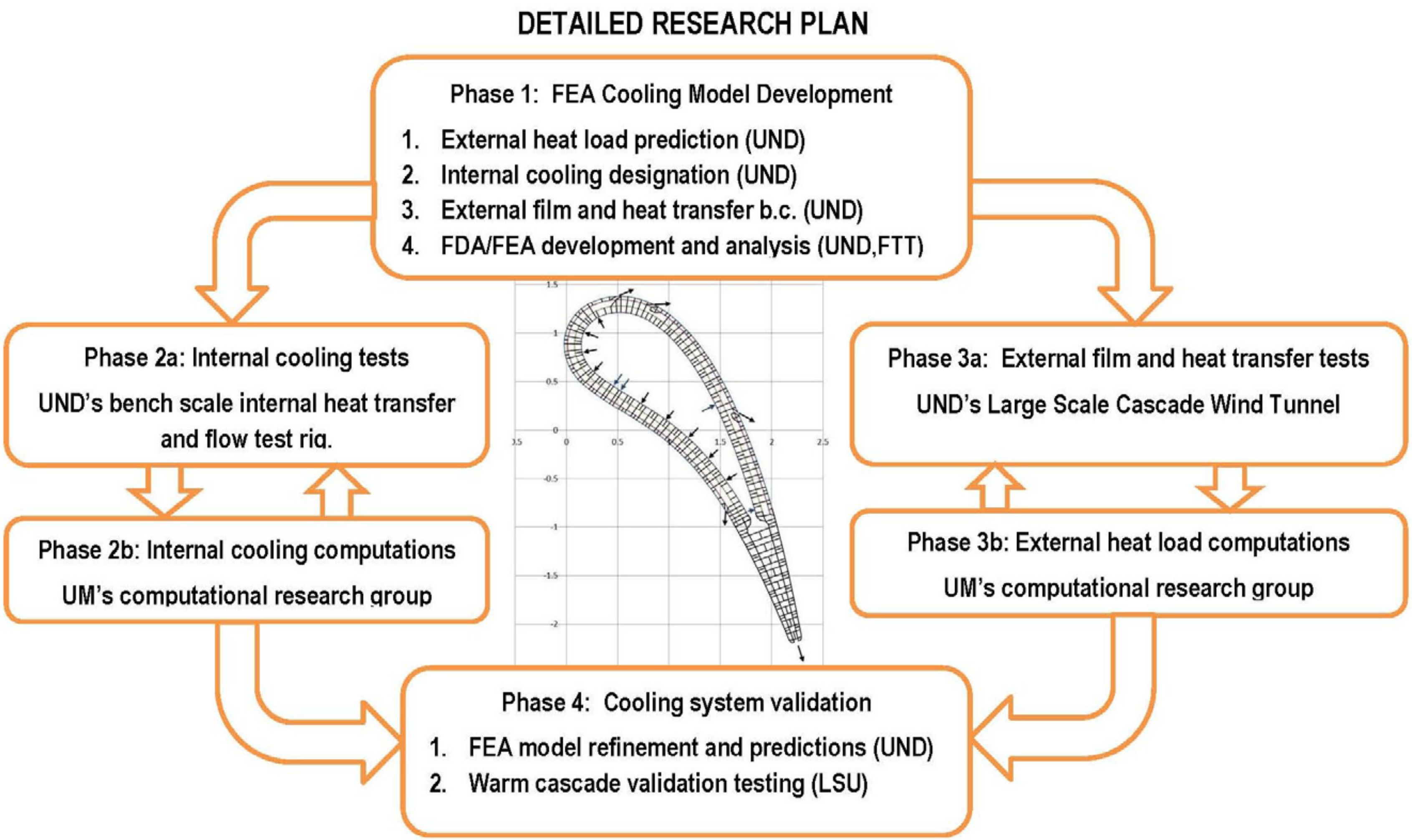
PRESENTATION OVERVIEW

- Motivation for this work and conceptual approach
- Brief overview of four phase program
- FEA analysis is being used to drive the development of internal and external boundary conditions:
- The FEA vane cooling model serves as a framework for integrating cooling technologies, both internal and external, for the leading edge, pressure & suction surfaces and the trailing edge.
- Bench scale rig is being used for internal cooling testing
  - UND is currently testing a variable hole size version of incremental impingement
  - UND is getting ready to test a converging trailing edge section with variable flow.
- A low speed cascade has been developed for the investigation of film cooling and heat transfer for the external heat load evaluation.
- Computational methods at UM will clarify physics of film cooling and internal cooling and serve to refine model boundary conditions.
- Warm cascade testing will be used for cooling system evaluation and validation based on the enhanced FEA vane model.

MOTIVATION AND CONCEPTUAL APPROACH

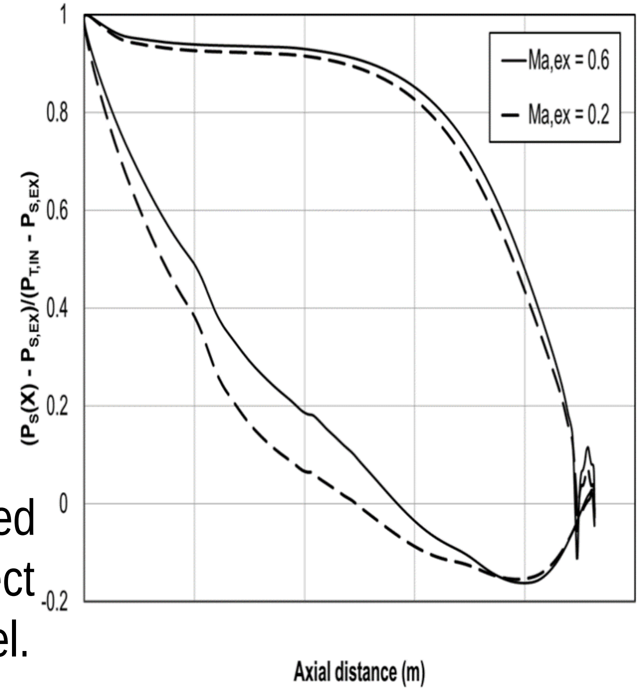
- Component cooling methods need to provide highly effective, reliable, and efficient cooling systems.
- Ideally, internal cooling methods need to achieve good levels of internal effectiveness before discharging cooling air onto surfaces in optimum films.
- While showerhead film cooling can be very effective, it can also very disruptive to the laminar boundary layers developing in the stagnation region and vicinity. Moreover, it is susceptible to clogging.
- Leading edge regions can be cooled internally to a high level of effectiveness eliminating the disruption of shower-head films and improving downstream film cooling levels.
- The efficiency and effectiveness of downstream cooling levels can be improved by using more optimal internal cooling concepts and external films.
- Covered trailing edge designs offer the best thermal protection while there is no conclusive evidence of higher aerodynamic losses.
- The local level of cooling effectiveness and the efficiency of cooling methods can be improved through the use of more flexible internal geometries. These geometries can be more optimally applied through experimentation combined with the use of advanced computational approaches.

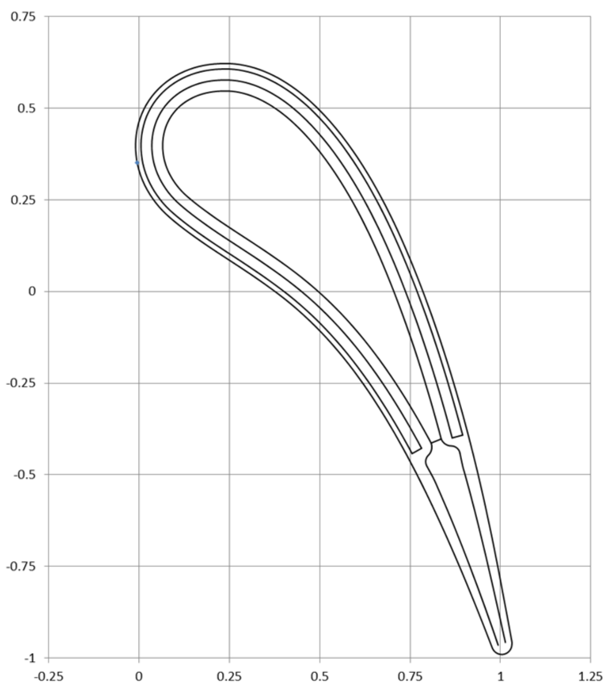
FOUR PHASE PROGRAM

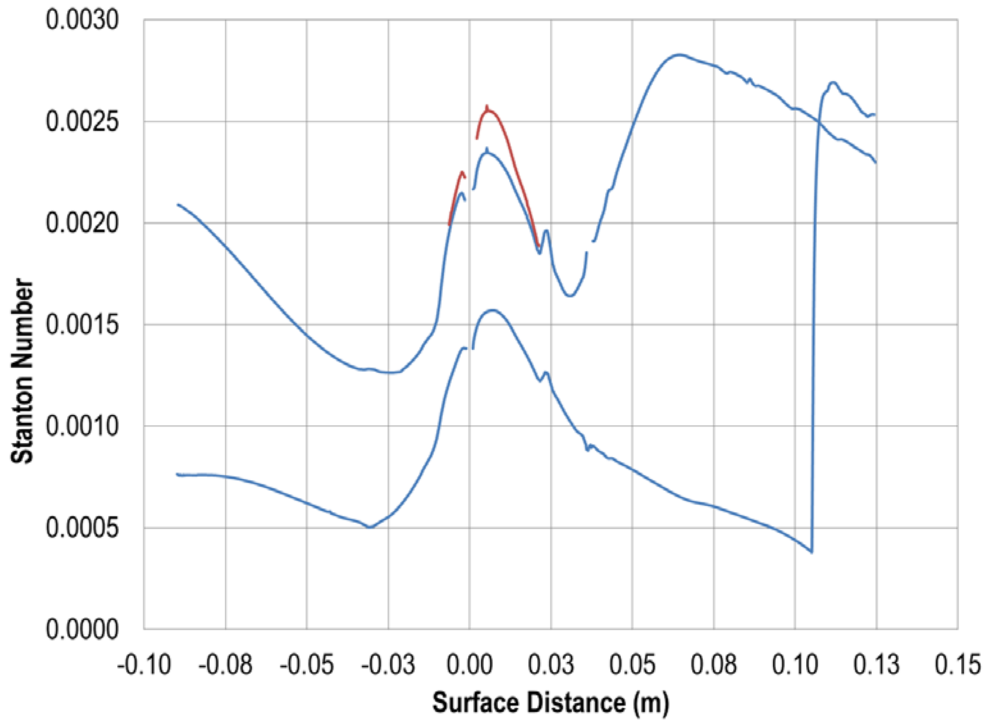


CHOSEN VANE DESIGN

- The chosen vane design included a generous leading edge both for reduced heat transfer and for more room for a double-wall internal cooling design.
- The vane pressure distribution was chosen to be aft loaded to slow transition, improve film cooling effectiveness and reduce aerodynamic losses.
- The surface heat load prediction was initially conducted using the ATM model of Ames which accounts for effect of free-stream turbulence and Mayle's transition model.





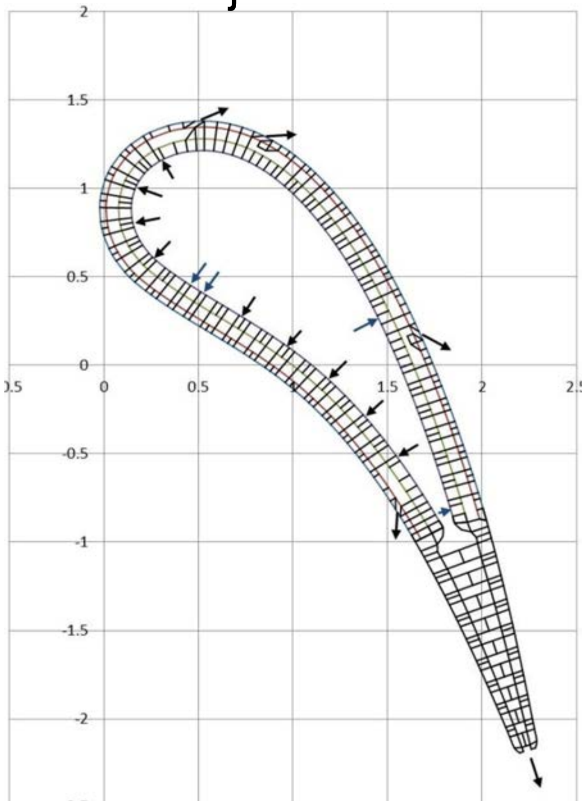


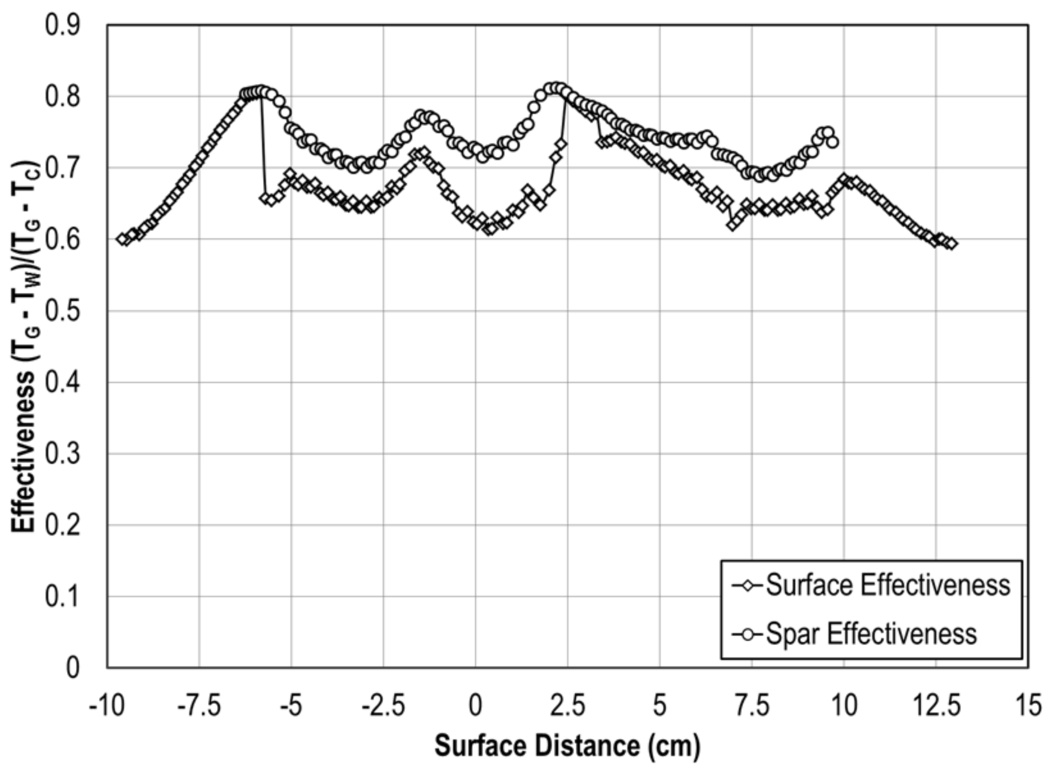
FINITE DIFFERENCE ANALYSIS

A finite difference analysis was used to initiate the analysis of the vane cooling model providing initial results and allowing the tuning of the coolant flows to meet cooling objectives.

The overall objective was to develop a design achieving a minimum effectiveness level, ϕ = 0.61. The resulting w+ = 2.203.

This objective was met except for the end of the trailing edge.





Initial Boundary Conditions for Finite Difference and Finite Element Analysis

Double Wall Cooling:

Internal heat transfer and pressure drop boundary conditions were supplied using existing data acquired for basic configurations. These configurations include incremental impingement and high solidity pin fin arrays.

Trailing Edge:

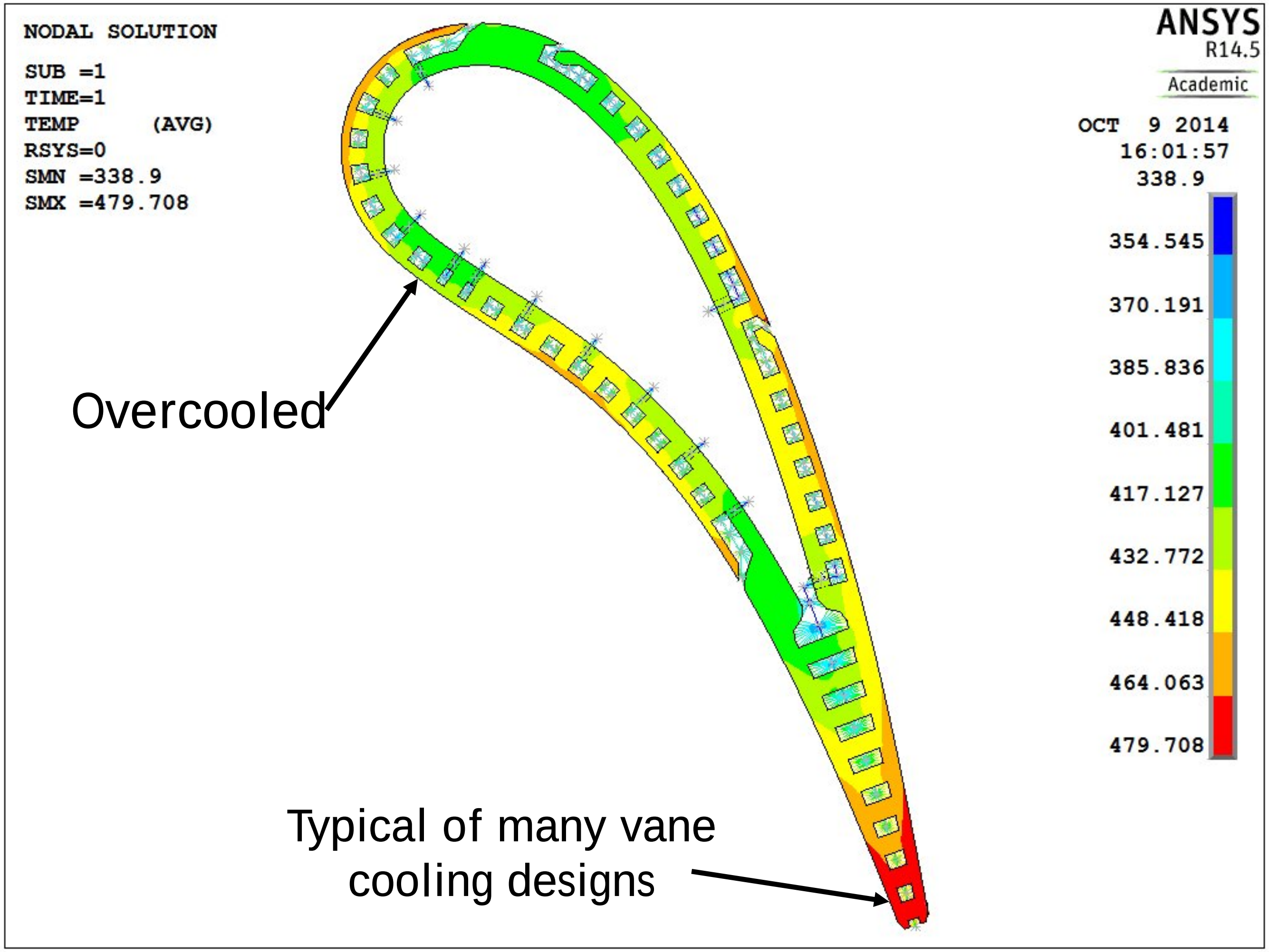
Internal heat transfer and pressure drop boundary conditions were supplied using existing data acquired for converging diamond shaped pedestal arrays.

Film Cooling:

Film cooling boundary conditions were provided from a slot film cooling database taken at the University of North Dakota. These boundary conditions are very sensitive to the inflow turbulence boundary condition and to a lessor extent the Reynolds number.

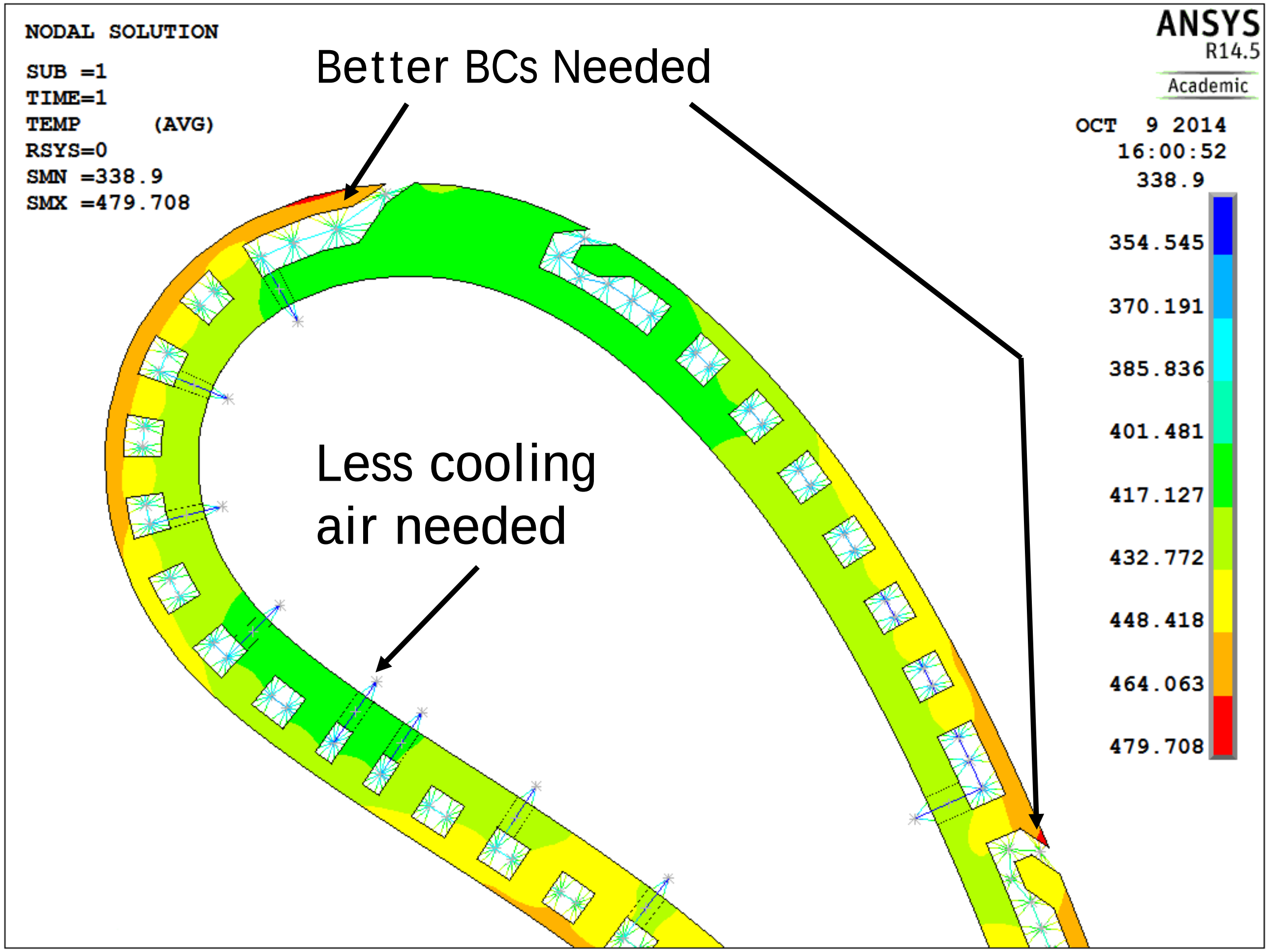
FINITE ELEMENT ANALYSIS: ANSYS

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.



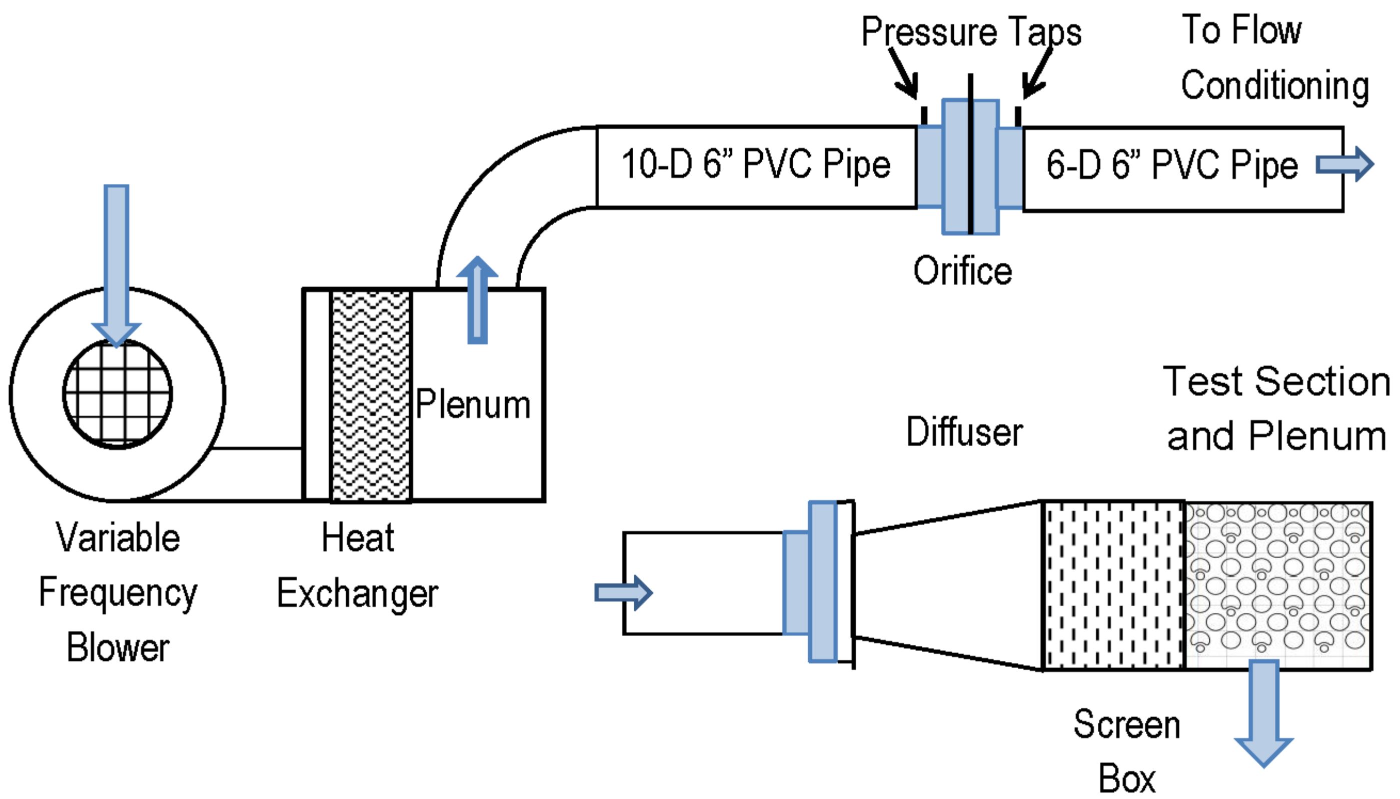
FINITE ELEMENT ANALYSIS ANSYS

The finite difference and finite element analyses also pointed to areas where better boundary conditions are needed.
This better information will be developed through a combination of bench scale testing with accurate inlet/exits and CFD.



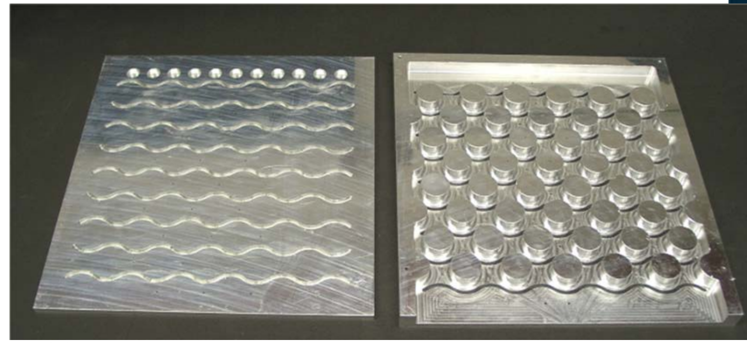
INTERNAL COOLING INVESTIGATION

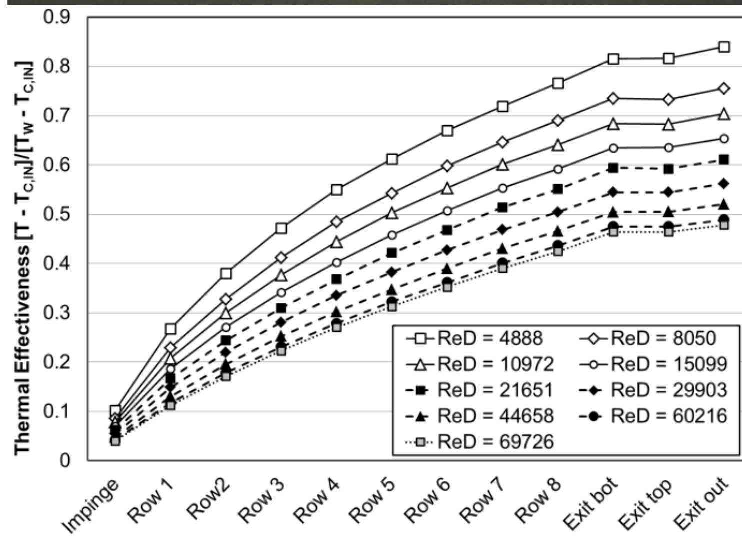
This bench scale internal cooling, flow and heat transfer rig, is being used for investigating configurations of incremental impingement, counter cooling, sequential impingement, and converging high solidity arrays. The internal cooling rig includes a high pressure blower with variable frequency drive,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

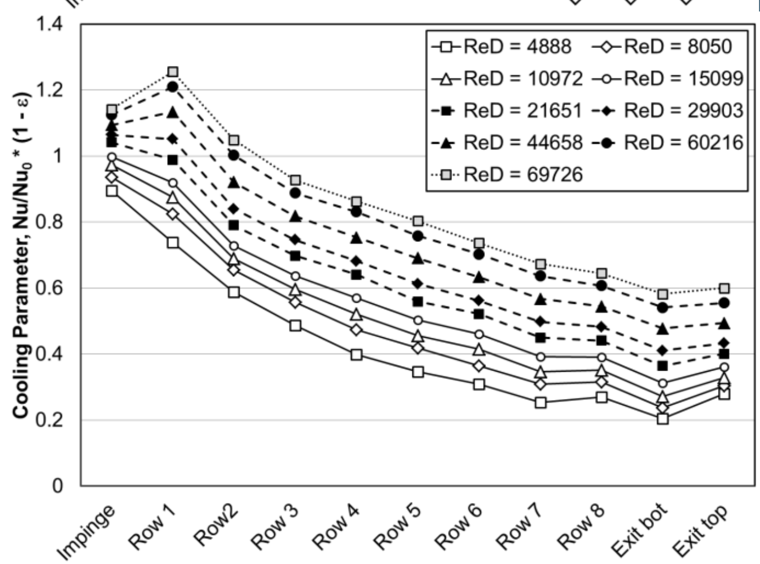


INTERNAL COOLING METHODS FOR LE

- In conventional high solidity arrays pictured at the right, cooling air temperatures rise rapidly resulting in a reduced ability to cool component surfaces adequately.
- In the configuration above air is initially injected into the 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-ε) Nu/Nu_0
- This cooling parameter quickly drops to unusable values for the stagnation region.

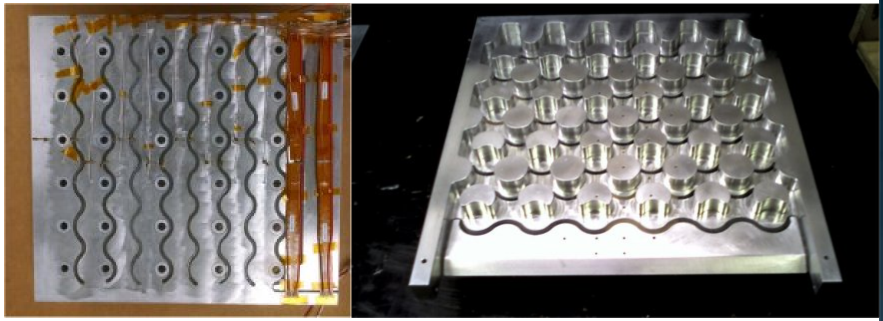


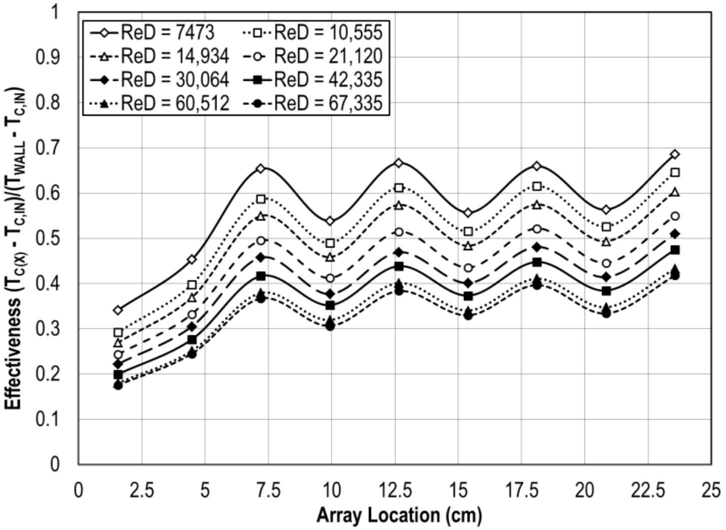


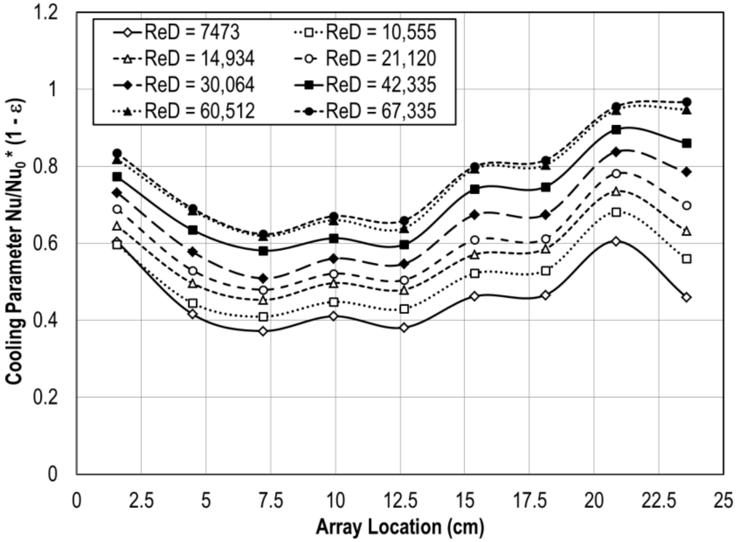


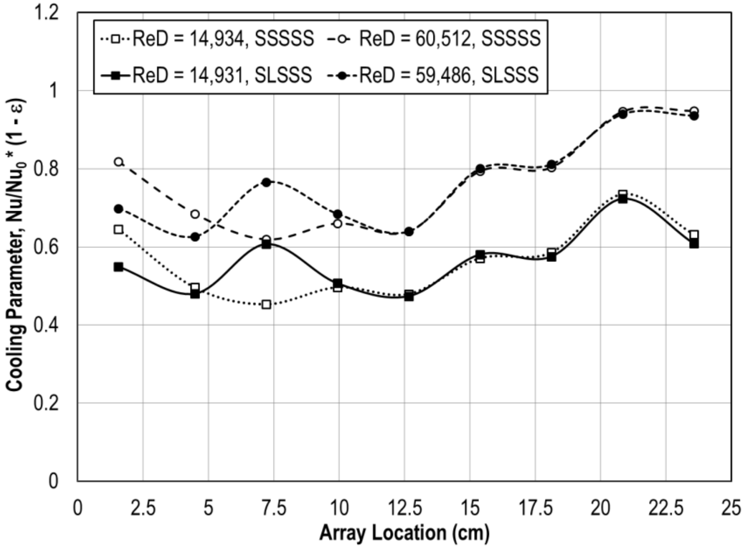
Incremental impingement

- Incremental impingement overcomes streamwise increase in 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.



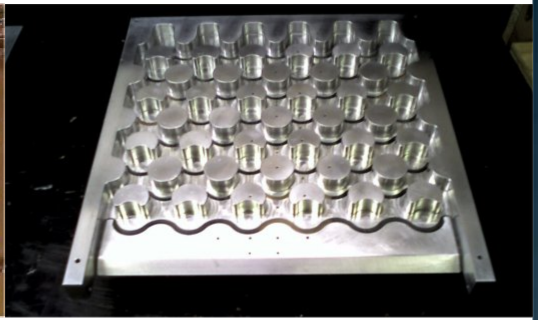


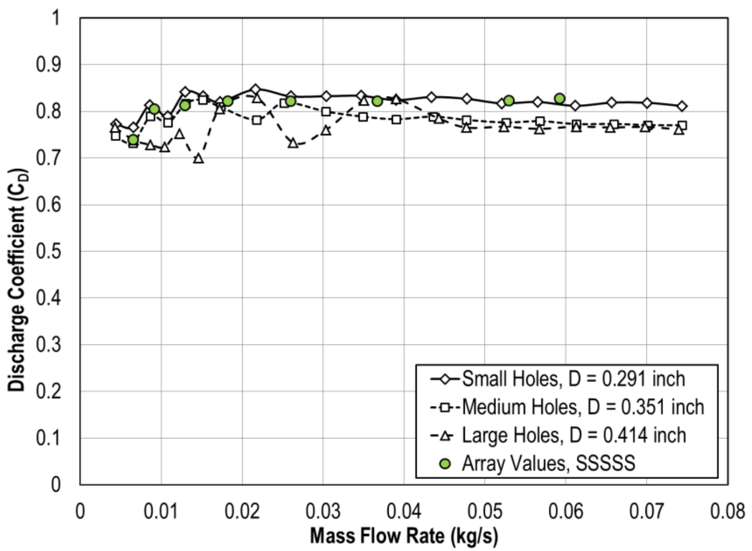


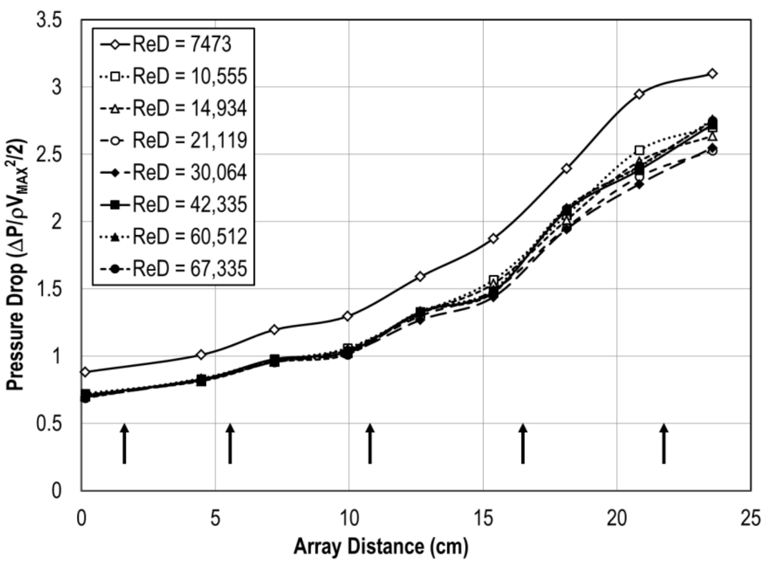


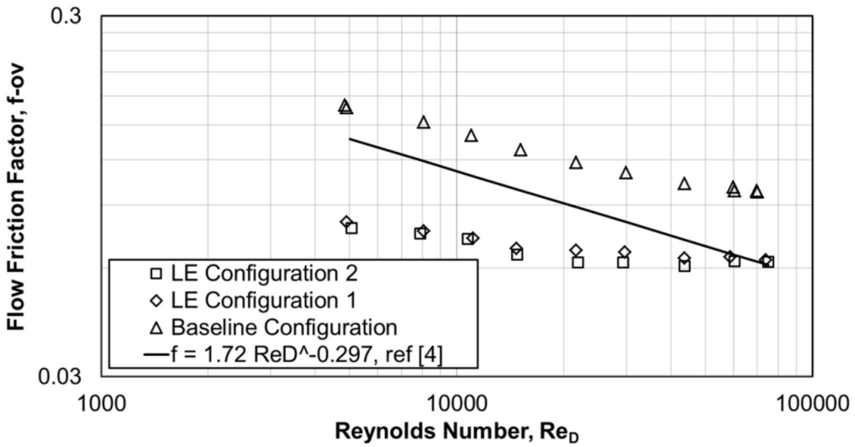
Incremental impingement

- Incremental impingement has a very predictable flow rate which is based on the local static pressure and an array Cd.
- Prior to testing the array Cd's were acquired to provide flow information.
- A comparison between the Cd's from the flow measurements for the top plate and the array mass balance are shown to the right & agree
- Incremental impingement has a much lower flow friction factor than conventional pin fins.
- We are currently planning to test the cooling array across a range of holes sizes & locations.



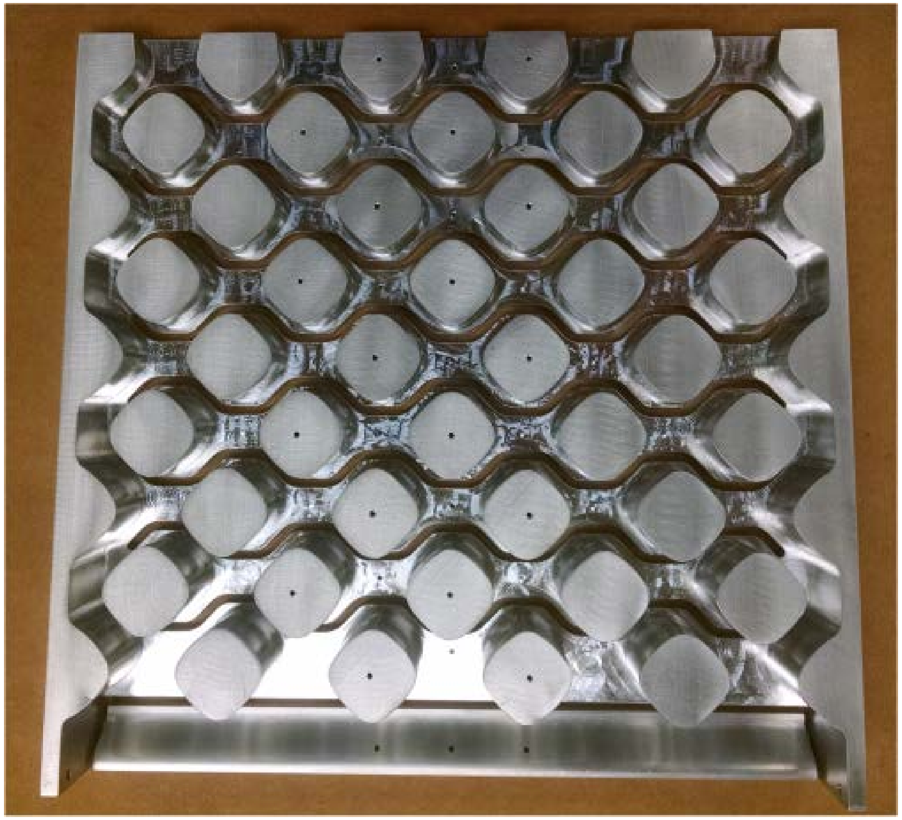






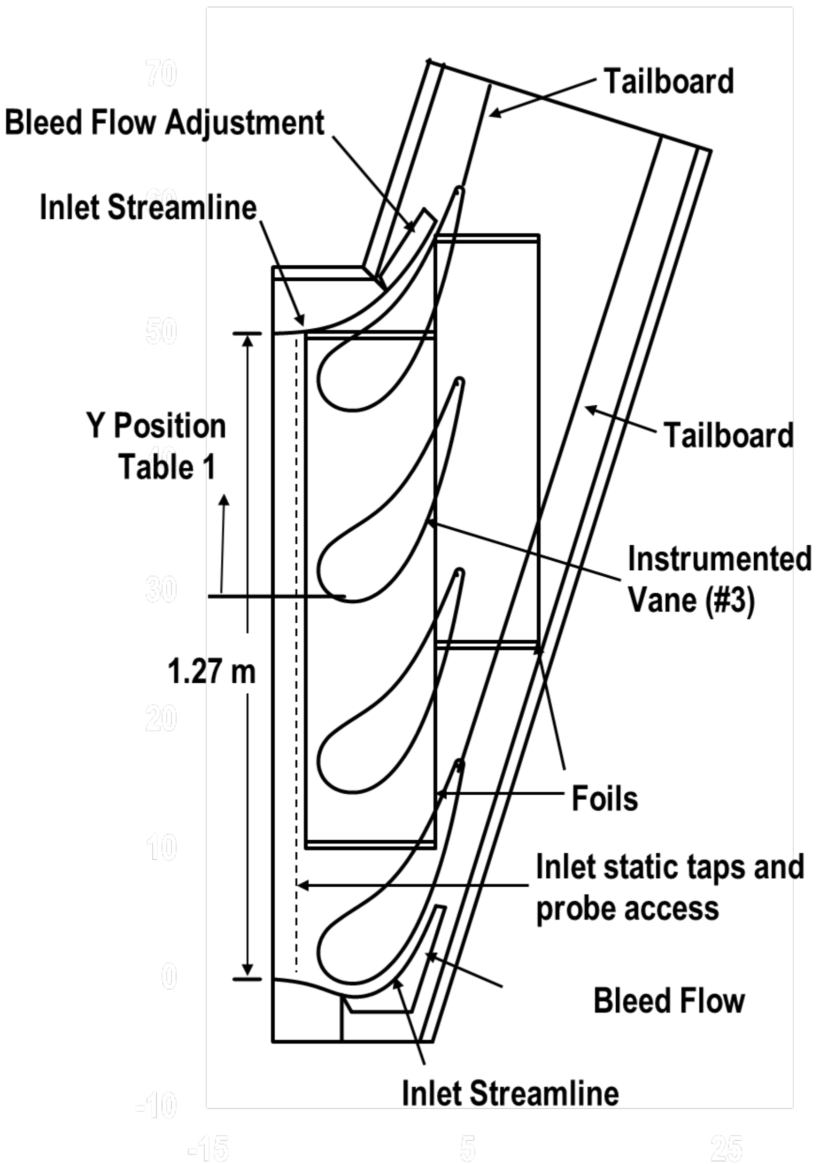
Covered Trailing Edge with Converging Array

- Converging pedestal arrays in trailing edge regions have often been attractive due to an increasing streamwise heat transfer coefficient which helps to overcome the coolant warm-up problem.
- Pressure drop also increases along the array as the walls converge.
- Varied exit areas will manage heat transfer levels. Relevant inlet geometries, including both symmetrical and off center inlets, will be tested to reflect the possible design options. These geometries help refine boundary conditions.

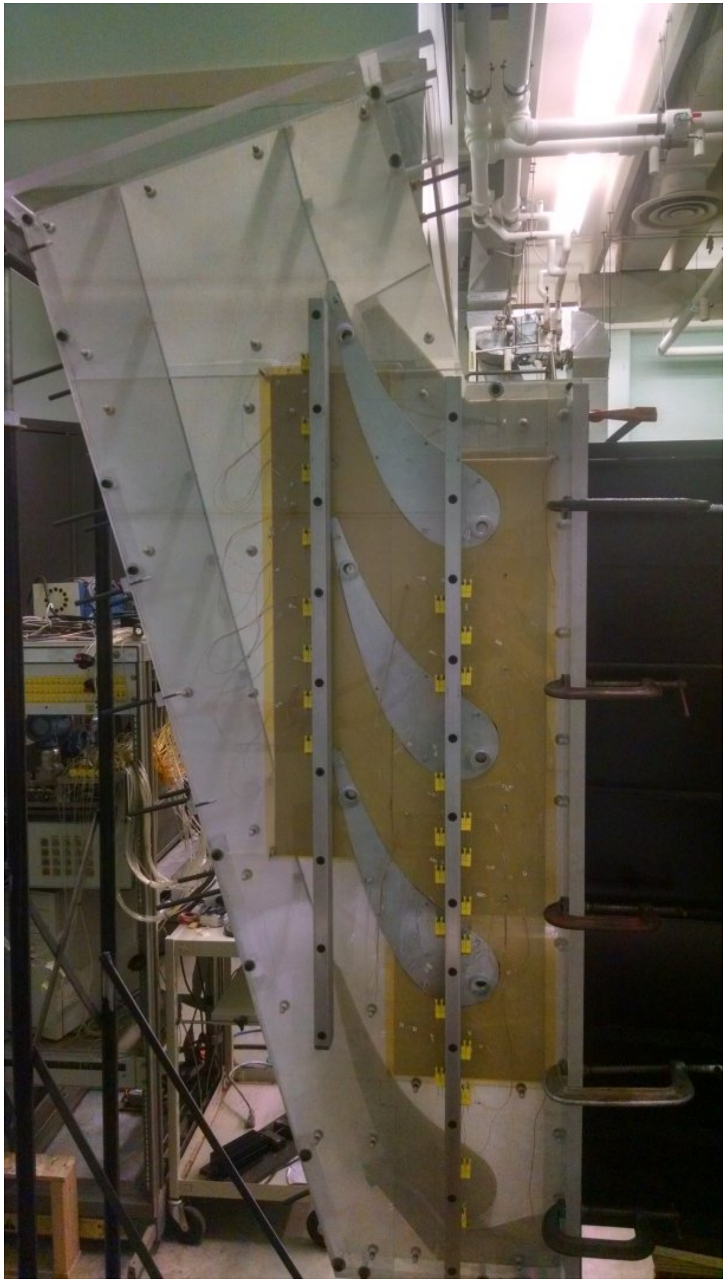


Large Scale Low Speed Cascade Testing

- UND is developing a large scale cascade to evaluate the film cooling effectiveness and the influence on heat transfer of the individual films subjected to a relevant range in turbulence conditions.
- UND/UM will use this information to help refine the heat transfer boundary condition for the LSU cascade.
- The cascade is fabrication is complete.
- We have begun taking initial measurements of pressure and we expect to begin 2D vane heat transfer measurements soon.

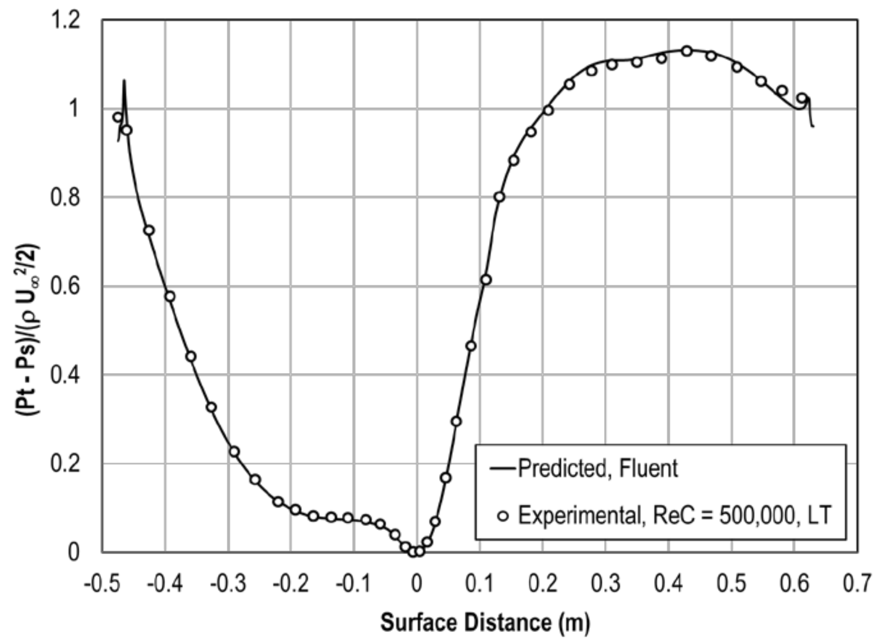


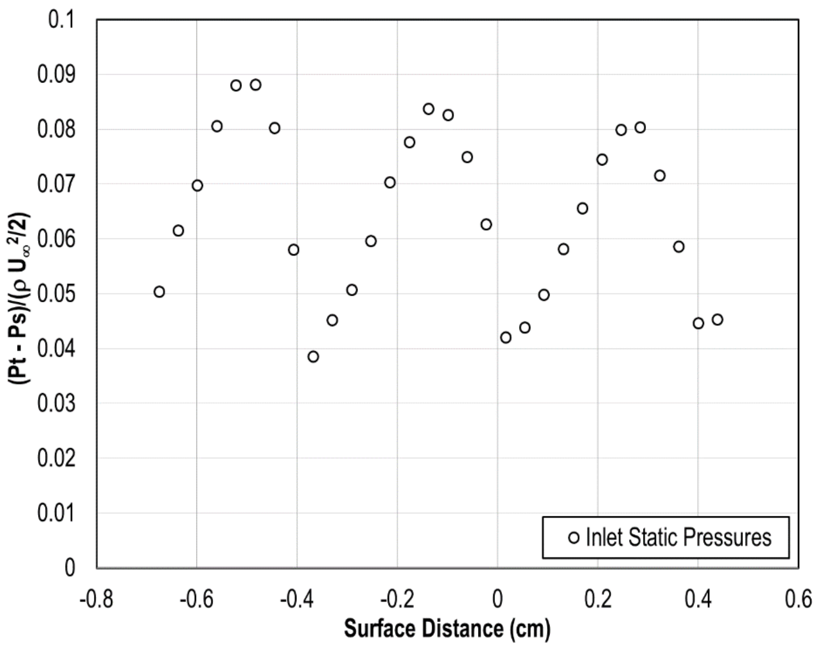
Large Scale Low Speed Cascade Testing

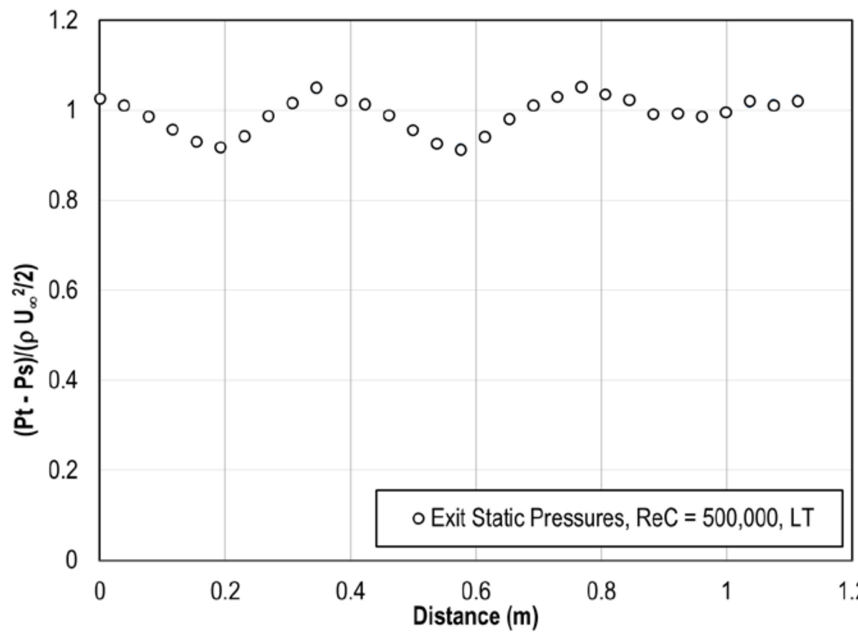


VANE CASCADE MEASUREMENTS

The initial vane pressure distribution matches the blade to blade analysis very well providing confidence in the experimental setup. The inlet and exit static pressure distributions indicate good uniformity and periodicity.

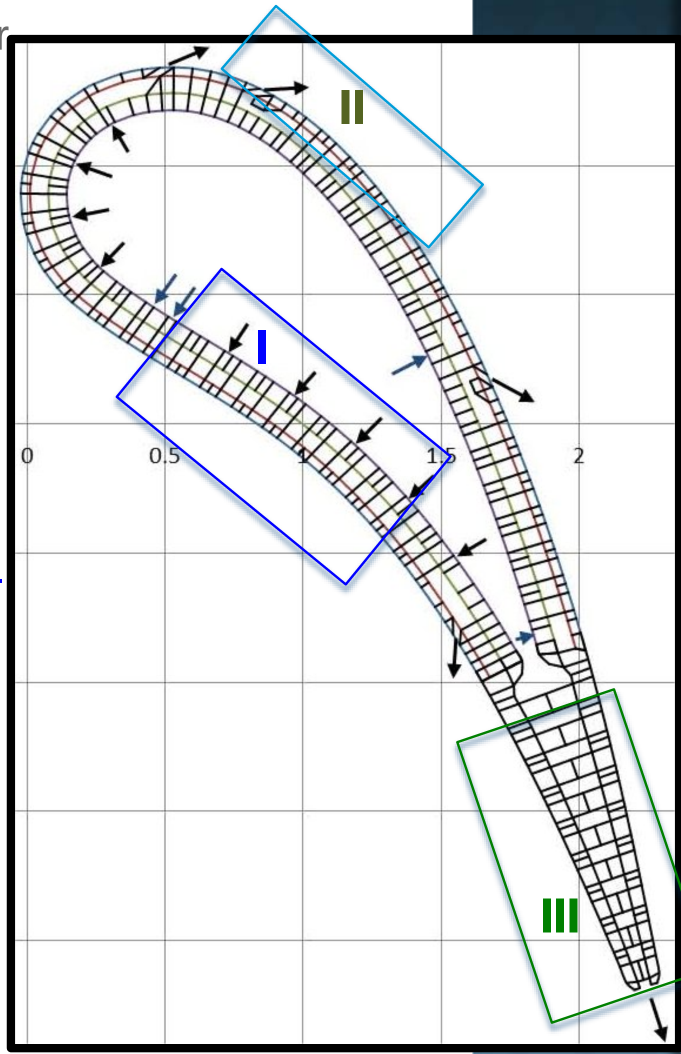






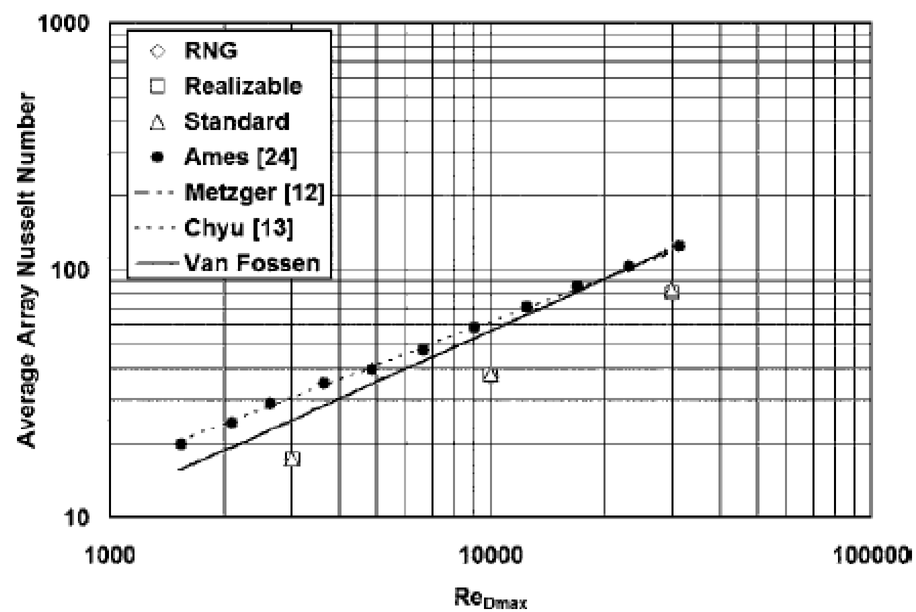
OVERALL COMPUTATIONAL STRATEGY

- Goals:
  - Develop a suite of HTC correlations that serve as input for a predictive design tool
  - Numerical optimization of geometric parameters and cooling design
  - Complement measurements with supporting computations that describe the flow physics
- Tasks:
  - Internal cooling with pedestals and incremental coolant impingement-UND data (I-LES)
  - Slot film cooling fed by a turbulated plenum-UND data (II-LES)
  - Trailing edge cooling with pedestals and converging geometry-UND data (III-LES)
  - Low speed cascade flow simulations (IV)
    - LES/DES with isothermal walls-UND data (IVa)
    - LES/DES with internal HTC correlations (IVb)
    - Predictive design tool with external and internal HTC (IVc)
  - High speed hot cascade flow simulations (V)
    - RANS validation with existing data (Va)
    - RANS w/ new vane- aero and HT with internal HTC correlations (Vb)



I-INTERNAL COOLING WITH PEDESTALS AND INCREMENTAL COOLANT IMPINGEMENT

- Wall-resolved LES study
- Baseline case with streamwise flow
- Incremental Impingement case
- Calculations are done for a range of Re and geometrical parameters
  - Validation (Ames & Dvorak, Busche et. al.)
  - HTC correlations

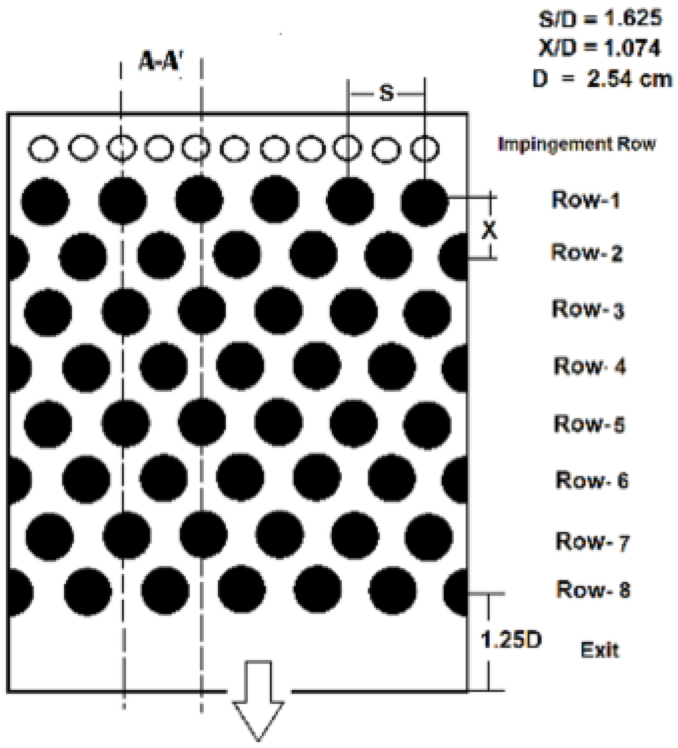


Comparing RANS w/ Data (Ames & Dvorak, 2006)

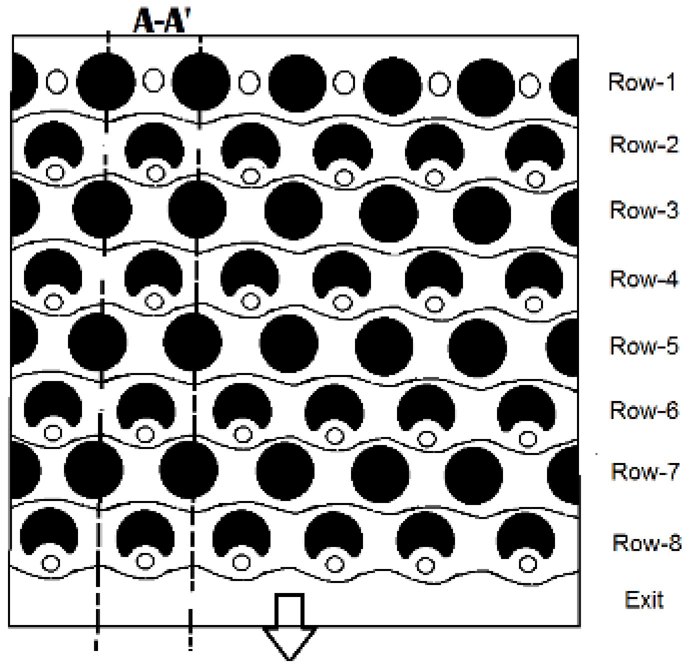
TWO TYPES OF CONFIGURATIONS

1) Baseline Configuration

2) Incremental Impingement Configuration



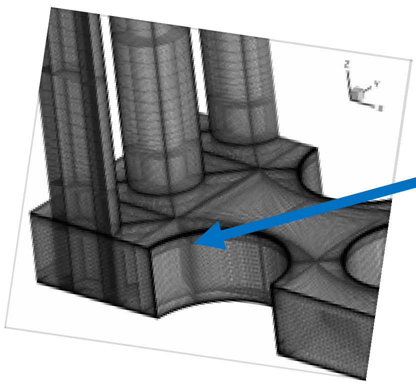
ONLY ONE IMPINGEMENT ROW

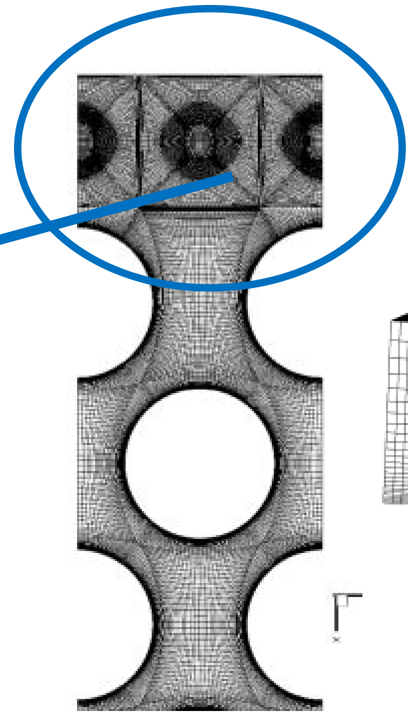


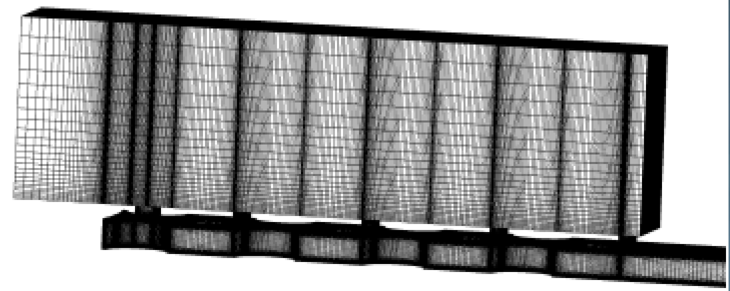
MULTIPLE IMPINGEMENT ROWS

*To save the computational resource, section A-A' is modelled using periodic boundary condition.

COMPUTATIONAL DETAILS







Mesh Parameter- 6.5M

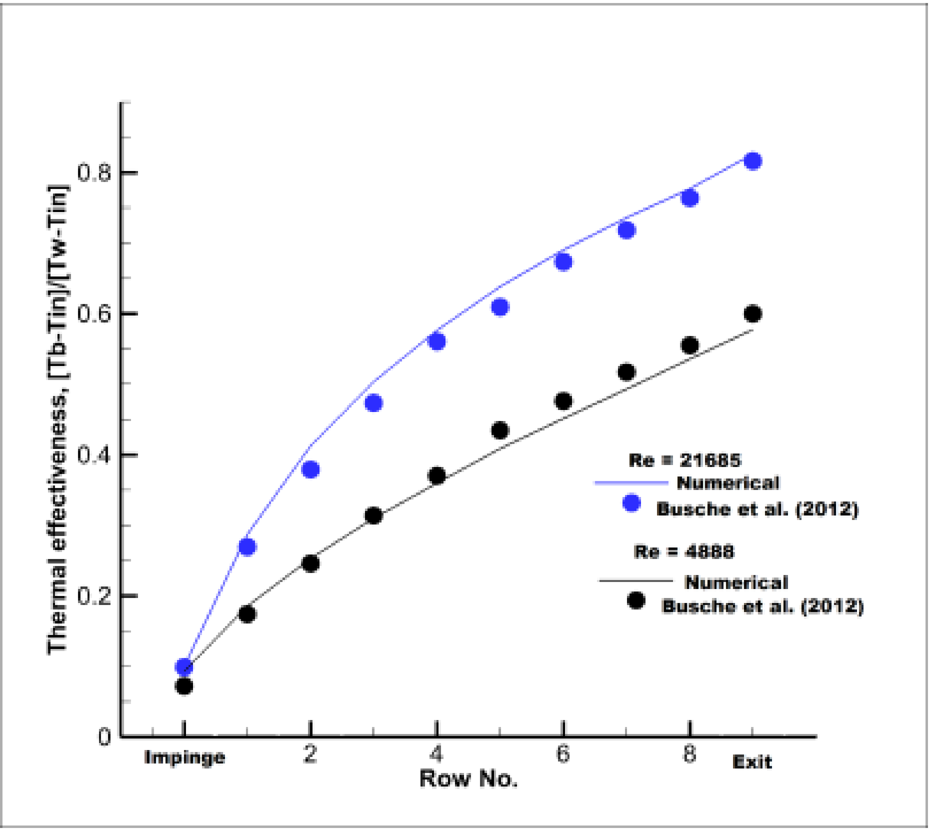
Y+ = 0.3- 0.8

$\Delta Z+$ (max) = 20-30

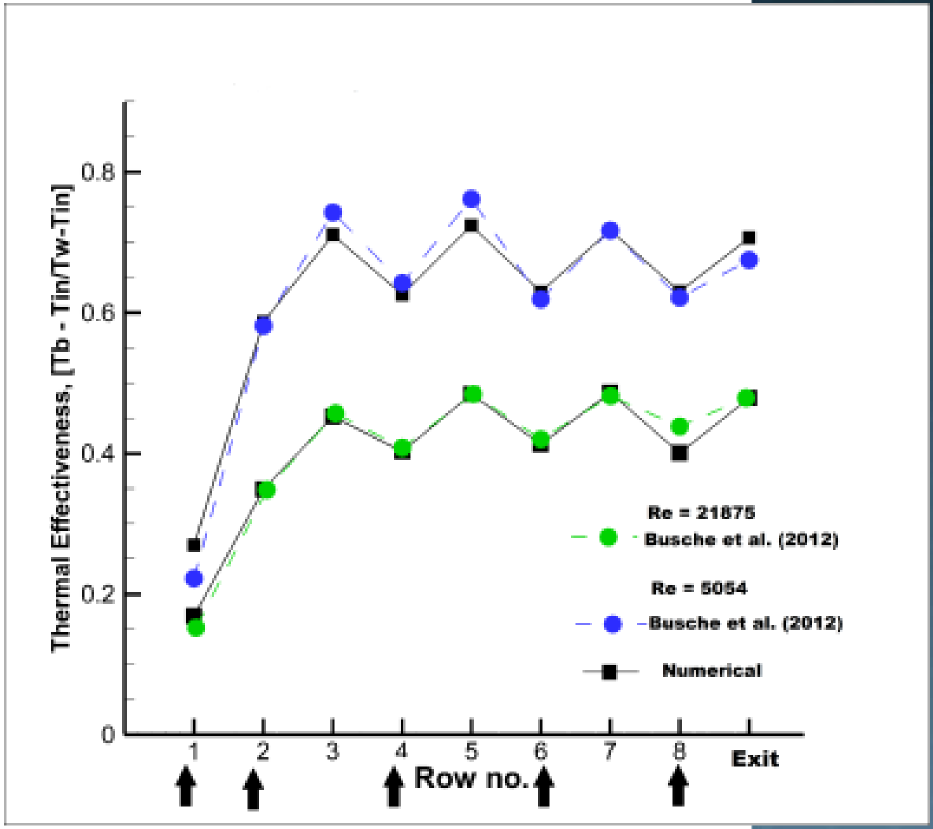
$\Delta X+$ (max) = 40-60

- In house CHEM3D code
- Fifth order WENO Scheme for convection;
- Second order CD scheme for diffusion
- Second order time integration
- Tested for scalability up to 1000 processors
- LES with D-S-L model

THERMAL EFFECTIVENESS PREDICTIONS AGREE WELL WITH DATA

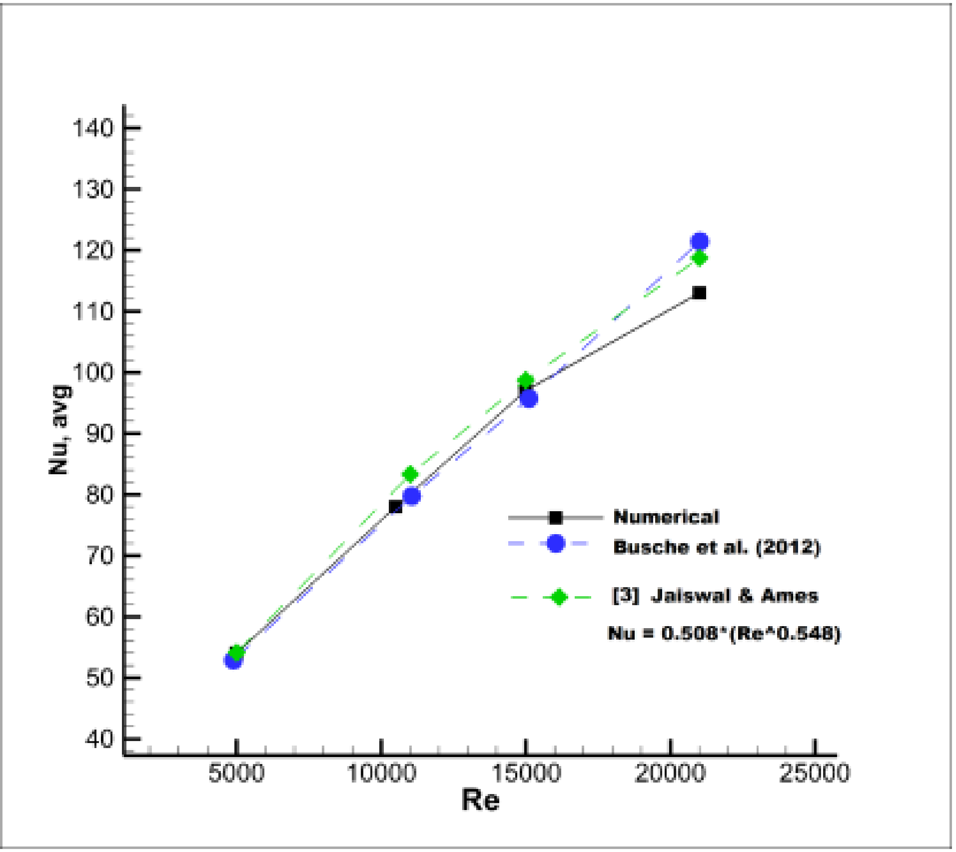


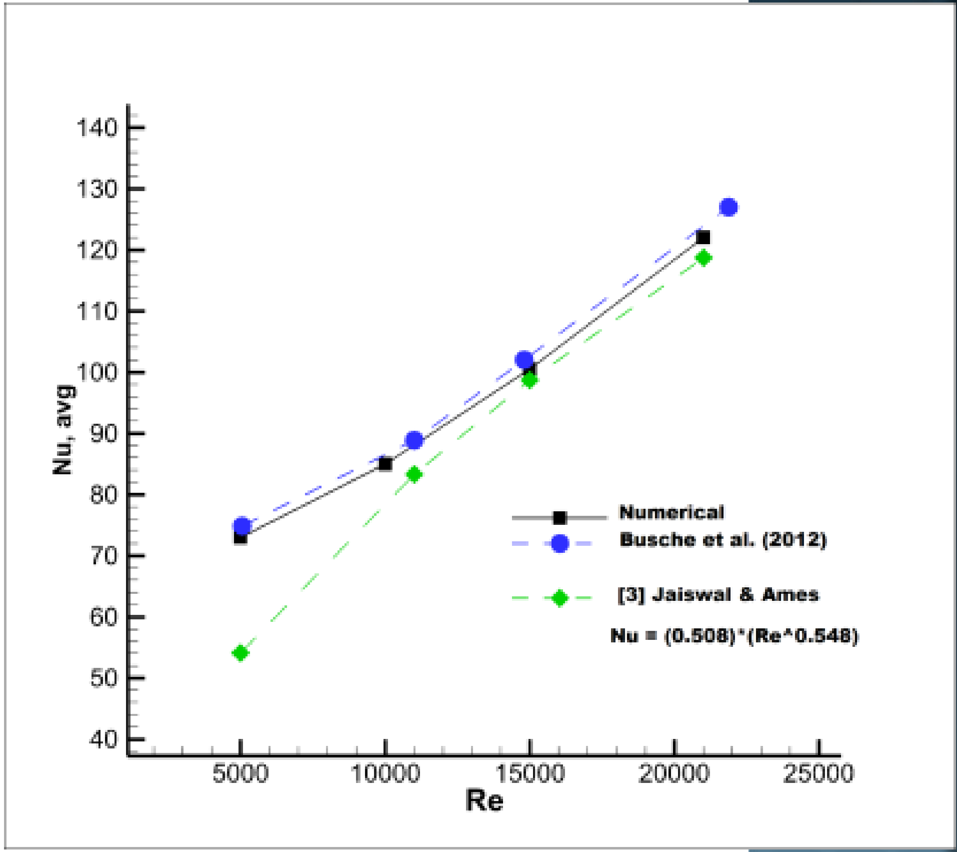
Baseline configuration



Incremental Impingement

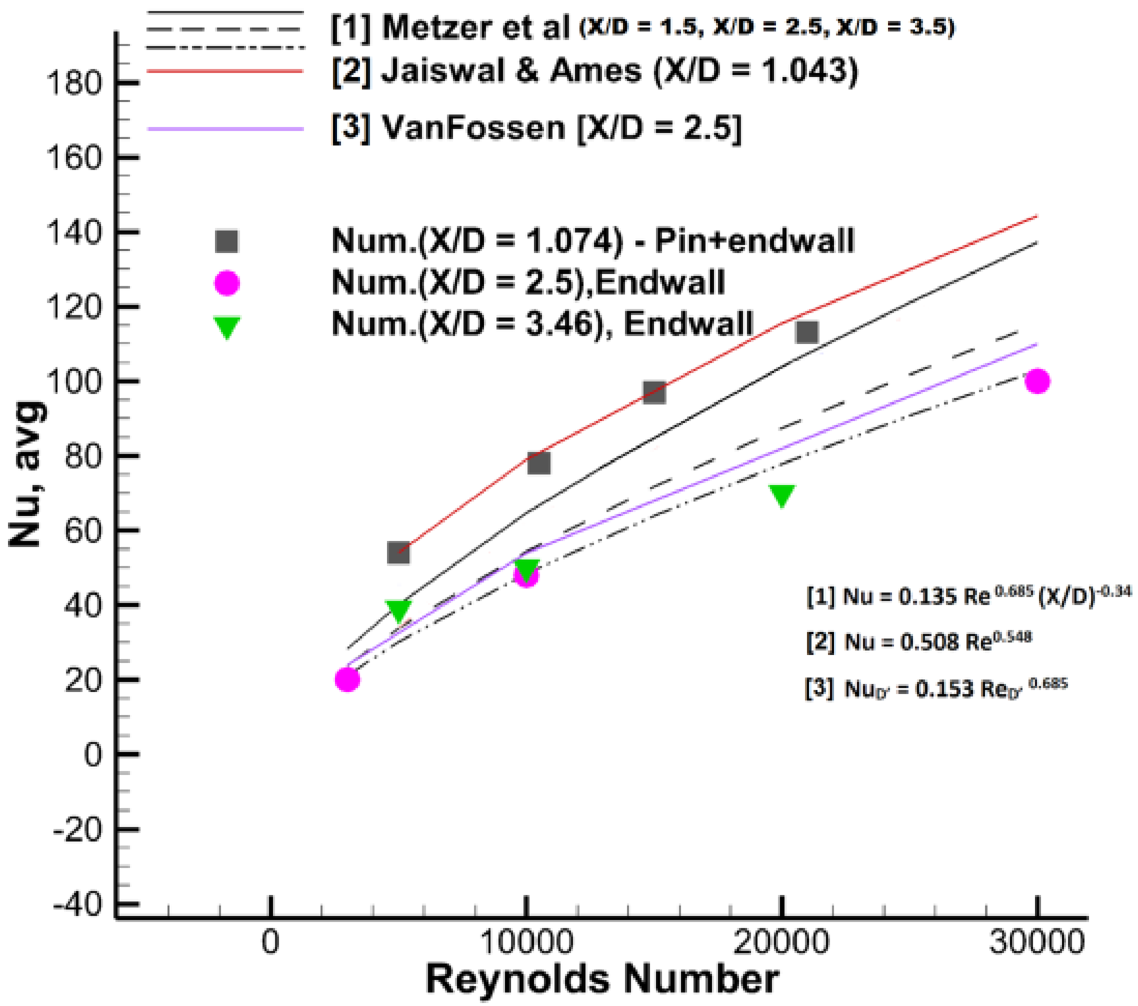
NUSSELT NUMBERS AGREE WELL WITH DATA.





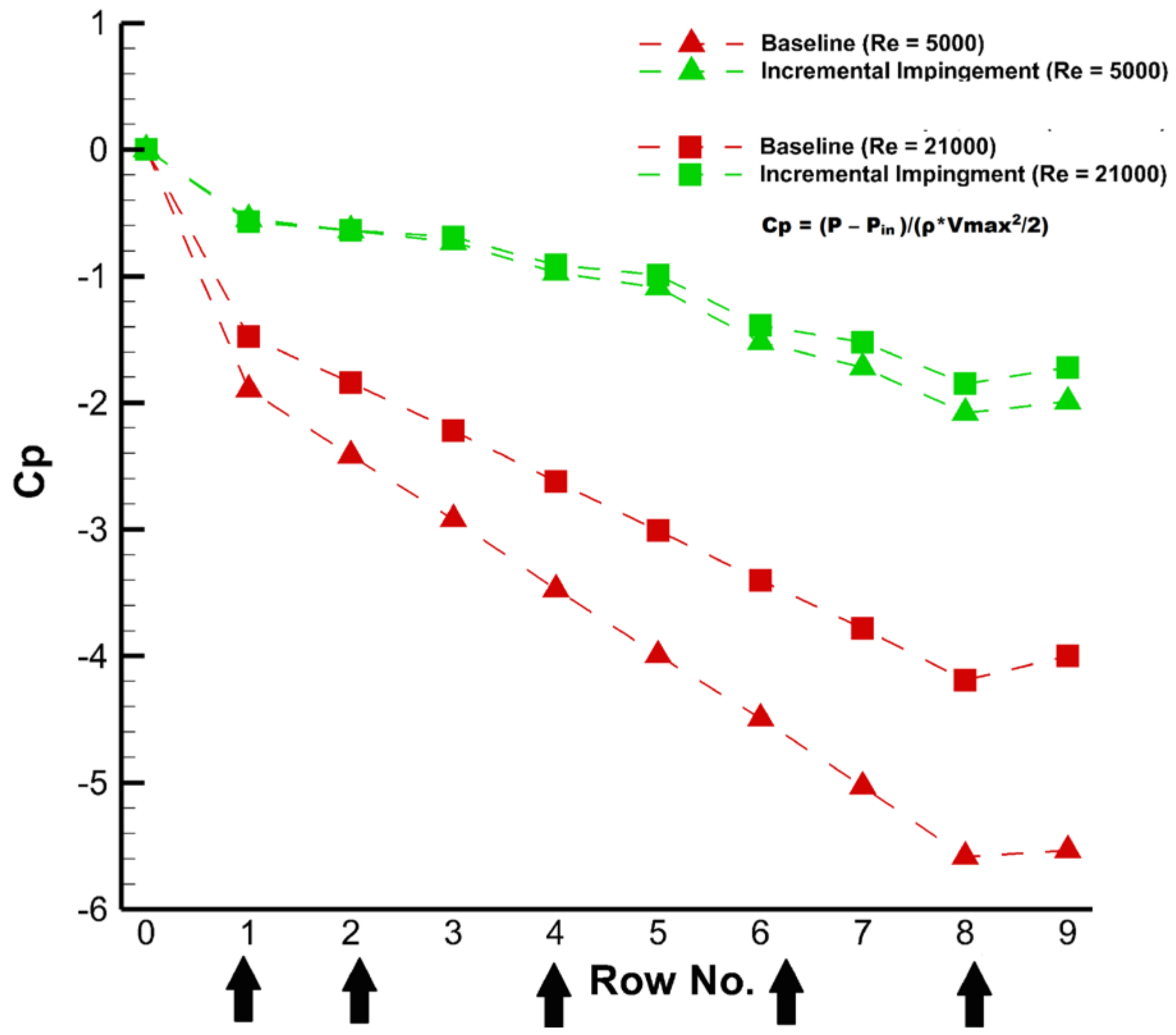
Baseline configuration **Incremental Impingement**

EFFECT OF STREAMWISE SPACING- NUMERICAL & EXPERIMENTAL COMPARISON

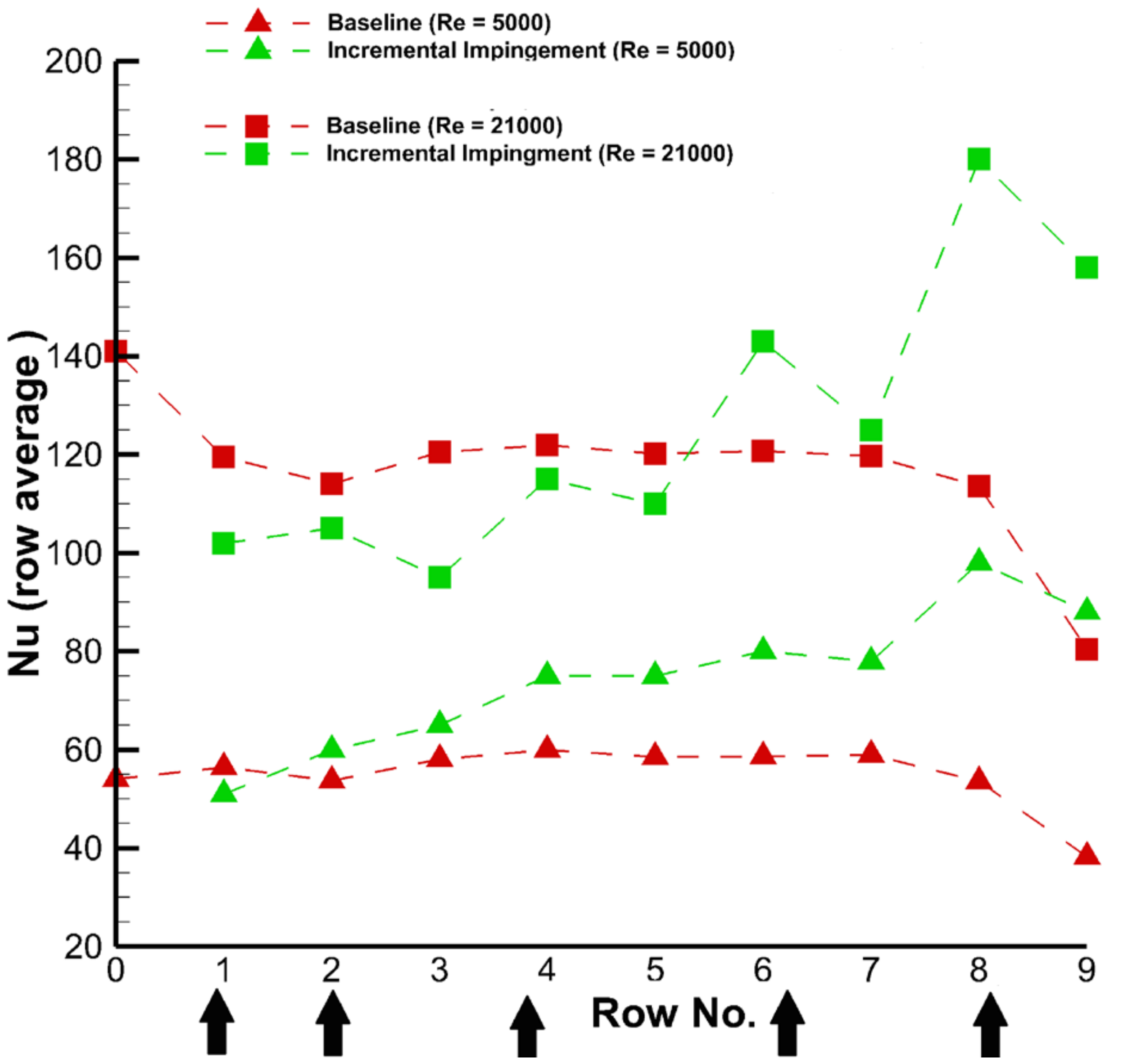


- Baseline correlations for average Nu, in the literature, do well.
- Need to develop row-by-row correlations
- Need to develop correlations for incremental impingement
- These correlations will serve as input into a FEA or design code.

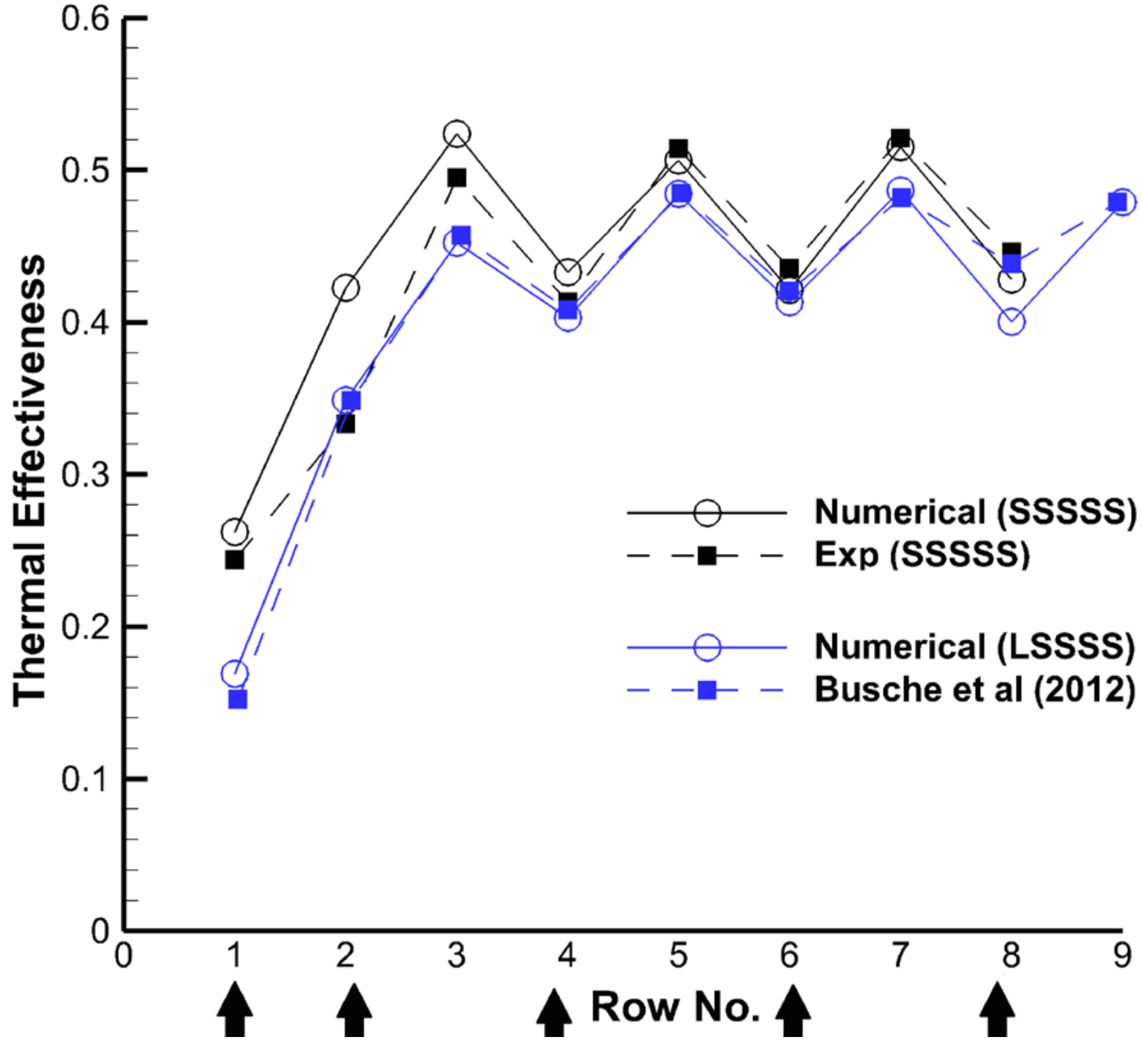
PRESSURE DROP FOR BASELINE AND INCR. IMPING.

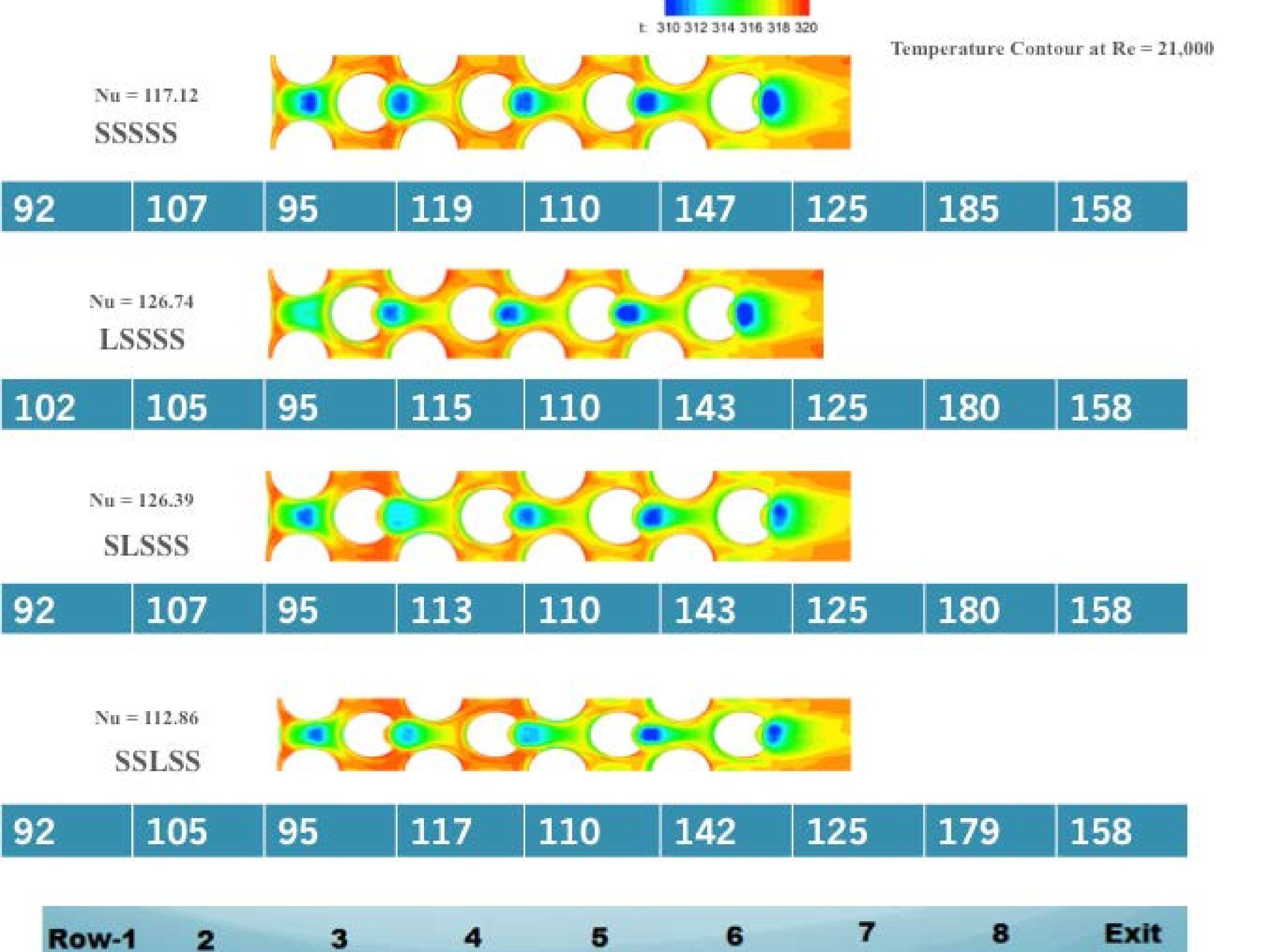


NU FOR BASELINE AND INCR. IMPING.



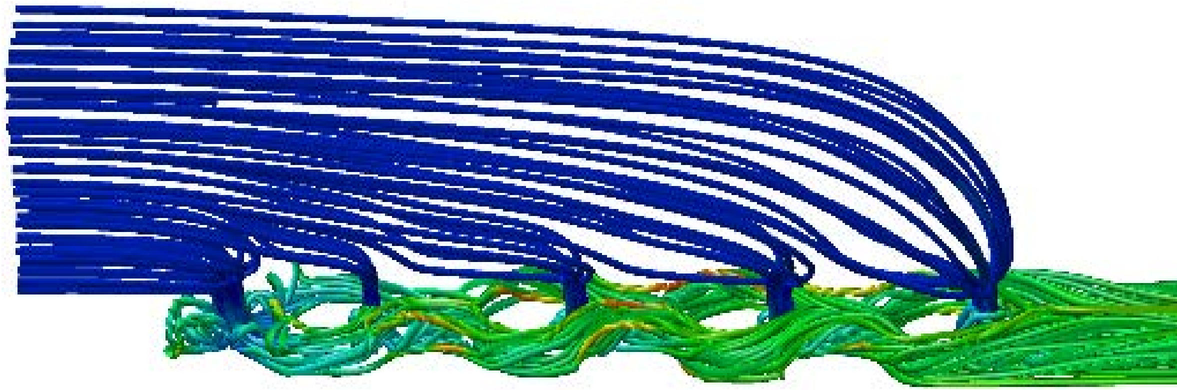
EFFECT OF HOLE SIZE

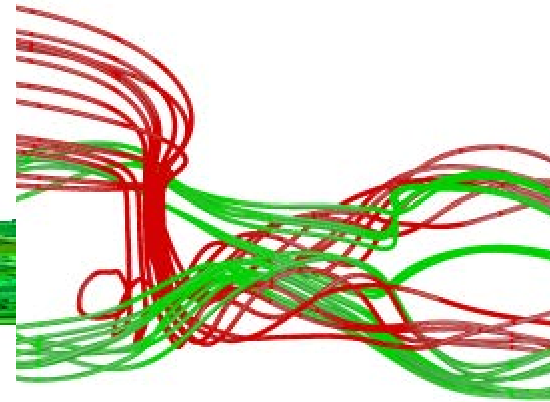


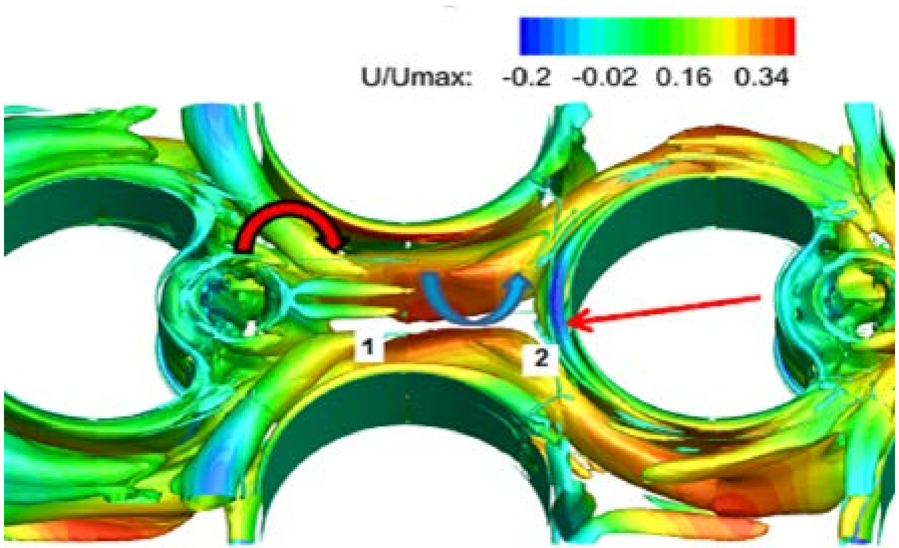


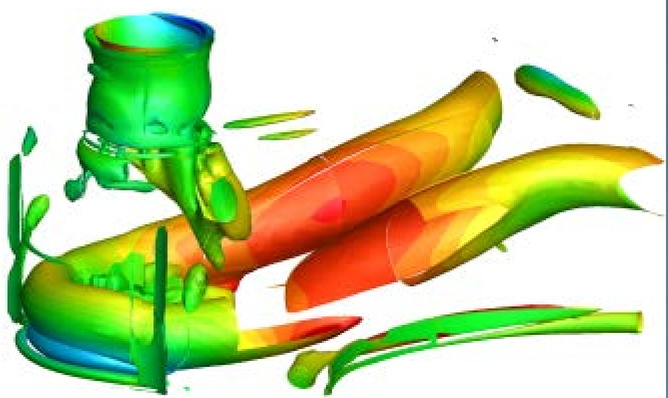
t: 310 312 314 316 318 320
Temperature Contour at Re = 21,000
Nu = 117.12
SSSSS
92 107 95 119 110 147 125 185 158
Nu = 126.74
LSSSS
102 105 95 115 110 143 125 180 158
Nu = 126.39
SLSSS
92 107 95 113 110 143 125 180 158
Nu = 112.86
SSLSS
92 105 95 117 110 142 125 179 158
Row-1 2 3 4 5 6 7 8 Exit

SOME FLOW PHYSICS



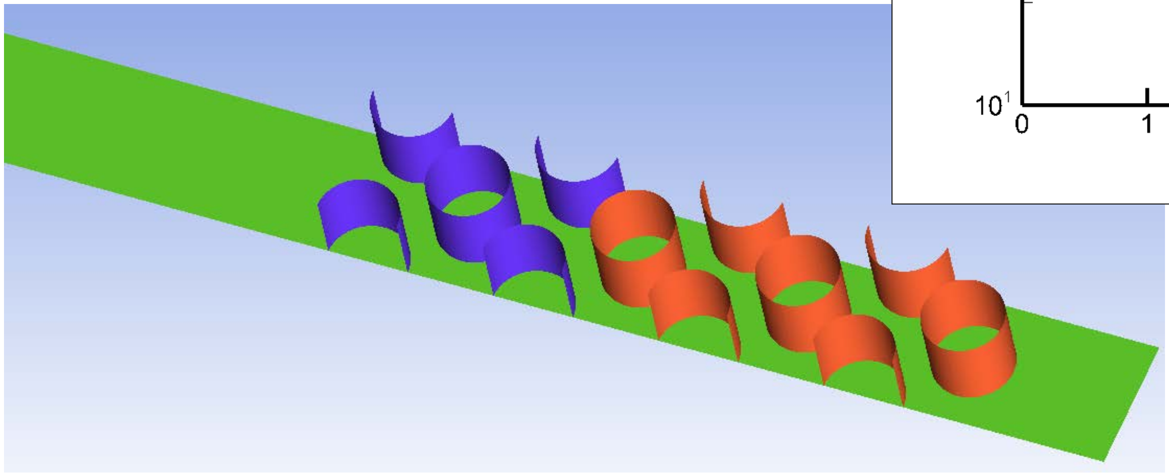


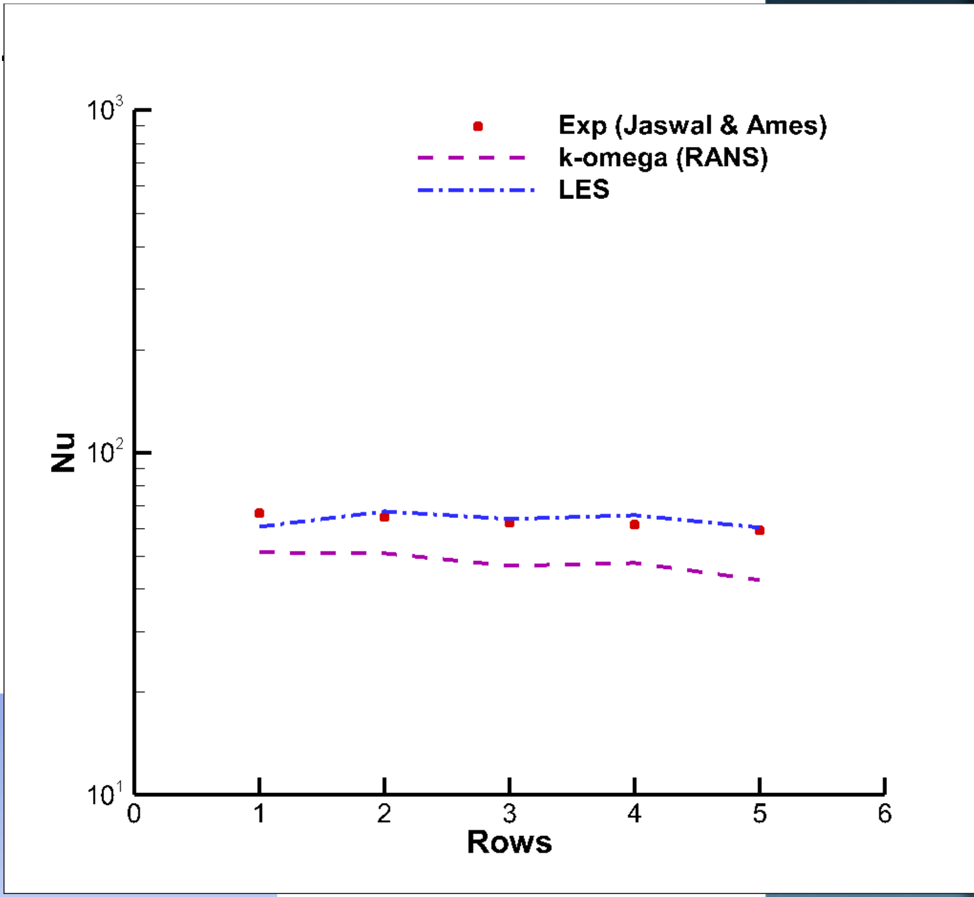




III. TRAILING EDGE COOLING W/ PEDESTALS

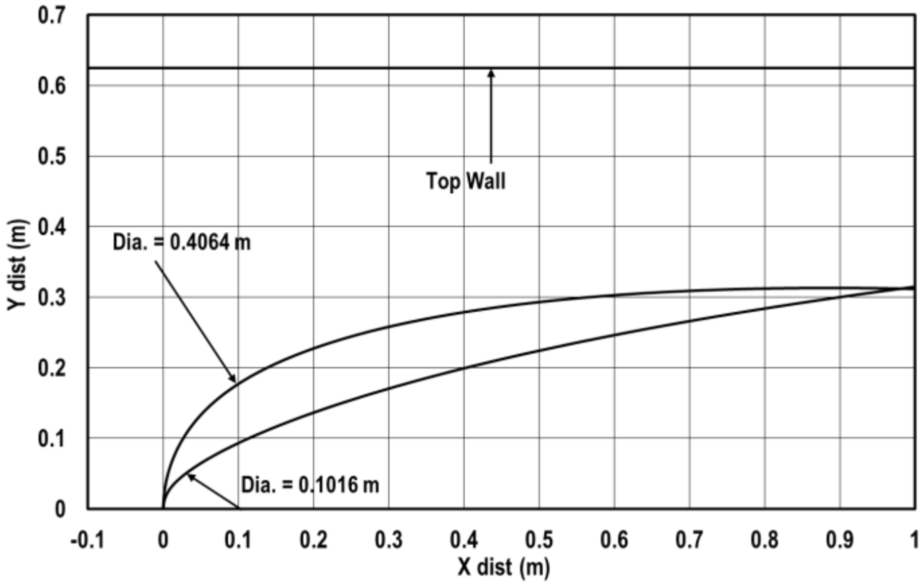
- Constant and converging cross-sections
- Round and diamond pedestals
- Entrance geometry effects
- Jaiswal and Ames (2013) data
- LES and RANS Study





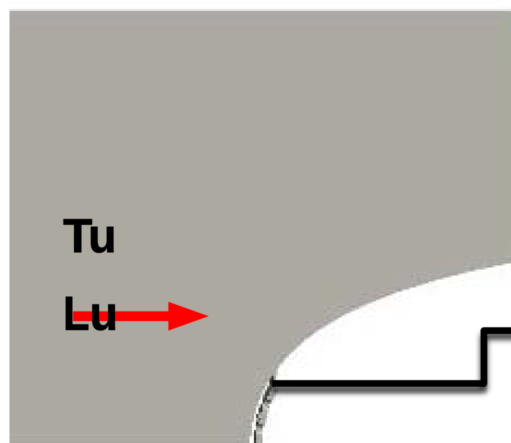
II. SLOT FILM COOLING FED BY A TURBULATED PLENUM

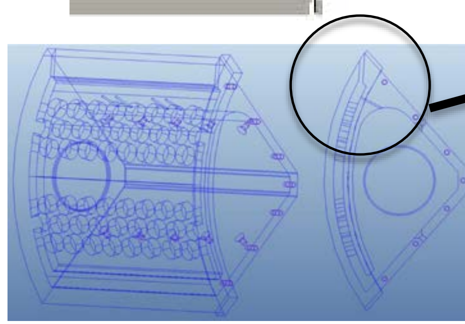
- Leading edge geometry with flow acceleration (SS)
- Slot cooling with a turbulated plenum
- Inflow turbulence effects
- Busche & Ames (2014) data
- LES and RANS study

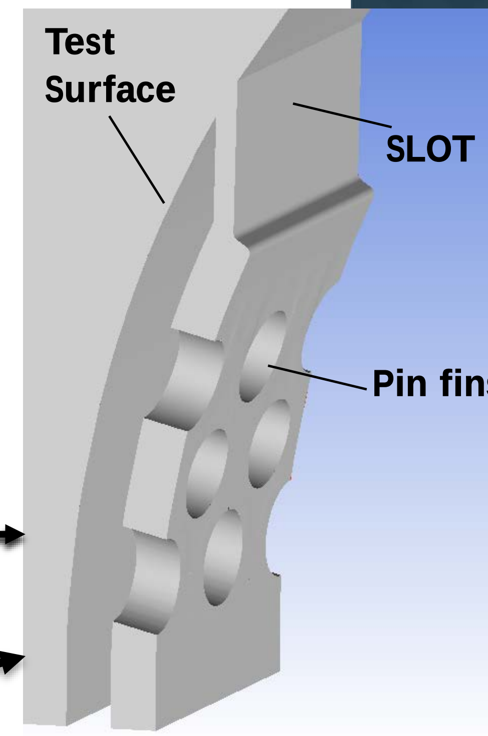


SLOT FILM COOLING IN AN ACCELERATING BOUNDARY LAYER

- Flow Characteristics
  - Free-stream Turbulence
  - Turbulence Length Scale
  - Blowing ratios
- Heat Transfer
  - Adiabatic Film cooling
  - Effect of free-stream turbulence
  - Effect of turbulence length scale
- OPENFOAM
  - 2nd order schemes
  - Dynamic SGS (LES)
  - K-w-SST (URANS)



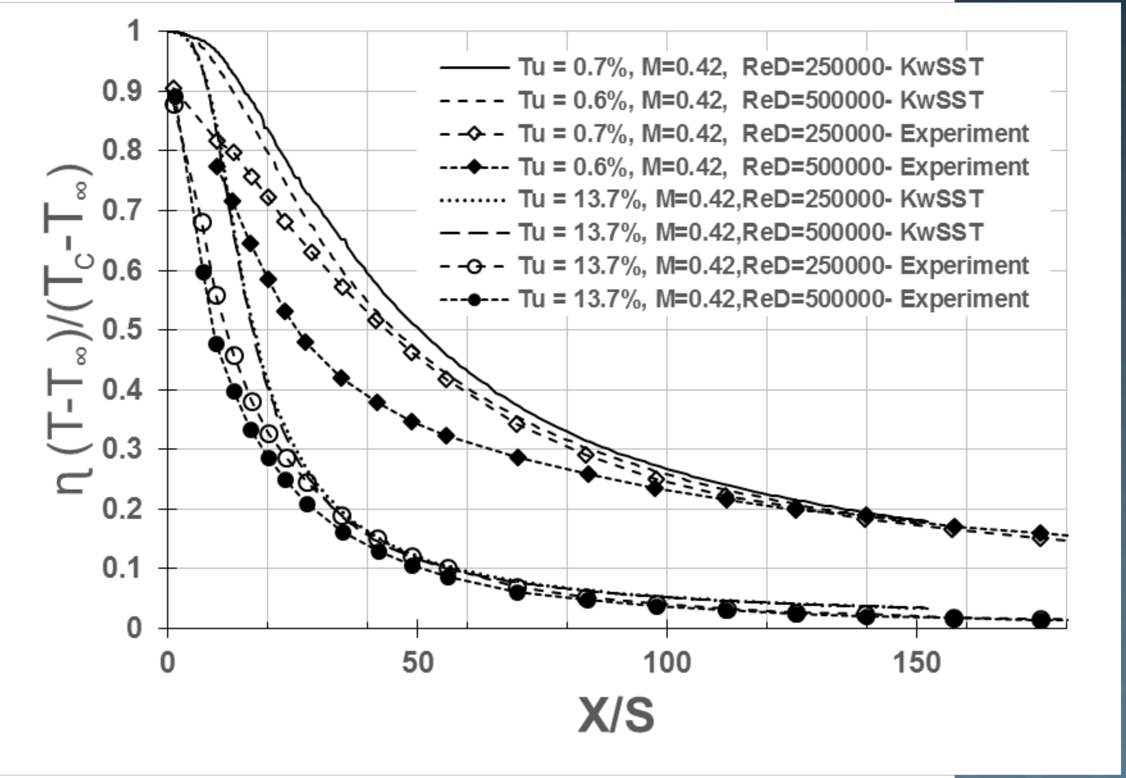




Geometry from Busche & Ames

URANS SIMULATIONS

- Results qualitatively agree with the experimental data
- Noticeable difference in predicted effectiveness just downstream of slot
- Thermal effectiveness is over predicted
- Numerical results agrees with experimental far downstream of slot
- Effect of free-stream on thermal effectiveness is qualitatively predicted
- Lack of predicting transition in higher Reynolds number

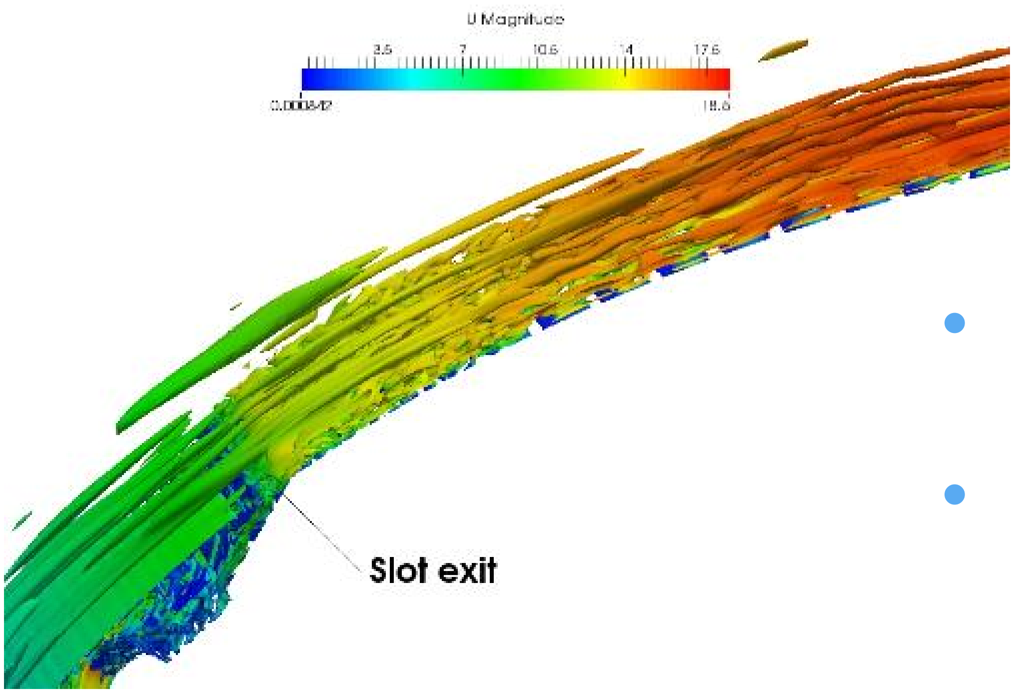


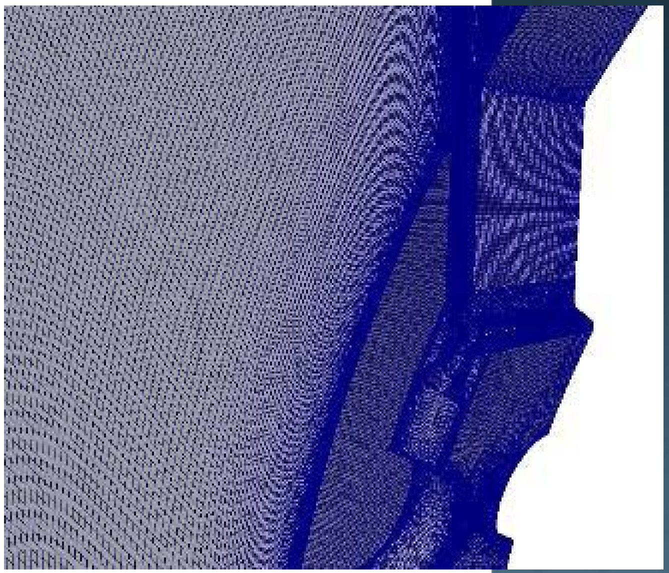
Experiments:

Busche, M. L., and Ames, F. E., 2014, "Slot Film Cooling Measurements on an Accelerating Test Surface Subjected a Range of Turbulence Conditions," pp. 1–12

LES SIMULATION

- SGS model: Dynamic Smagorinsky
- Average y^+ of 0.33
- Grid size of 13 million



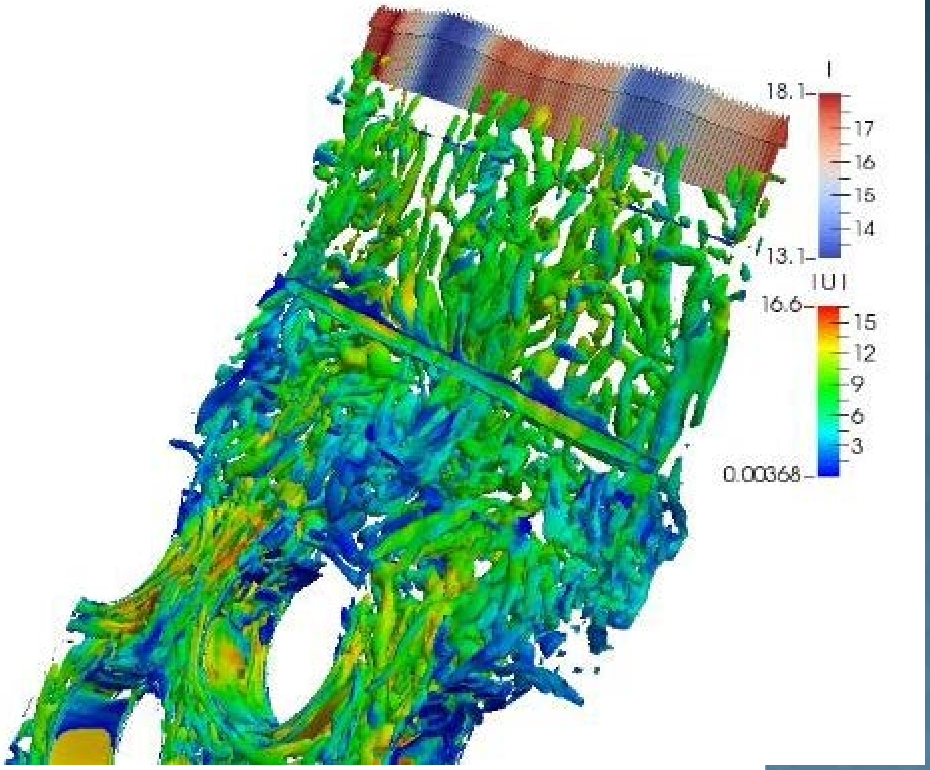


- Divergence free Synthetic Eddy Method is used for generating turbulent at Inlet
- Turbulent at inlet adjusted to get near 1% turbulence intensity at measured point in experiments

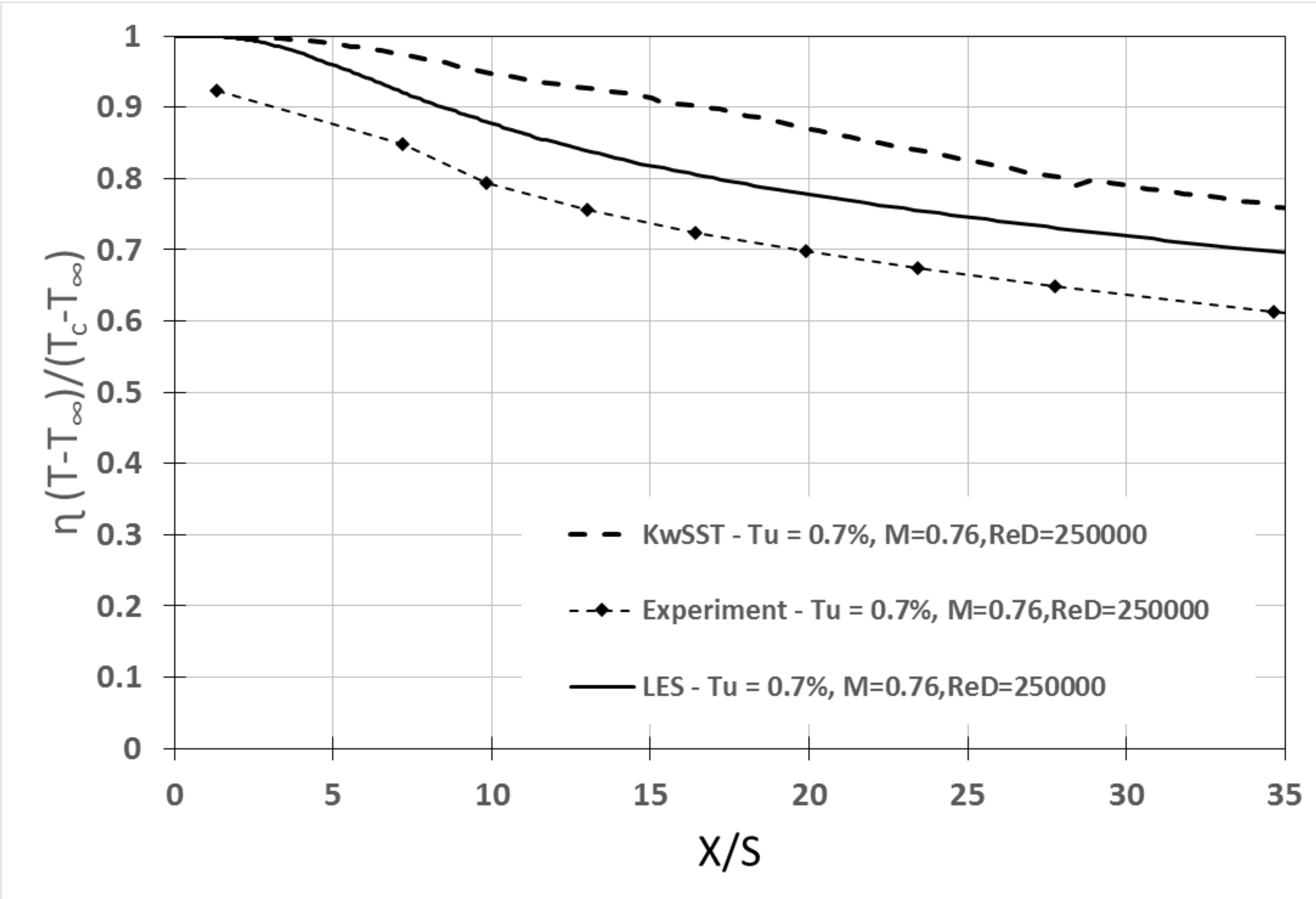
* Poletto, R., Craft, T., and Revell, a., 2013, “A New Divergence Free Synthetic Eddy Method for the Reproduction of Inlet Flow Conditions for LES,” Flow, Turbul. Combust., 91(3), pp. 519–539.)

TURBULENCE OF PLENUM

- Non-uniform velocity distribution at slot exit
- Presence of turbulence at coolant jet although it faces high contraction rate in two special directions
- Non-uniform turbulence intensity at slot exit



THERMAL EFFECTIVENESS (LES & RANS SIMULATION)



SUMMARY AND CONCLUSIONS

- The current project is structured to advance the technology readiness of three internal cooling methods as well as a computational predictive tool for predicting slot film cooling:
  - Incremental impingement for surfaces near and around the leading edge
  - Counter cooling for cooling suction surfaces
  - Converging pedestal arrays for cooling trailing edge regions
- The current project is based on a four phase approach to develop thermally efficient, effective and flexible cooling methods.
  - The first phase was to develop an FEA model of an advanced cooling design
  - The second phase is to develop an experimental database and computational tools for the three internal cooling methods
  - The third phase is to develop computational methods for film cooling based on an experimental database being acquired in a large scale cascade
  - The final phase will be to compare an updated FEA model with the results of a warm cascade test.
- At UND we are currently testing incremental impingement for cooling vane leading edge and downstream regions.
  - Results look encouraging and computational methods appear accurate.
- At UND we have begun to baseline our new large leading edge vane cascade.
  - Presently, the cascade appears to exhibit good 2D aerodynamics.