Revolutionizing Turbine Cooling with Micro-Architectures Enabled by Direct Metal Laser Sintering

The Ohio State University

Aerospace Research Center

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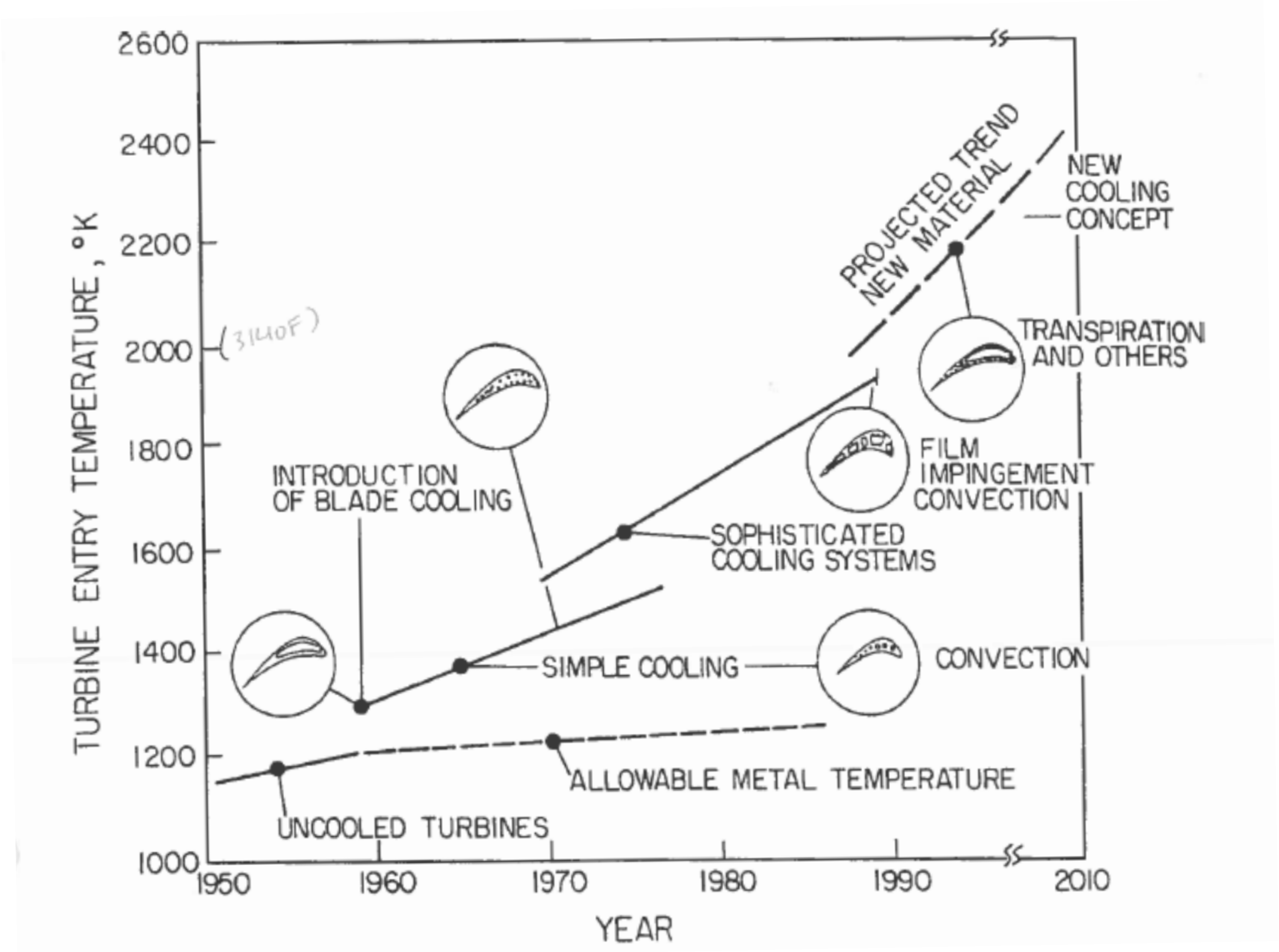
(4 Nov 2015 – NETL UTSR Workshop)

Motivation

Turbine Cooling – “Where did we come from?”



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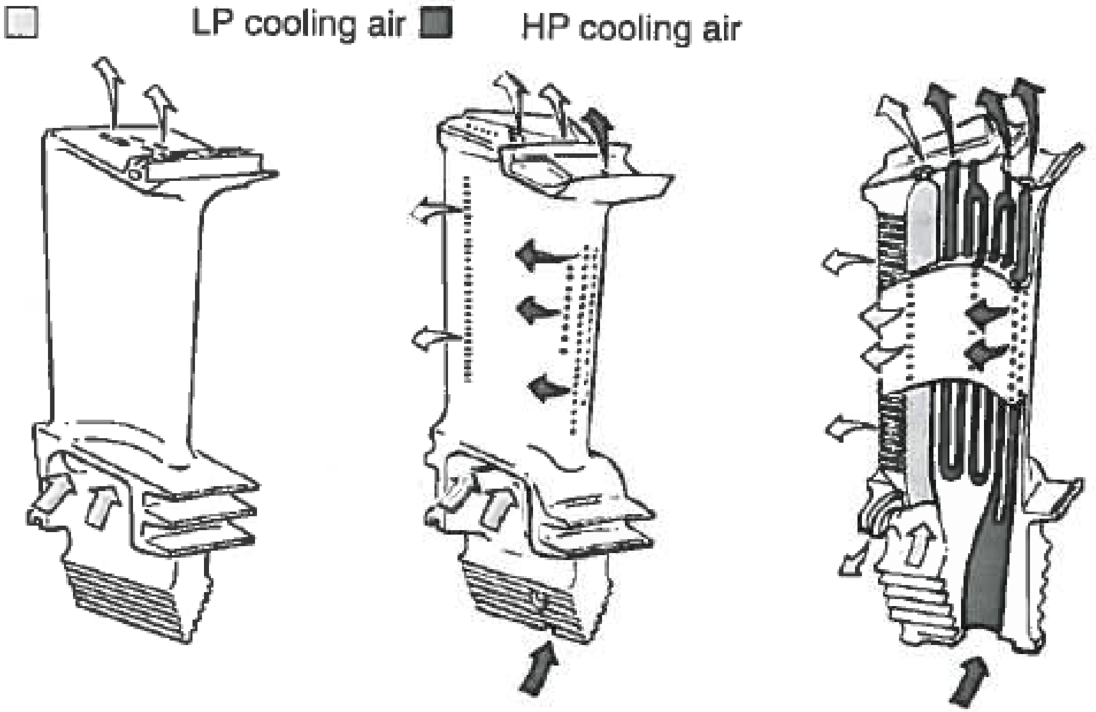


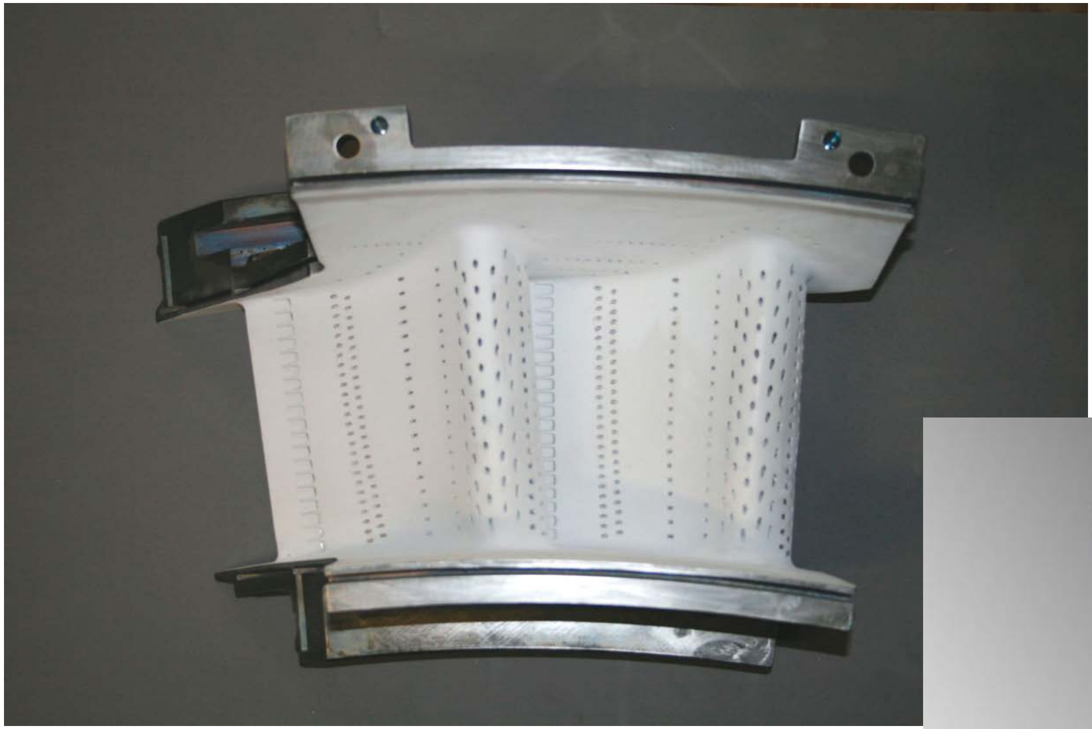
Convection
Single pass
(1960)

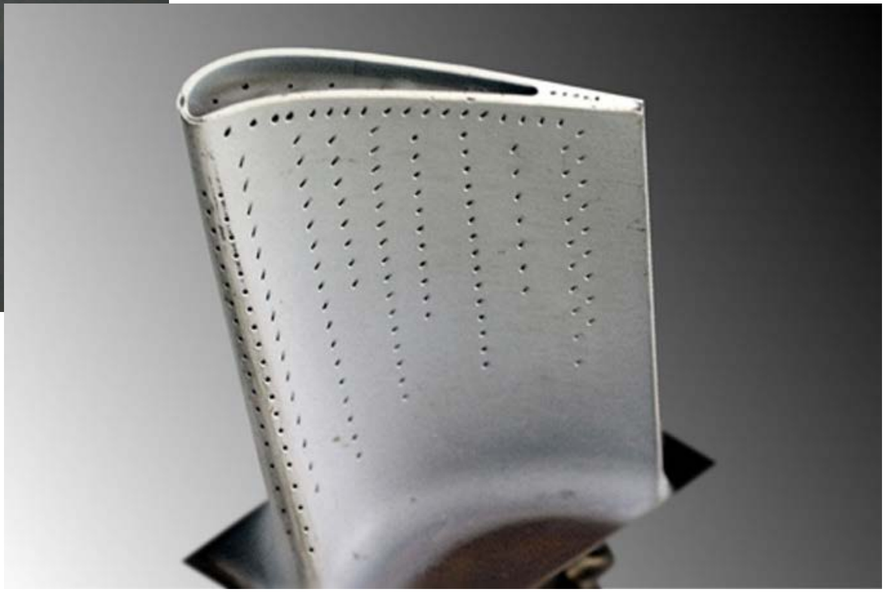
Convection (single pass-multiple feed) and film
(1970)

Convection (Quintuple pass-multifeed) and film cooling

Motivation

State-of-the-Art in Turbine Cooling – "Where are we now?"

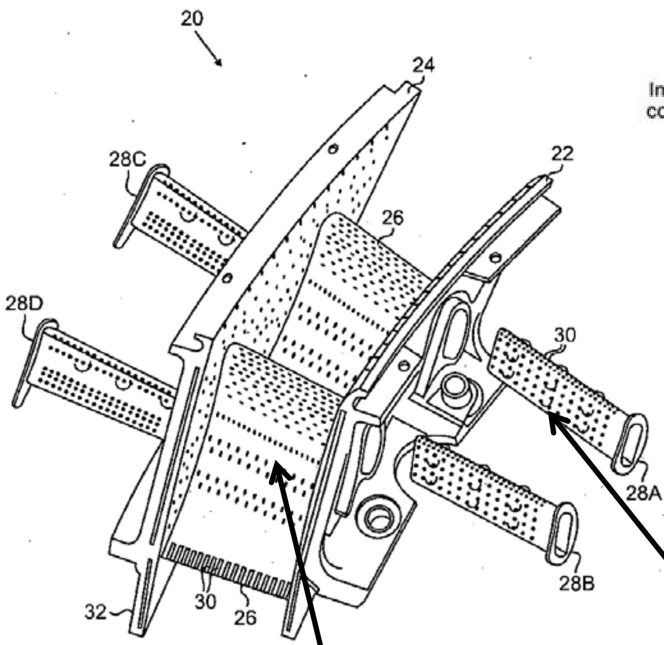


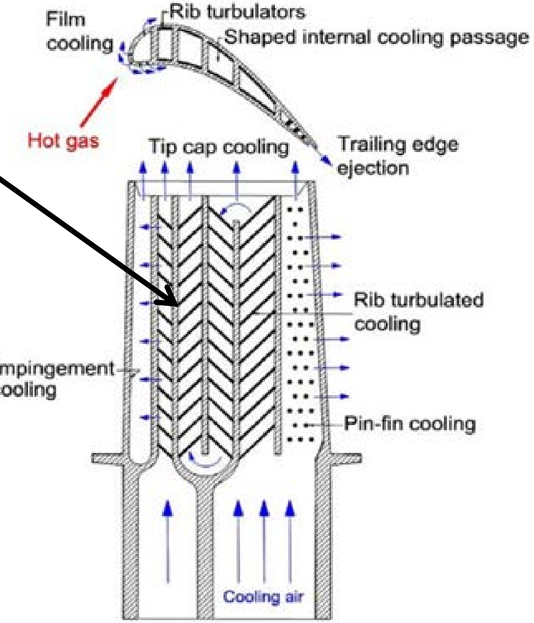


Motivation

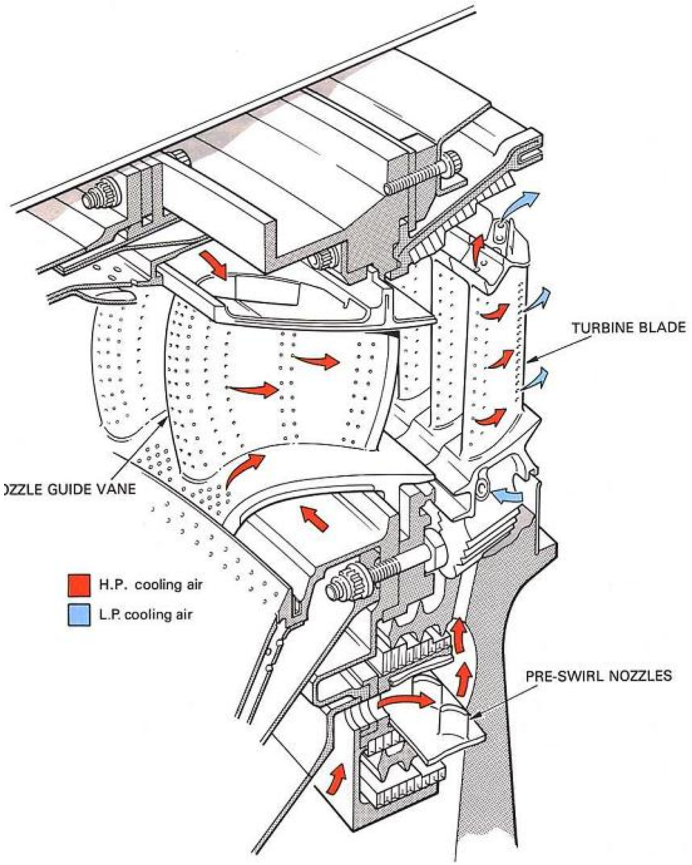
State-of-the-Art in Turbine Cooling – “Where are we now?”

Turbulated serpentine internal cooling passages





(Gupta et al., 2012)

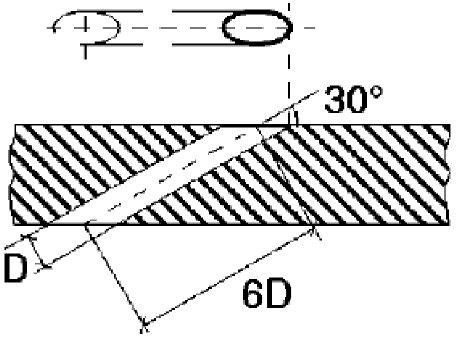


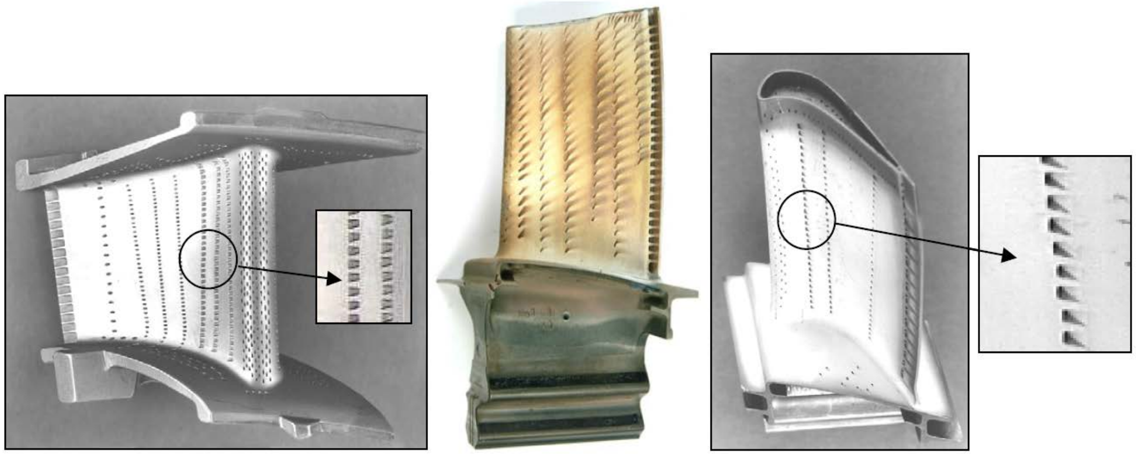
Double walled impingement cooling.

Film Cooling.

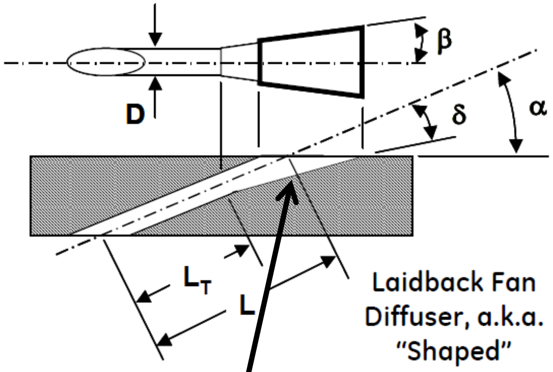
Motivation

State-of-the-Art in Turbine Cooling – “Where are we now?”



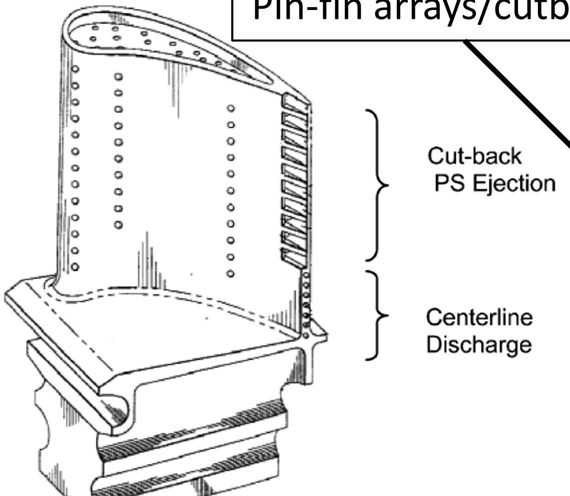


(from Bunker, IGTI2010)

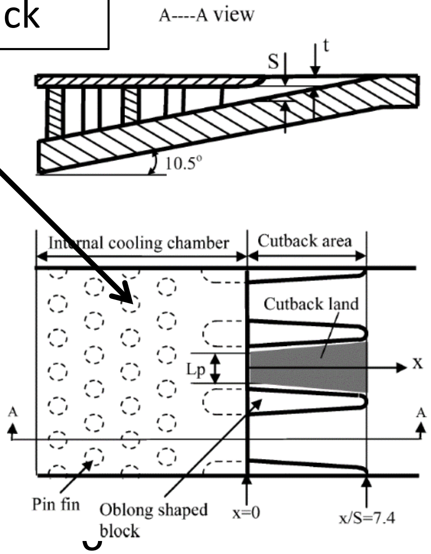


Shaped film holes

Pin-fin arrays/cutback



(from Cunha and Chyu, 2006)



Motivation

Current Manufacturing Process – Investment Casting

Lost wax

Ceramic cores

Motivation

Current Manufacturing Process – Laser Drilling and plunge EDM

Photo courtesy PRIMA/Laserdyne

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Critical Need

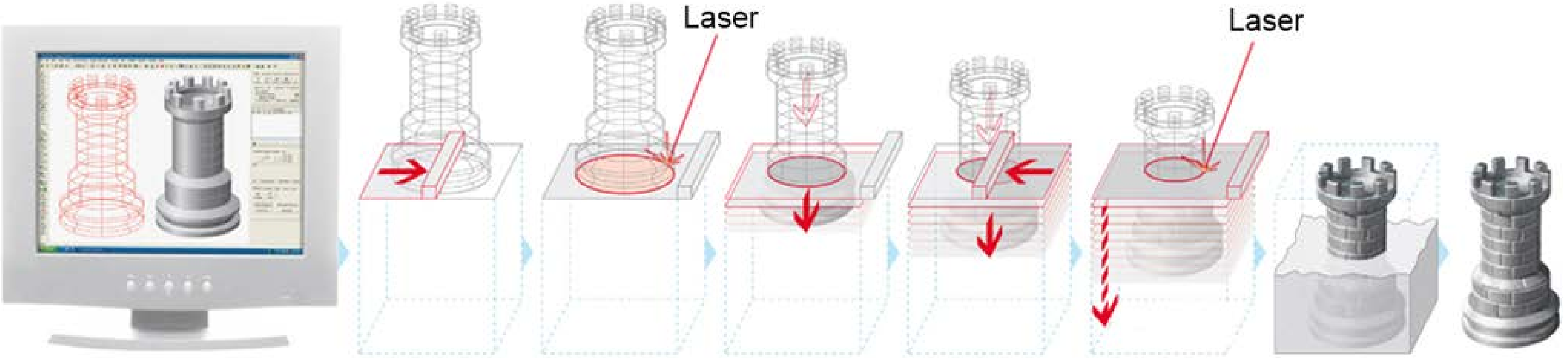
Topic #3 from the 2015 UTSR FOA: "The key goal of this topic area is to support the development of advanced internal cooling strategies including advanced impingement for airfoil cooling and advanced near wall cooling techniques. ….. The increased turbine inlet temperature likely required to achieve 65% combined cycle efficiency will further increase turbine component heat loads, requiring even more advanced, efficient, and effective cooling techniques. Therefore, research is needed in this topic area that can support manufacturers as they design hot gas path components with sufficient cooling capabilities."

DMLS

Where will these advances come from…

Direct Metal Laser Sintering

DMLS Process



3d Geometry model

layer of powdered material is applied to building platform

Powdered material is solidified into a cross-section of a model with laser

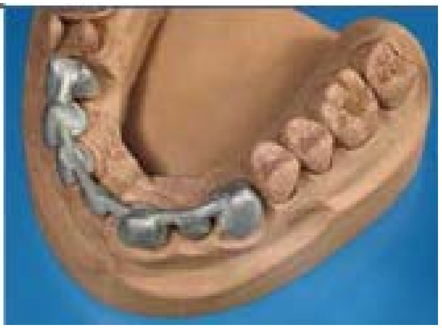
Building Platform is lowered

The next layer of powder is applied

The process repeats itself until the part is complete

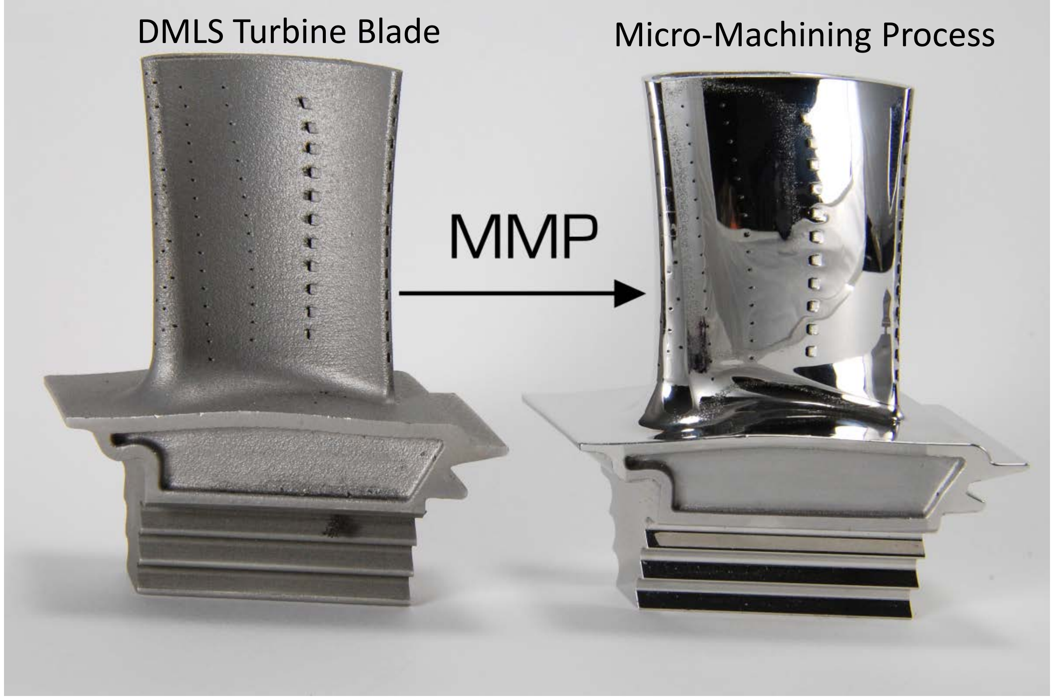
Unused powder is removed

Finished Part

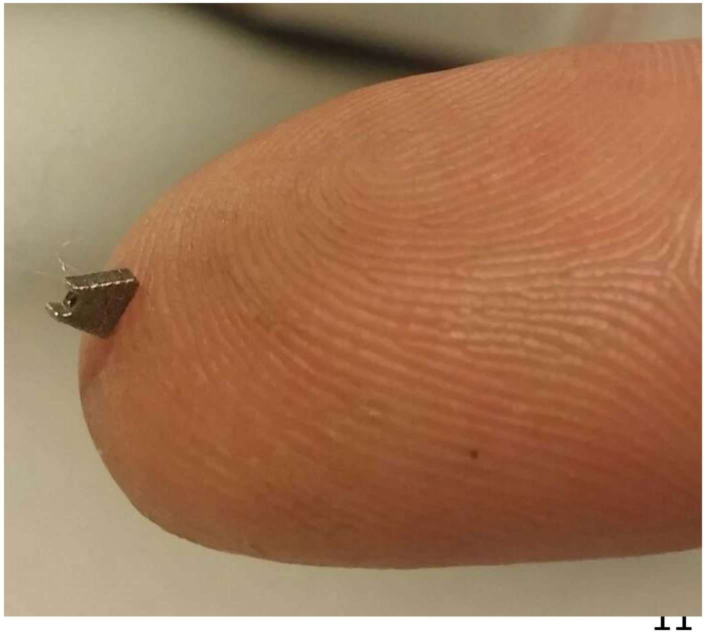




Direct Metal Laser Sintering

Can you fabricate a cooled turbine blade with DMLS?



Just how small can the features be?



Direct Metal Laser Sintering

QUOTES FROM UTSR WORKSHOP – TUESDAY A.M.

"To take advantage of additive manufacturing, you need to start with the design." - Bill Brindley, Pratt & Whitney

"DMLS enables novel designs." - Karl Wygant, Samsung Techwin America

"Challenges become opportunities!" – David Teraji, Solar Turbines

"Additive manufacturing moving from nicety to necessity." – Boeing

"Manufacturing as an enabler rather than as a burden." - Sanjay Sampath, Stony Brook University

"Ability to make macroscale parts with microscale features." Suman Das, Georgia Tech

Objectives

- Explore innovative cooling architectures enabled by additive manufacturing techniques for improved cooling performance and reduced coolant waste.
- Leverage DMLS to better distribute coolant through microchannels, as well as to integrate inherently unstable flow devices to enhance internal and external heat transfer.
- Demonstrate these technologies
    1. at large scale and low speed.
    2. at relevant Mach numbers in a high-speed cascade.
    3. finally, at high speed and high temperature.
- Complement experiments with CFD modeling to explore a broader design space and extrapolate to more complex operating conditions.

Research Team

TEAM LEAD
Focus: Experimental Fluid Mechanics and Heat Transfer

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Co-PI
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Arif Hossain
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Co-PI
Focus: Experimental Fluid Mechanics, Fluidic Oscillator Development

Dr. Jim Gregory
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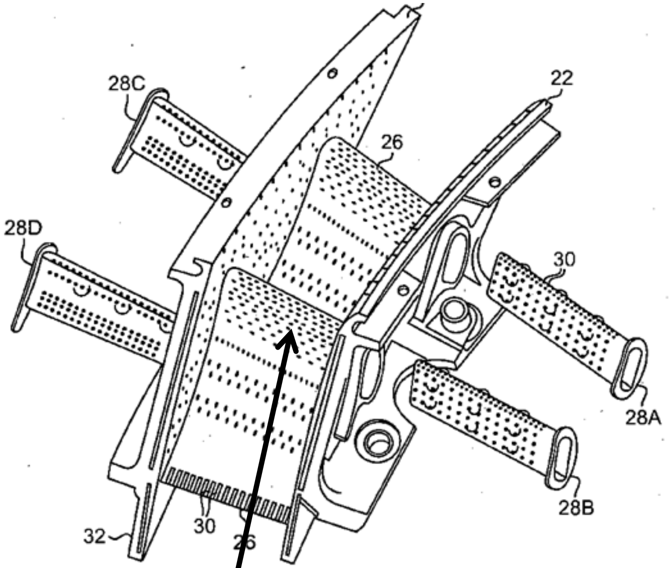
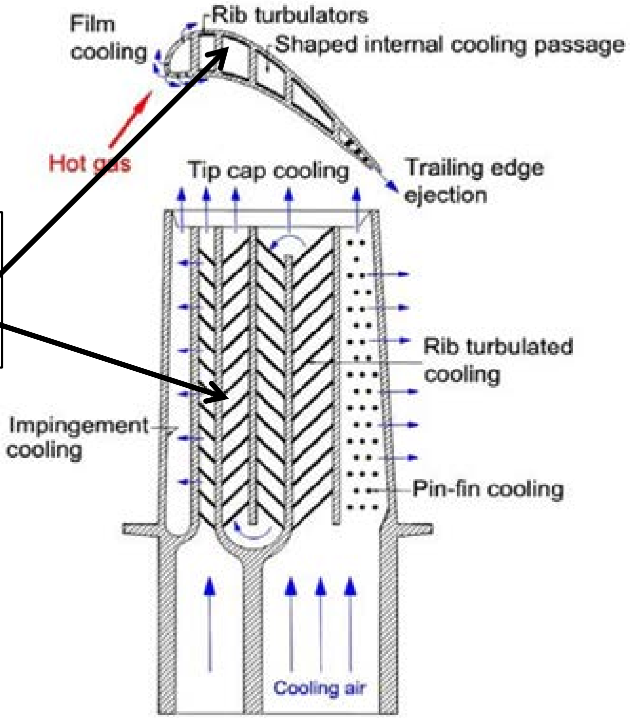
Ohio State University
Columbus, OH

Cooling Designs Enabled by DMLS



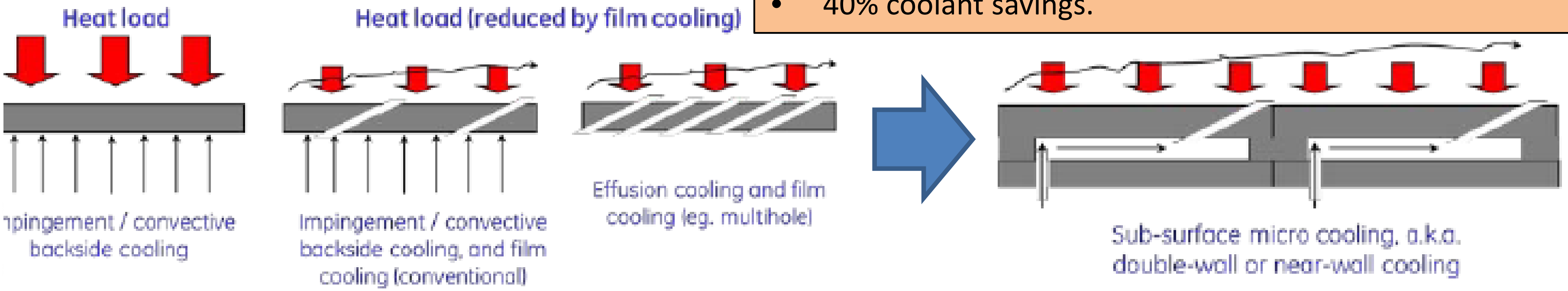
All film cooling holes fed from the same reservoir – YET not all regions NEED the same coolant flowrate!

Blade is cooled from the center – YET only surface needs cooling!



Bunker (IGTI 2013) showed that "<u>skin cooling</u>" could yield

- 25% cooling flow reductions
- 50% thermal gradient (stress) reductions.
- 40% coolant savings.



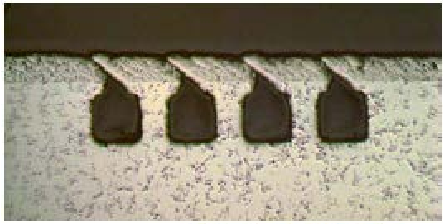
pingement / convective backside cooling

Impingement / convective backside cooling, and film cooling (conventional)

Effusion cooling and film cooling (eg. multihole)

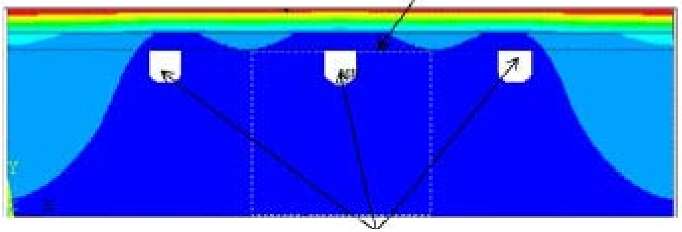
Sub-surface micro cooling, a.k.a. double-wall or near-wall cooling

Cooling Designs Enabled by DMLS



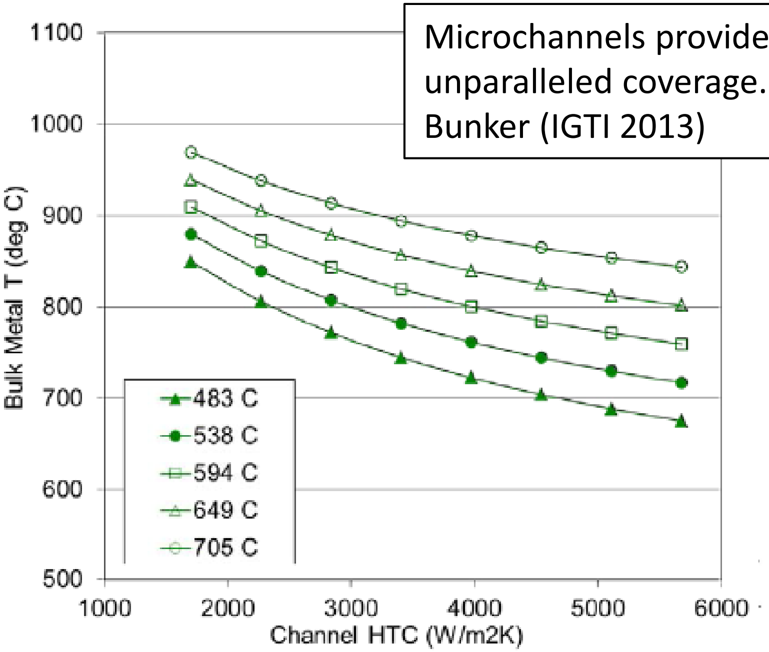
H_g = 2837 W/m2/K
T_g = 1260°C; P_g =17 atm
(T_g is the film temperature)

Substrate Bulk T averaging region inside box

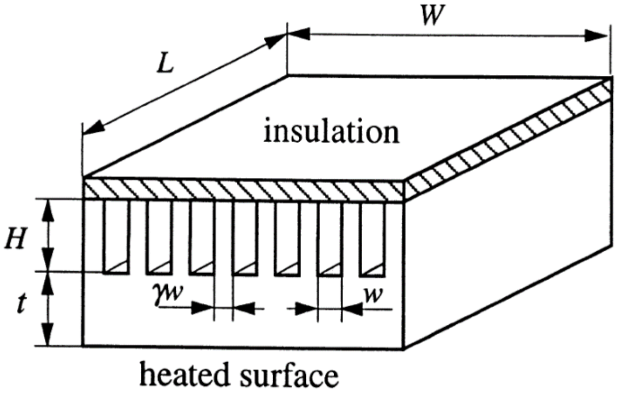


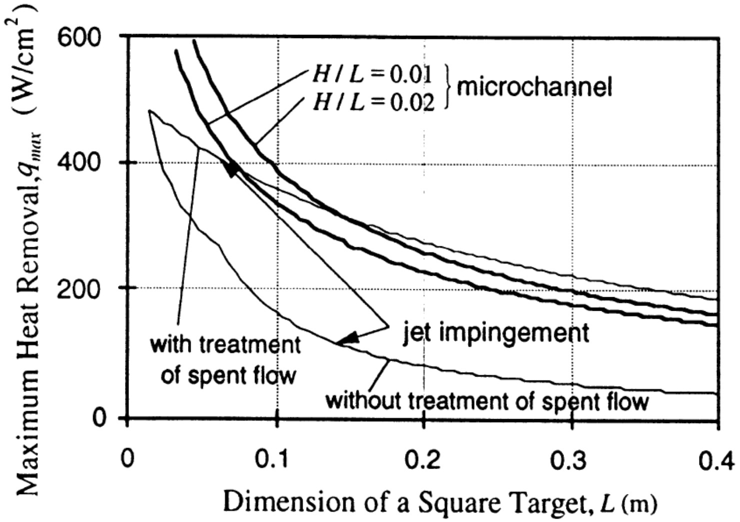
0.51 mm TBC
0.38 mm NiCrAlY bondcoat

3.43 mm Ni alloy substrate



Microchannels provide unparalleled coverage. Bunker (IGTI 2013)

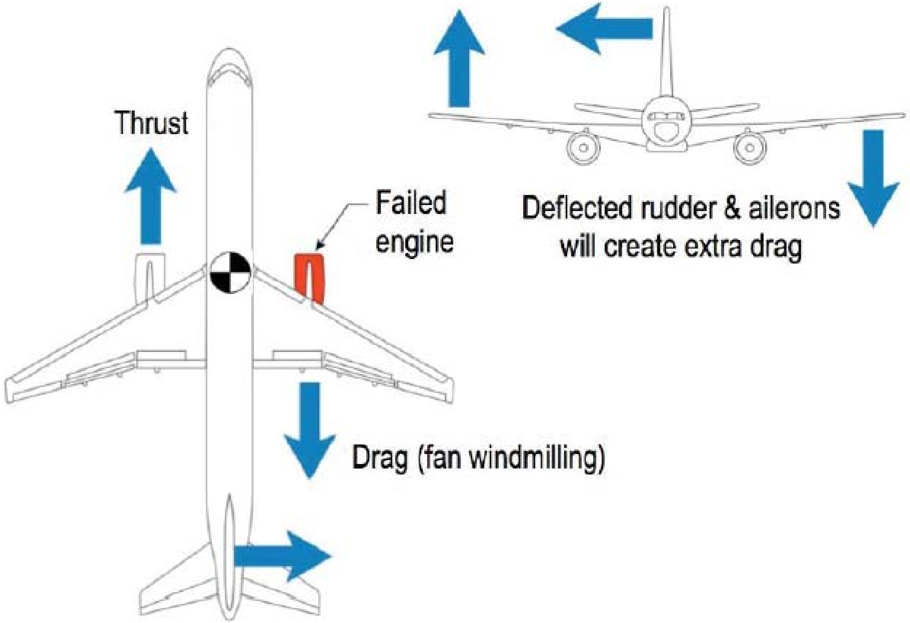


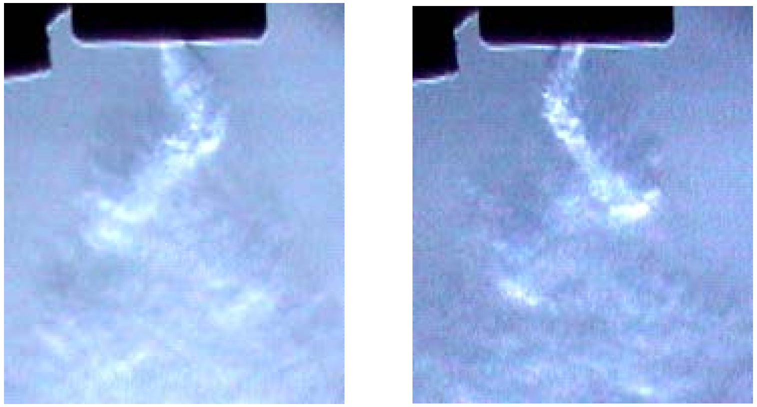


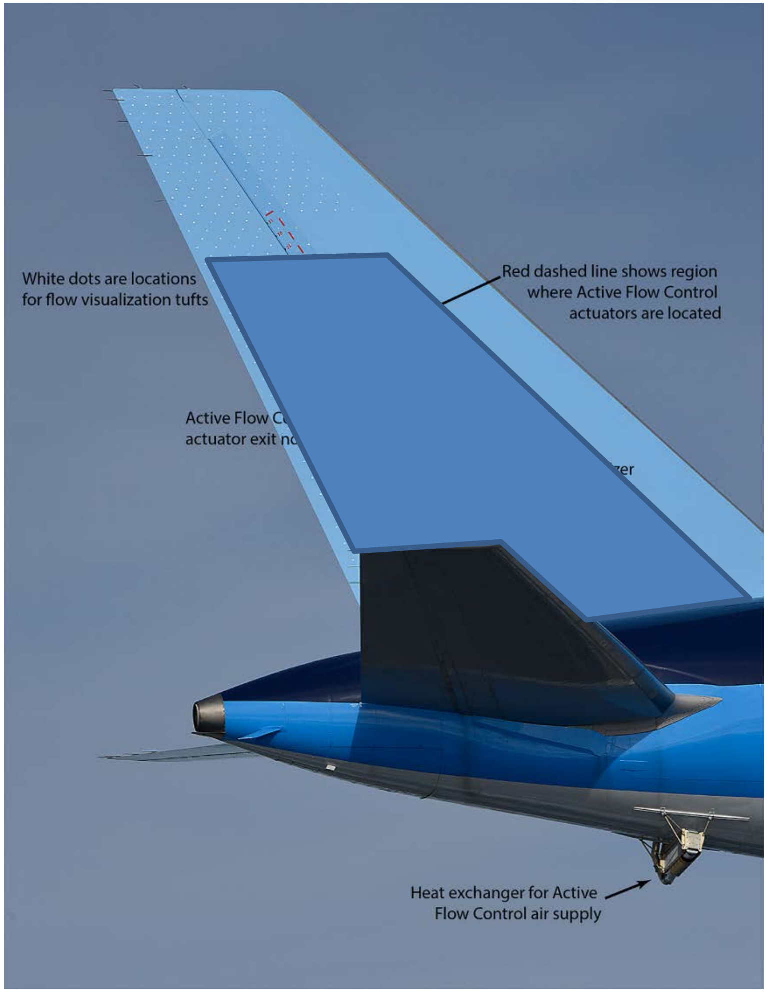
Lee and Vafai (IJHMT 1999) showed microchannel cooling is superior to backside jet impingement cooling

Cooling Designs Enabled by DMLS

Sweeping Fluidic Oscillators for flow control



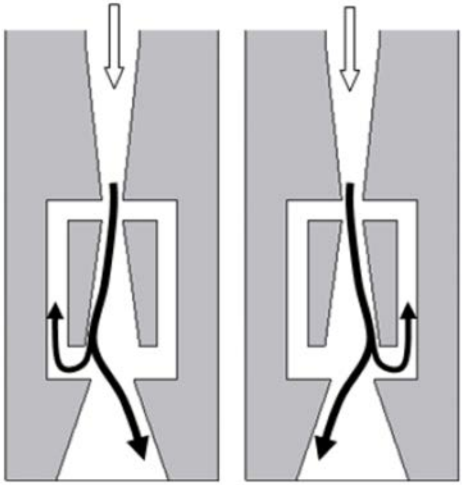




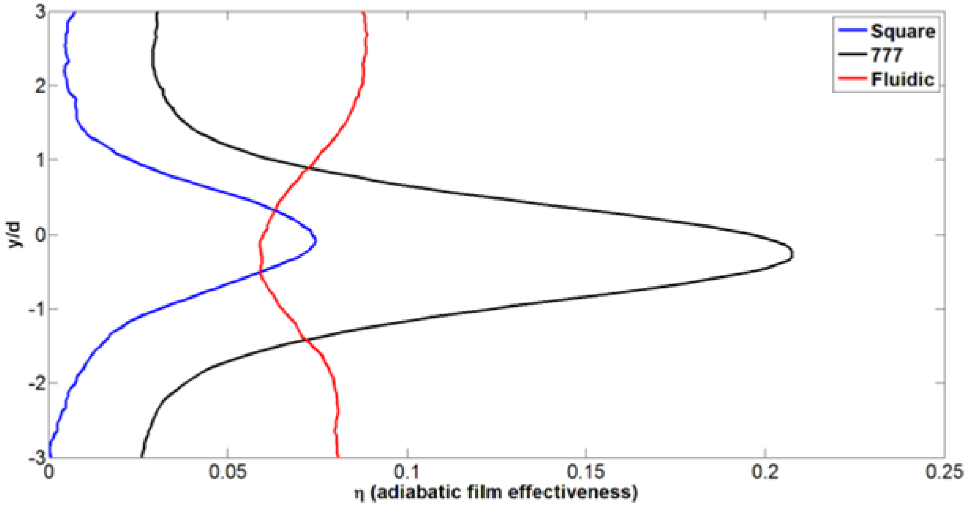
…and many other applications…

Cooling Designs Enabled by DMLS

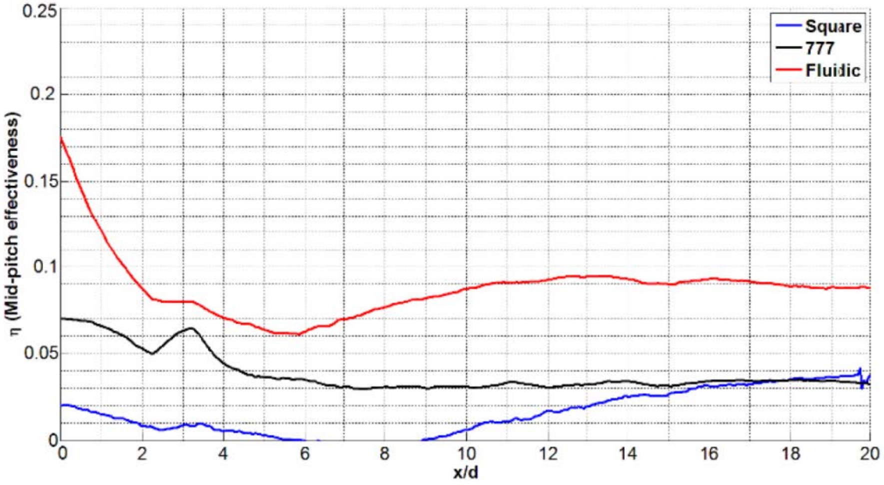
Sweeping Fluidic Oscillators

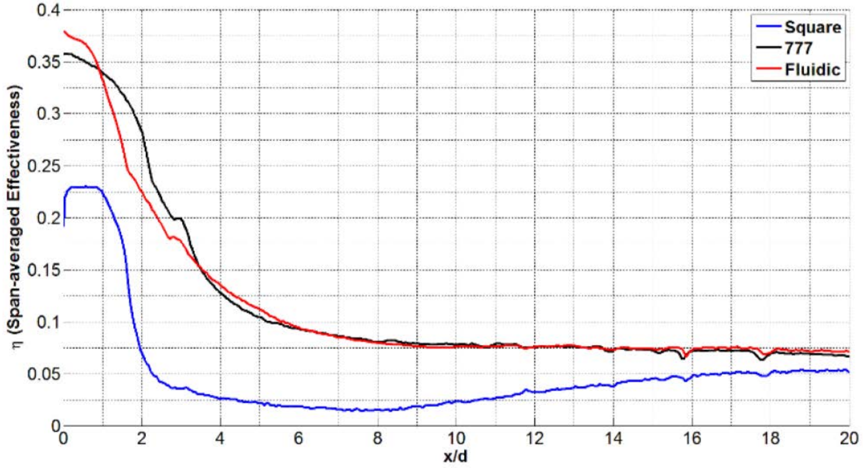


Thurman et al. (IGTI2015) experimentally studied application to film cooling.

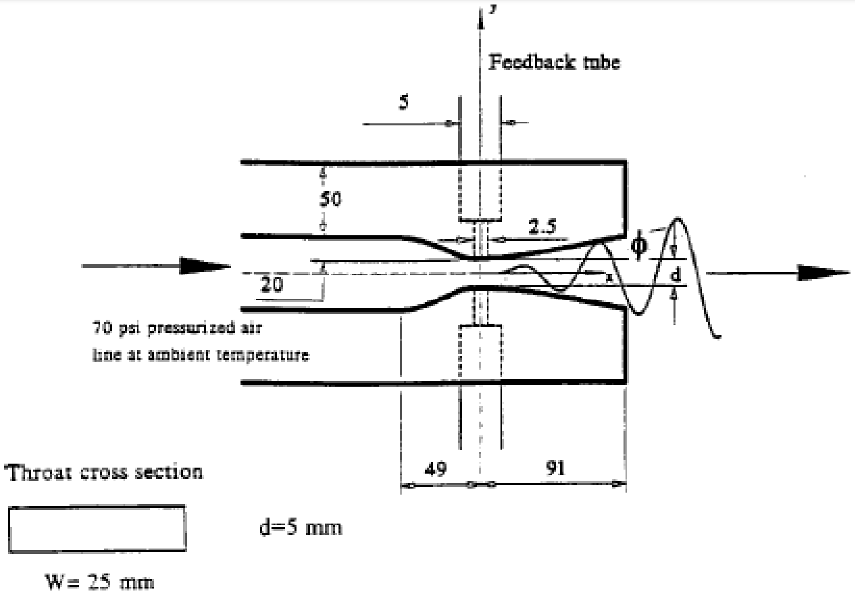


Sweeping film cooling yields higher midpitch film effectiveness. More uniform coverage.



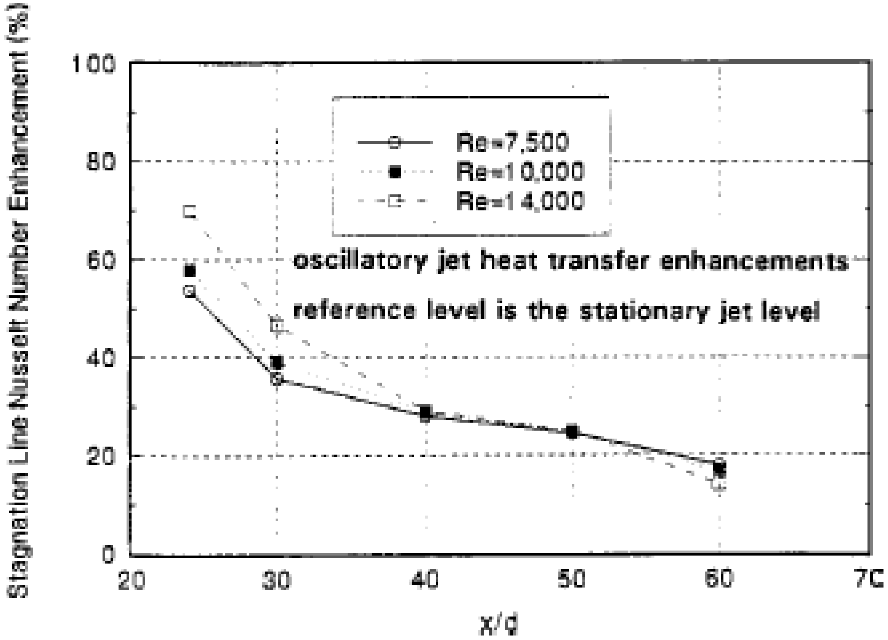


Cooling Designs Enabled by DMLS

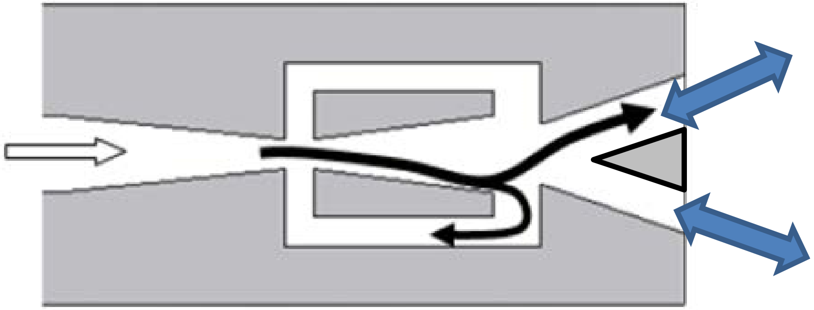


Pulsed impingement cooling jet (Camci & Herr, JHT 1999)

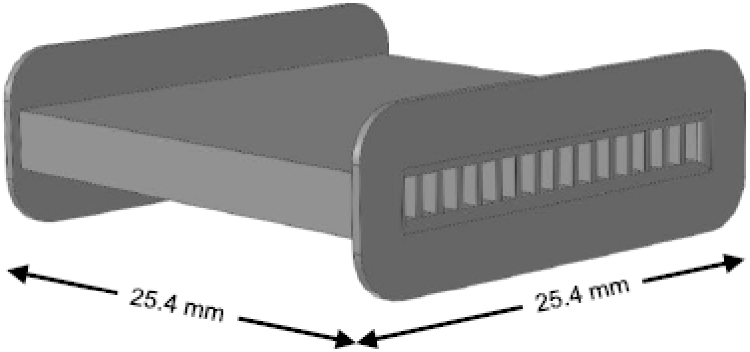
- 40-60% heat transfer enhancement compared to steady jets for x/d<30
- No external input required to produce oscillation



Pulsing Fluidic Oscillators (Gregory)



Potential Concerns with DMLS



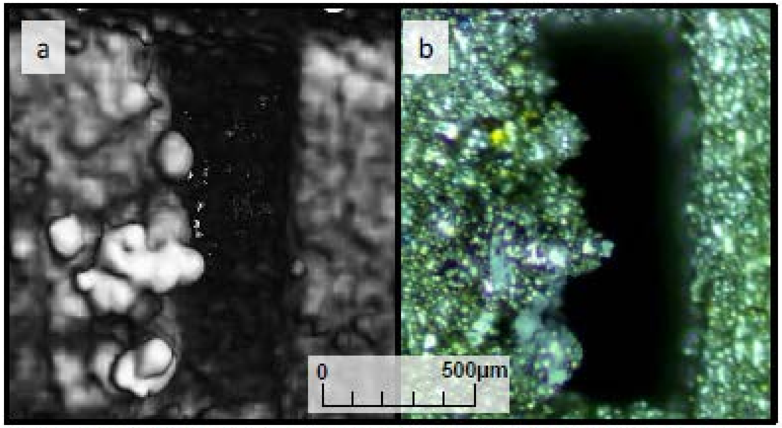
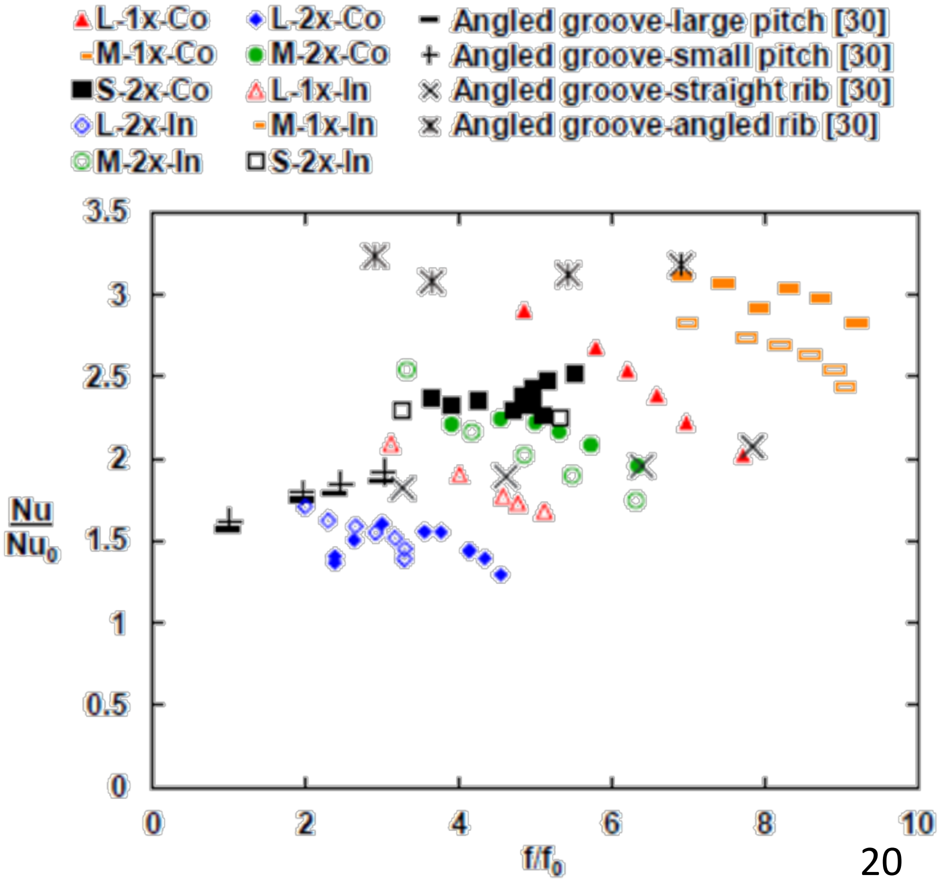


Figure 5. Image of the opening of a single channel of the M-2x-Co coupon a) digitally reconstructed from CT scan data and b) collected with a light microscope.

Stimpson et al. (IGTI2015)

- Microchannel array – additive manufacturing.
- Elevated roughness levels
- High pressure drop for same heat transfer augmentation
- Natural “roughness” obviates need for ribs.



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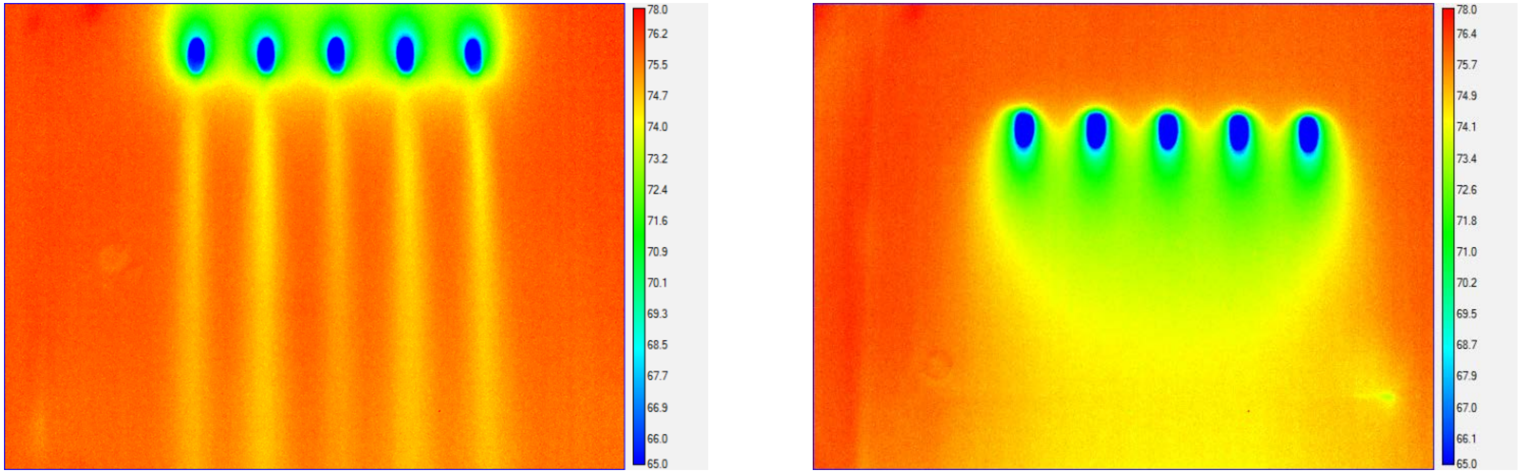
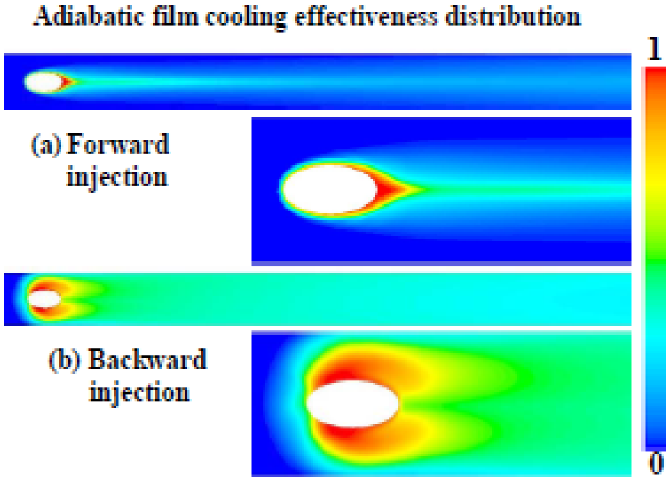
Innovative Cooling Designs

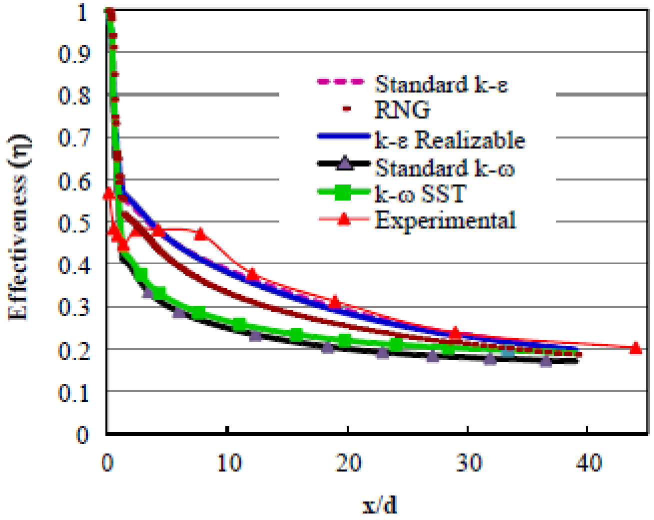
Reverse Film Cooling



IR Images of Surface Temperature (Ameri and Shyam, unpublished 2015)

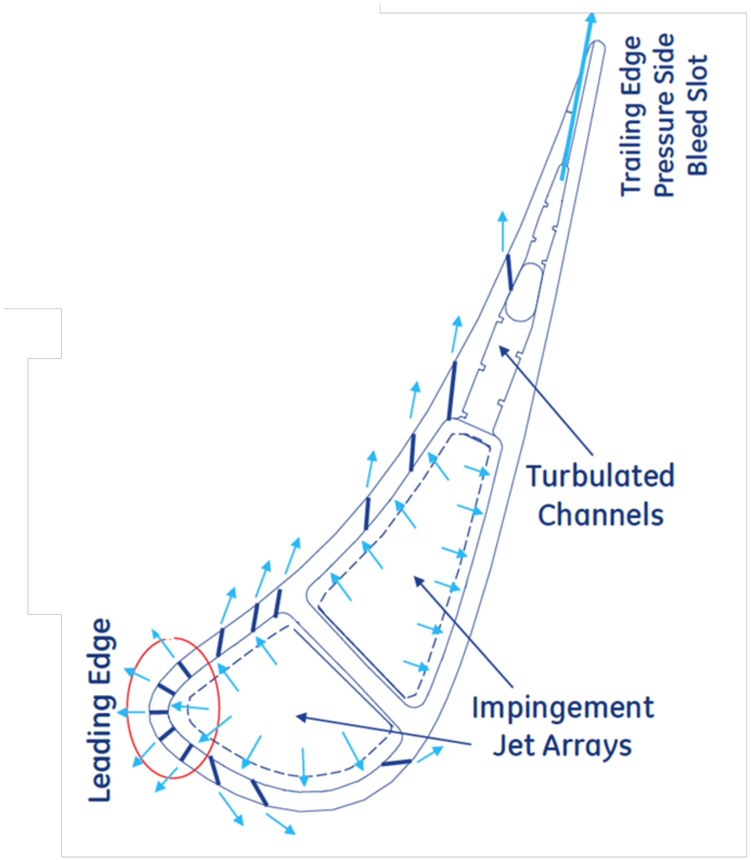
Calculation vs. Experiment (Li et al., Energy and Power 2013)





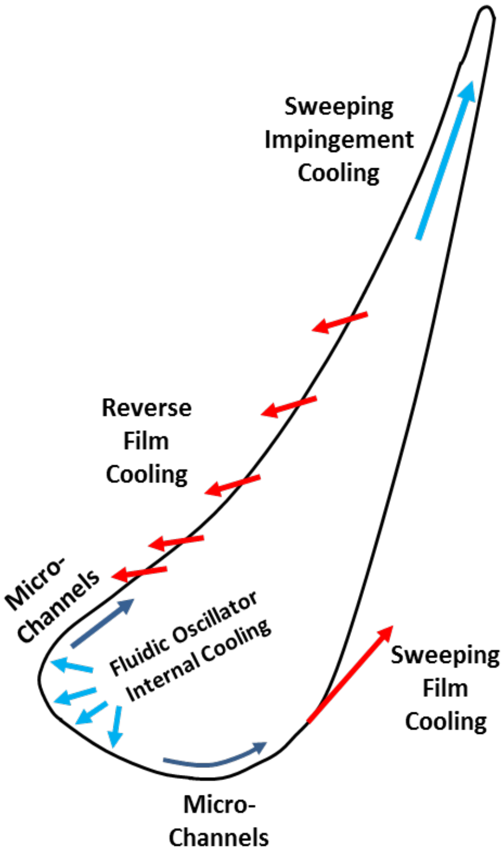
Innovative Cooling Designs

Combine all promising technologies on single NGV.



(a)

(Bunker, IGTI 2013)



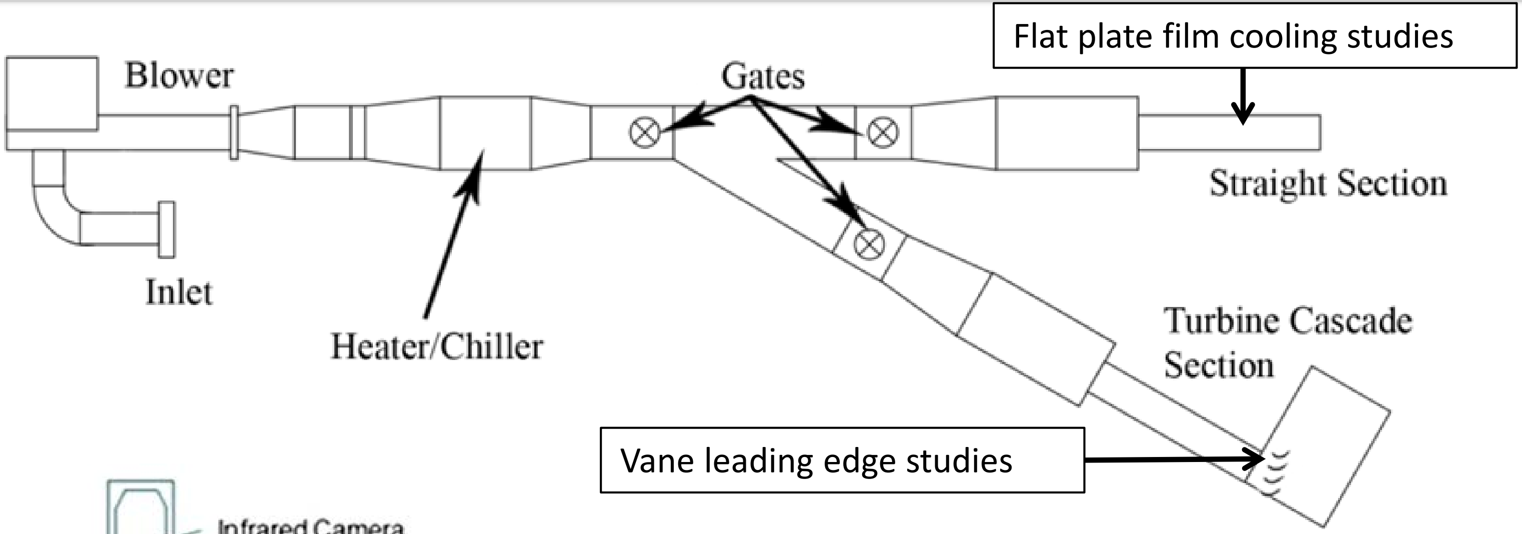
(b)

(Notional DMLS NGV Model)

Turbine Heat Transfer Facilities

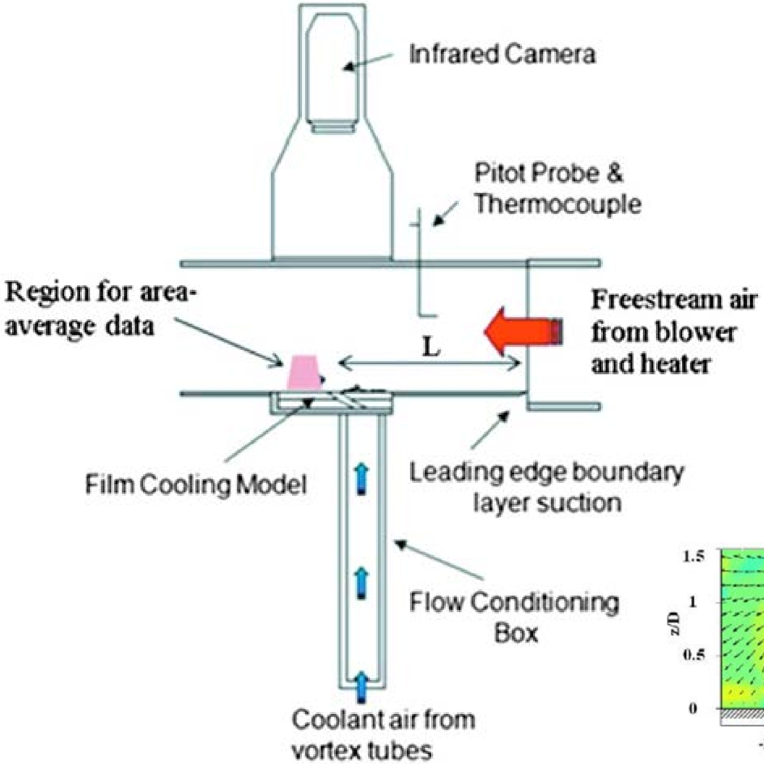
- For innovative concepts to be viable, must be vetted in facilities that simulate the real operating environment
- Graduated complexity
  - Low speed, large scale
  - High speed, smaller scale
  - High speed, high temperature, small scale

Low Speed Large Scale Tunnel

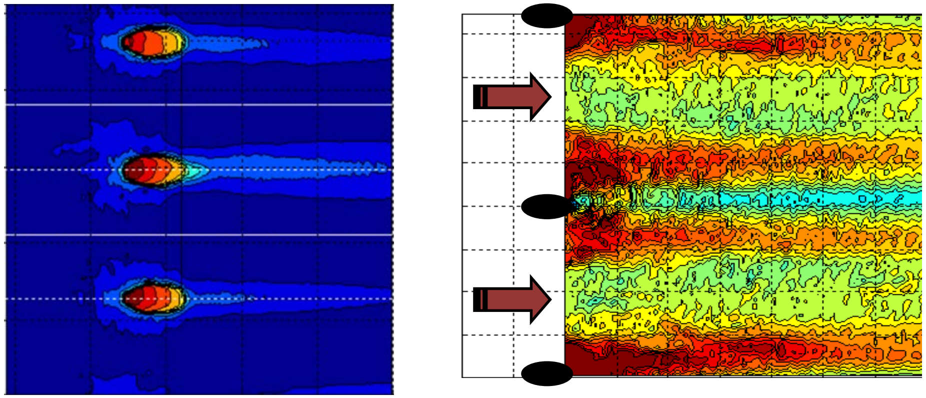


Flat plate film cooling studies

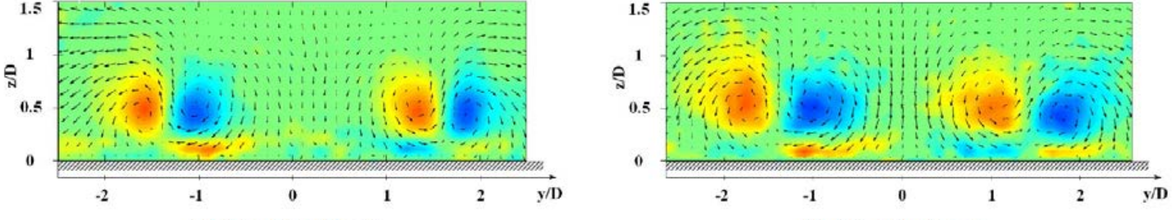
Vane leading edge studies



IR Camera provides film effectivenes and heat transfer



PIV for velocity field and vorticity (shown below)

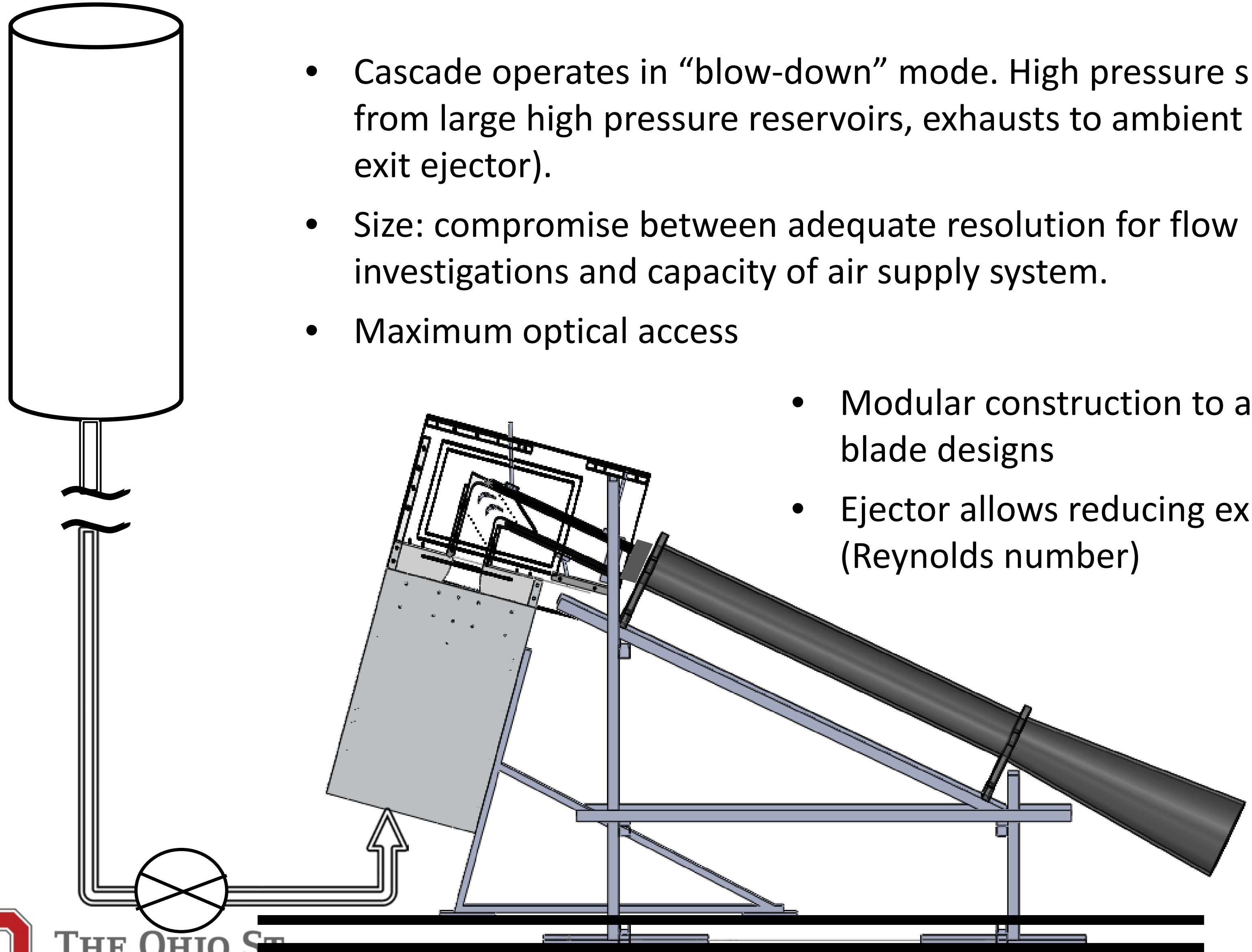


(c) $Tu = 0.7, x/D = 7$

(d) $Tu = 10, x/D = 7$

Transonic Turbine Cascade

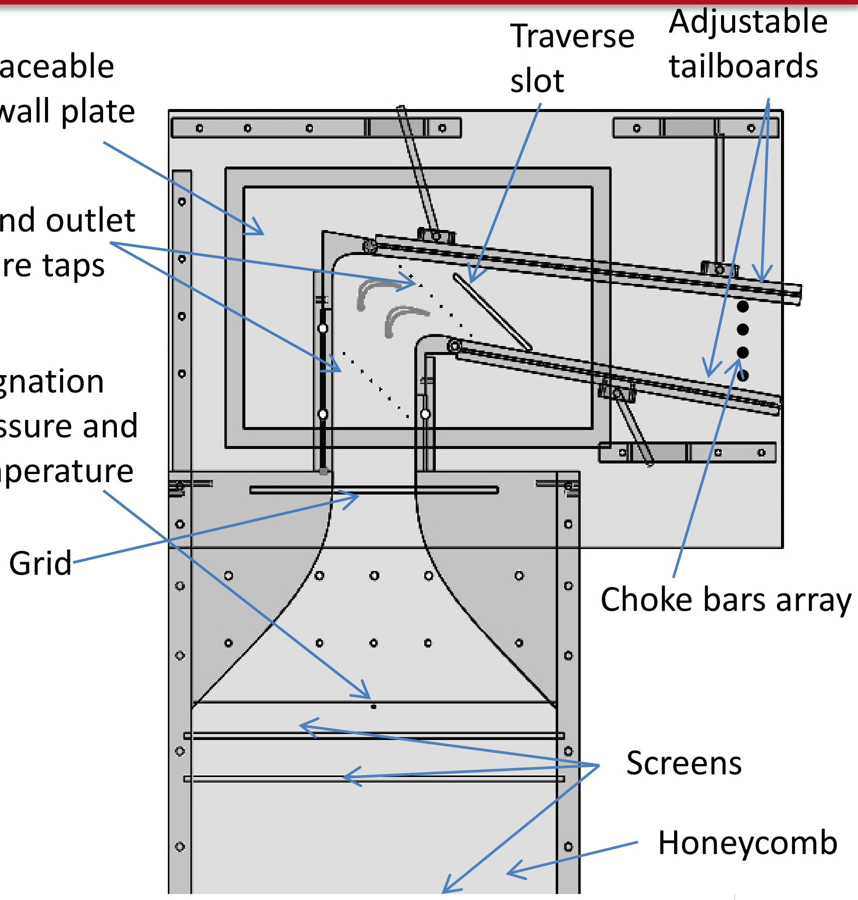
- Cascade operates in “blow-down” mode. High pressure supplied from large high pressure reservoirs, exhausts to ambient (without exit ejector).
- Size: compromise between adequate resolution for flow investigations and capacity of air supply system.
- Maximum optical access

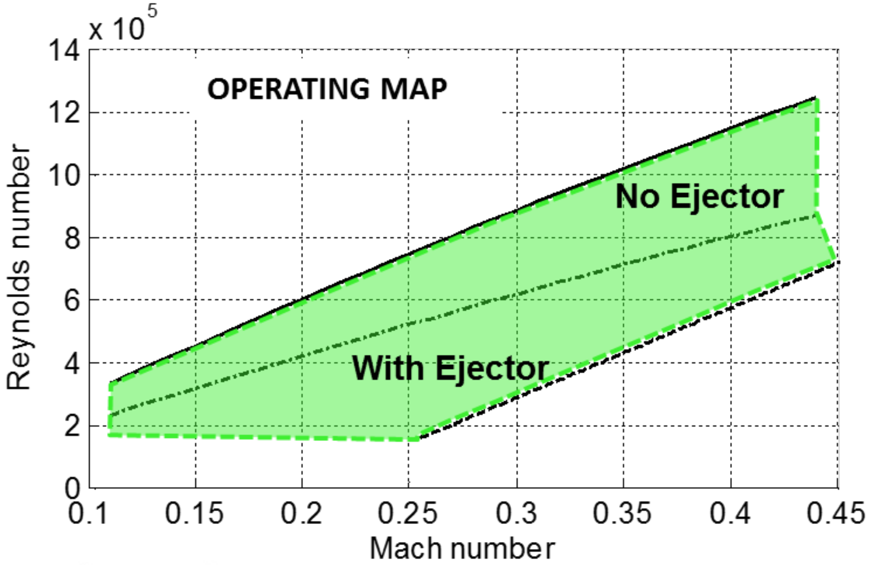


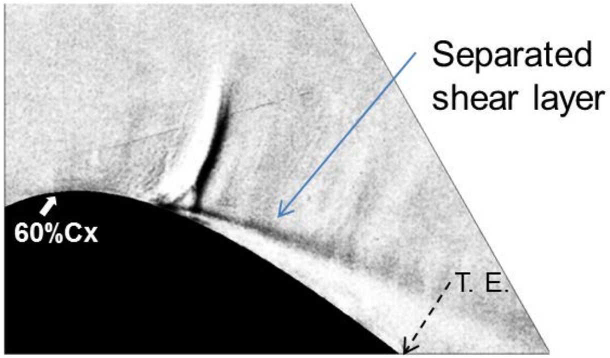
- Modular construction to allow new blade designs
- Ejector allows reducing exit pressure (Reynolds number)

Transonic Turbine Cascade

- Adjustable tailboards to insure periodicity
- Choked bar array in exit duct insures Mach number distribution in the cascade independent of Reynolds number
- Flow conditioned by screens and honeycomb: 4.4:1 contraction: inlet flow uniformity 1.5%. Tu = 1%
- Tu augmented with upstream passive grids
- Inlet and exit wall pressure taps
- Traverse slot for wake surveys

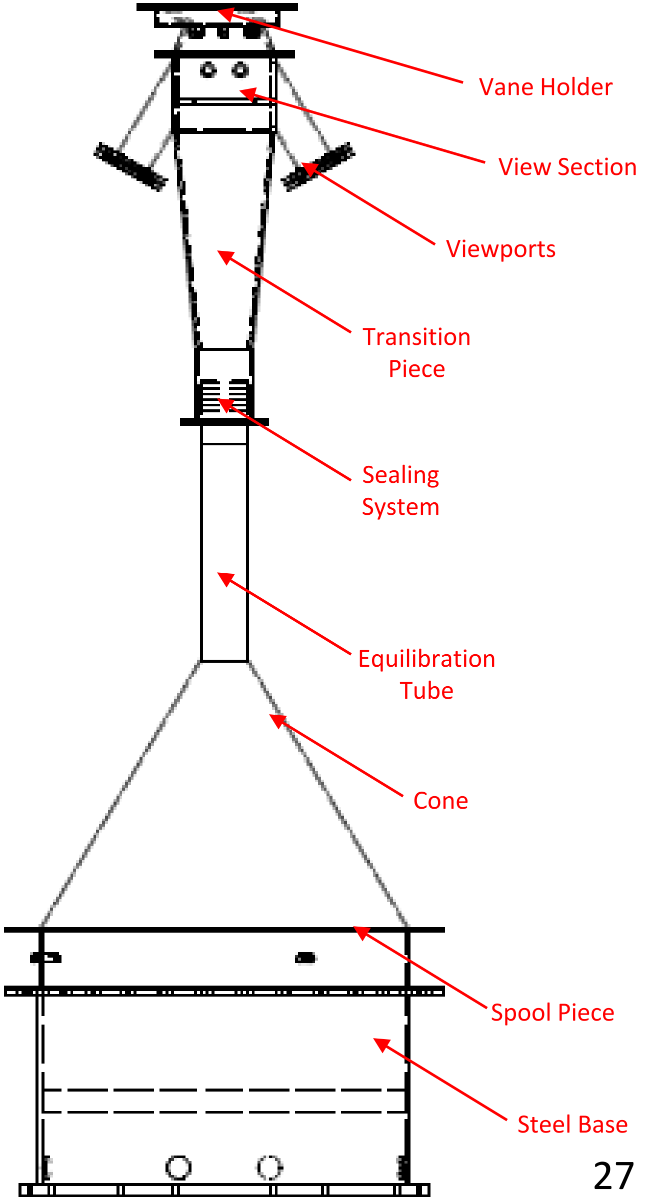






Turbine Reaction Flow Rig (TuRFR)

- Natural gas burning combustor rig
- Combustor exit flow accelerated in cone nozzle
- Transition from circular to annular sector
- Real vane hardware (industry supplied) installed in annular cascade sector
- Tt4 up to 1120°C (2050°F)
- Inlet Mach number ~ 0.1
- $300,000 < Re_{cex} < 1,000,000$
- Adjustable inlet temperature profiles
- Adjustable inlet turbulence profiles (through dilution jets)
- Film cooling from vane casing and hub (density ratio 1.6-2.0)



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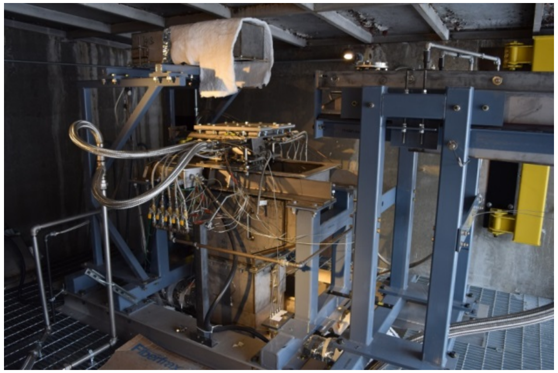
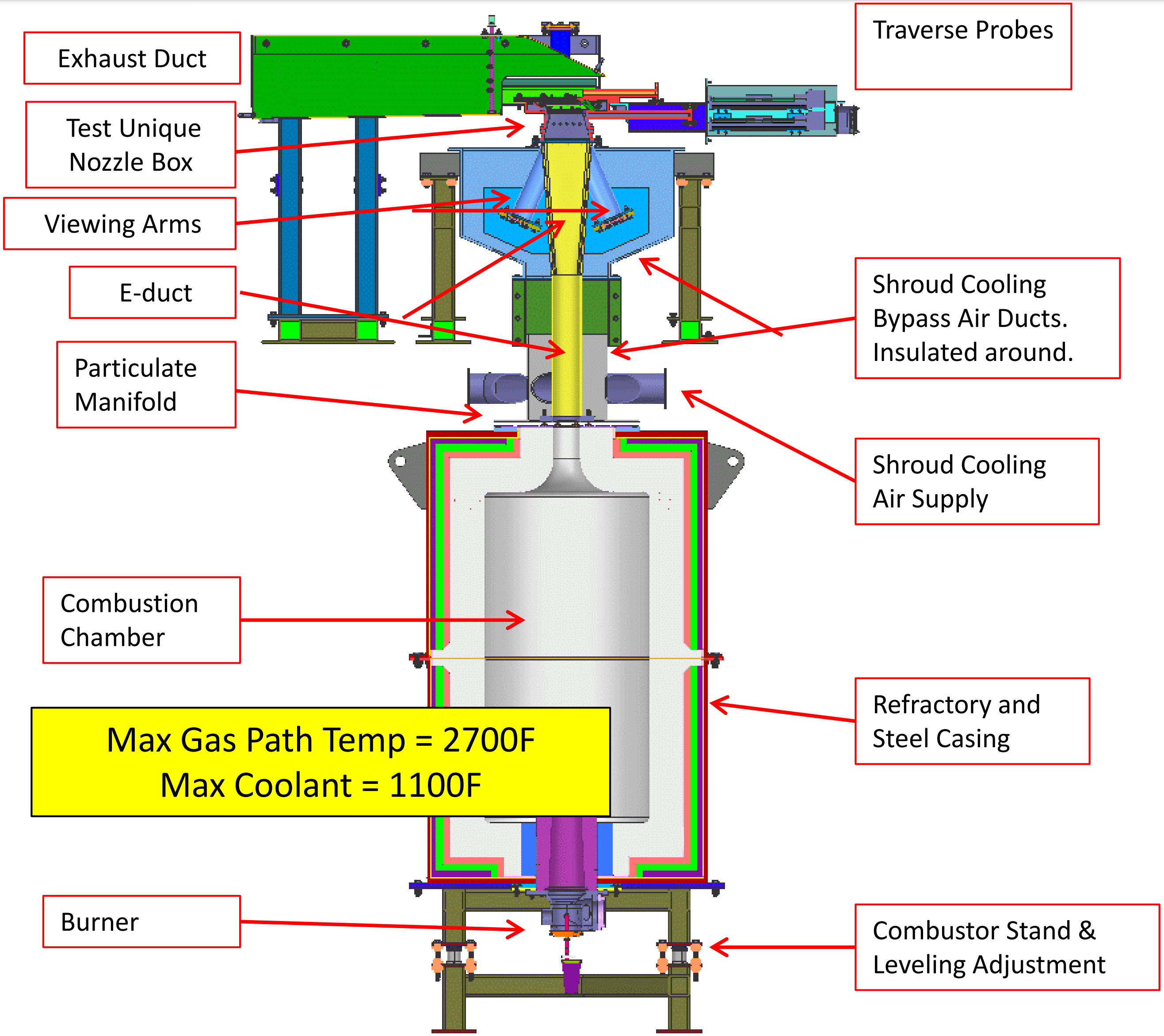
TuRFR II





Exhaust Duct

Test Unique Nozzle Box

Viewing Arms

E-duct

Particulate Manifold

Combustion Chamber

Max Gas Path Temp = 2700F
Max Coolant = 1100F

Burner

Traverse Probes

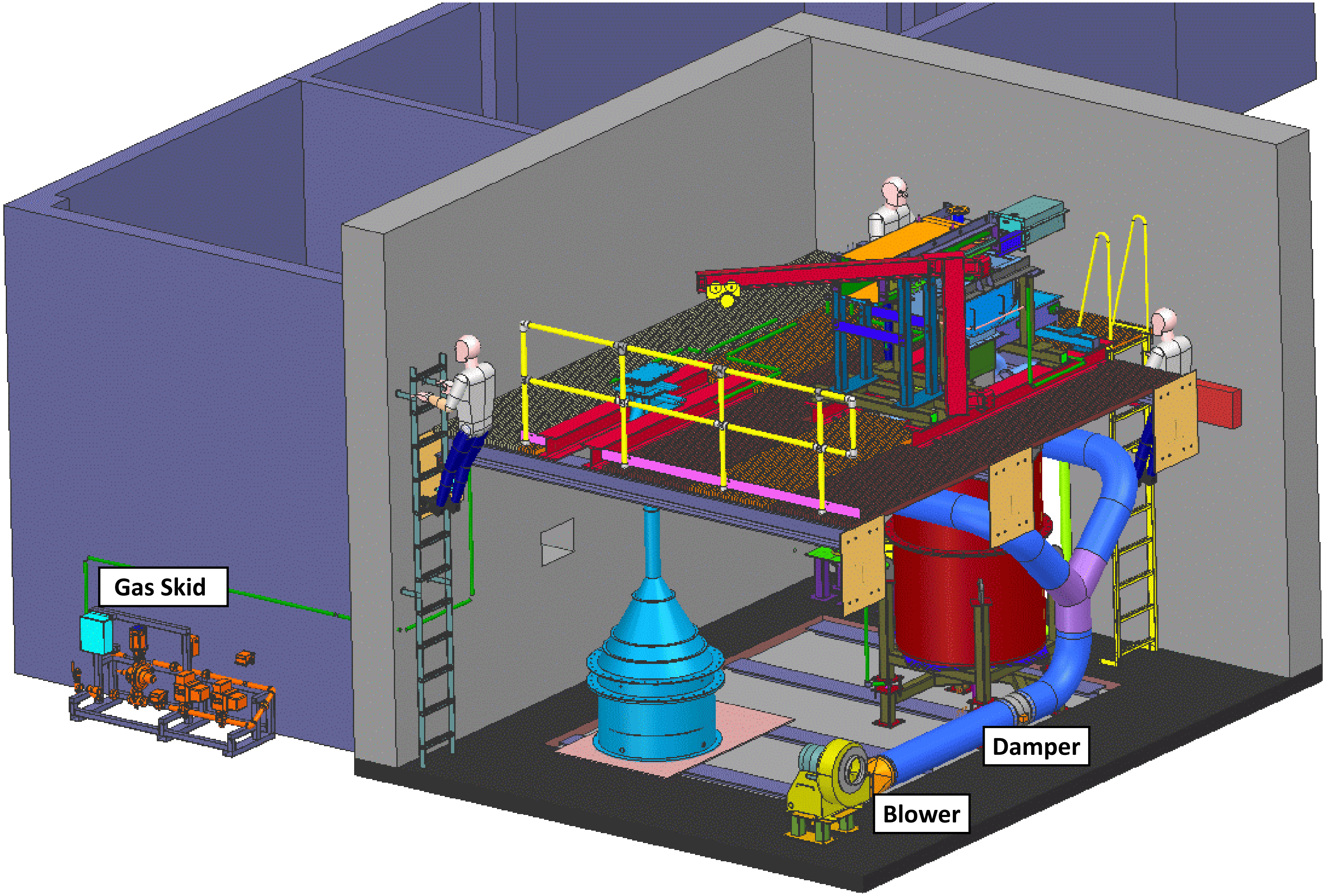
Shroud Cooling Bypass Air Ducts. Insulated around.

Shroud Cooling Air Supply

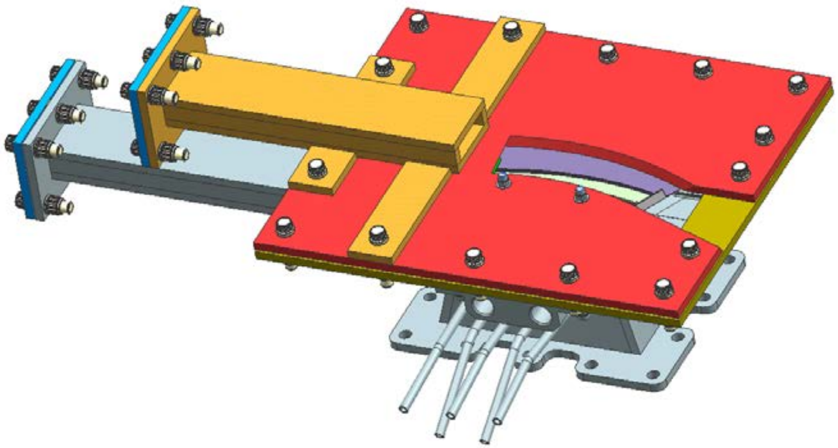
Refractory and Steel Casing

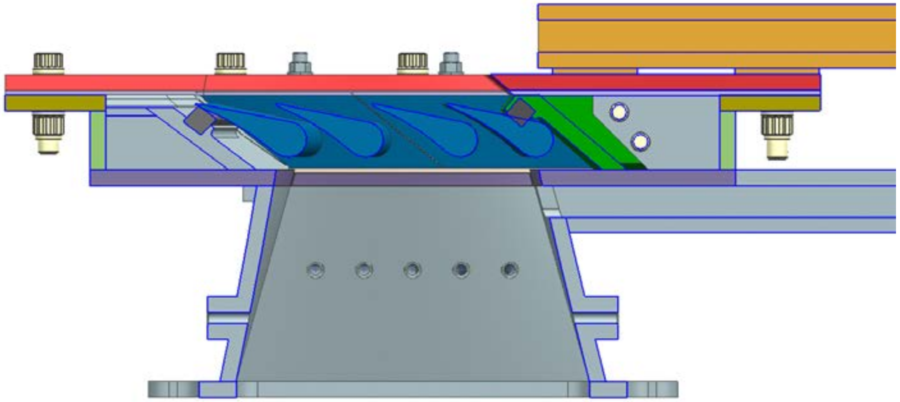
Combustor Stand & Leveling Adjustment

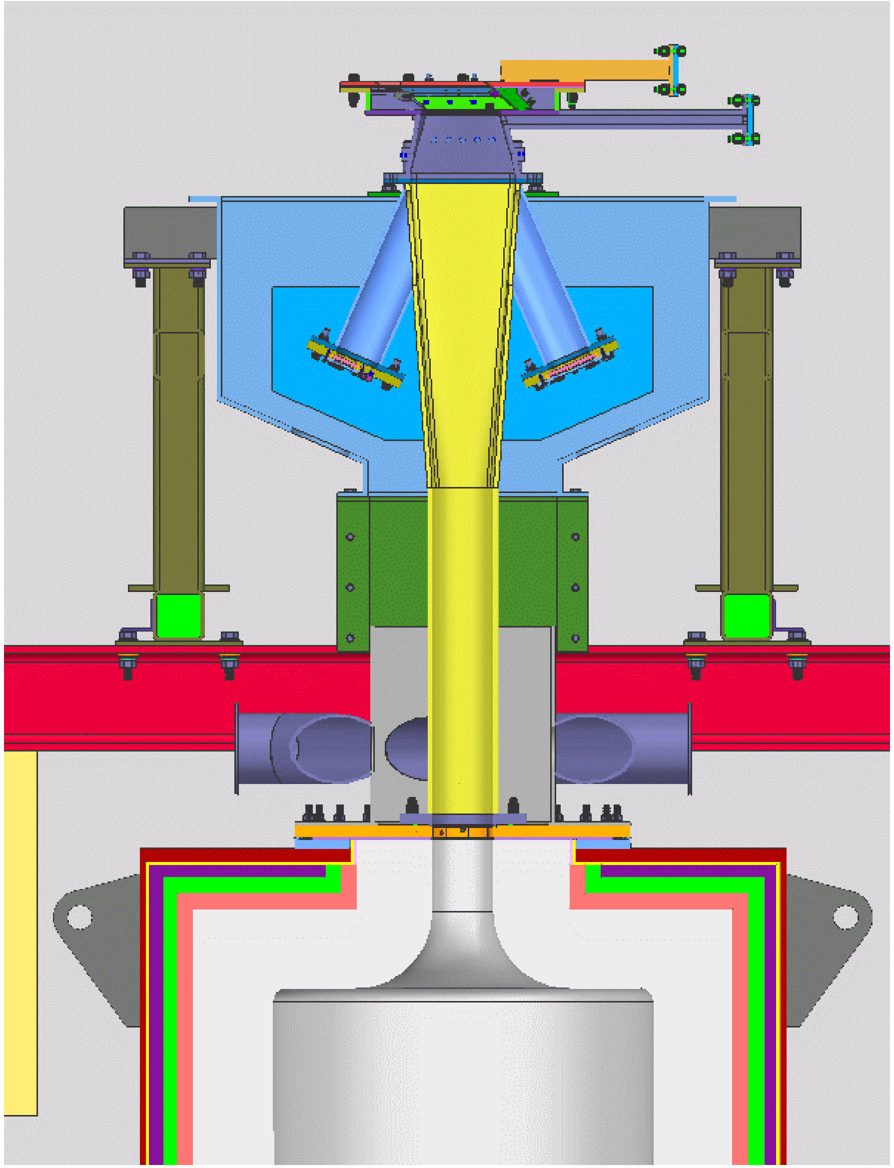
TuRFR I & II



TuRFR II

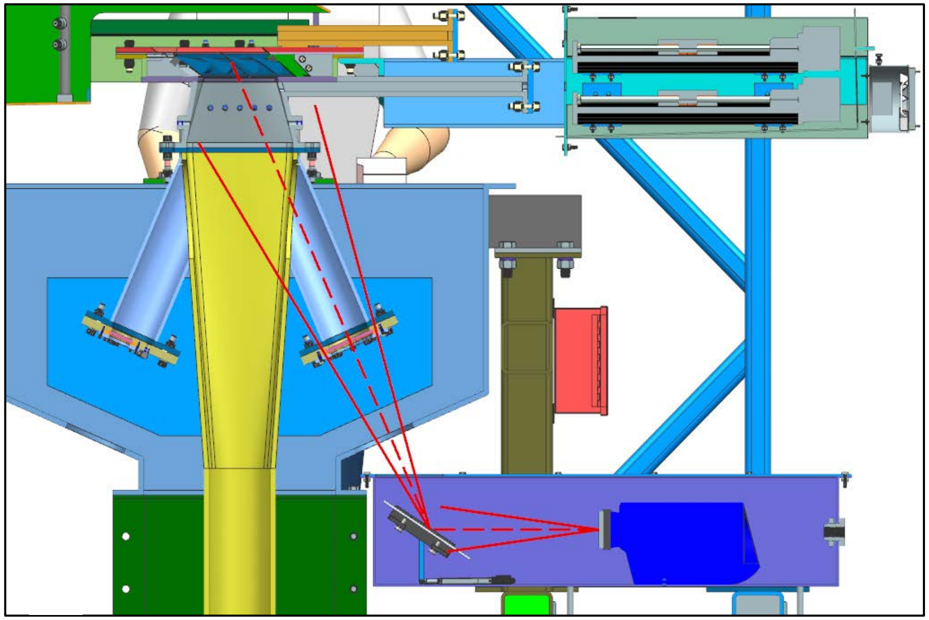




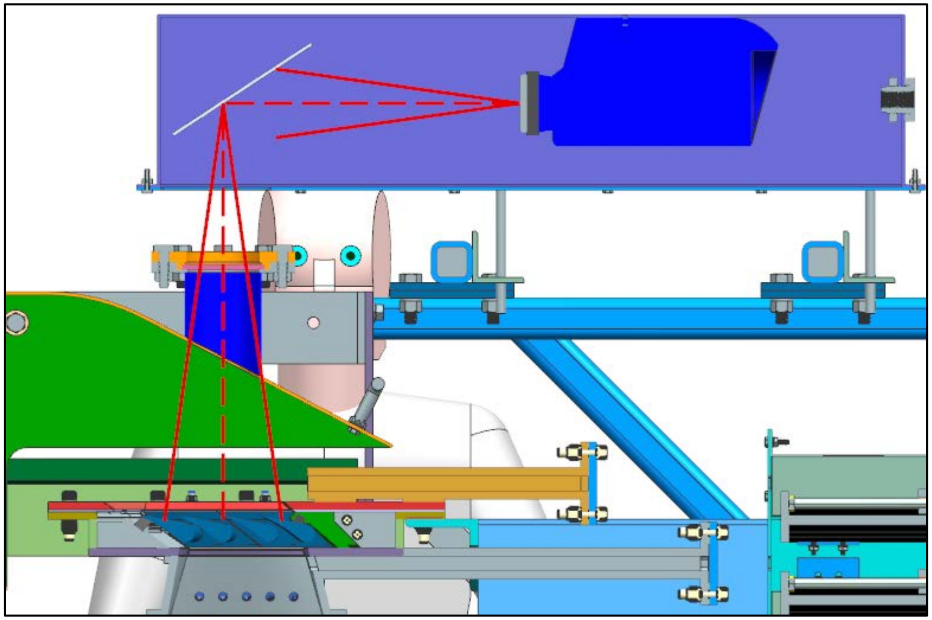


Optical Access

CAMERA IN LOWER POSITION



CAMERA IN UPPER POSITION



PHASE 1: Concept Exploration

- Use available literature to identify most promising cooling designs:
    - Pulsed fluidic oscillators for internal cooling of leading and trailing edges
    - Sweeping fluidic oscillators for external film cooling
    - Reverse flow film cooling from microchannel circuits for pressure surface
    - Microcooling circuits replace showerhead cooling
- Low-speed wind tunnel testing with scaled geometry
    - Characterize cooling effectiveness and heat transfer
    - Test variants of geometry to determine optimum
    - Test sensitivity of each design to manufacturing tolerances
- Develop computational models of each cooling design
    - Generate flow solutions for each initial geometry
    - Validate solutions with experimental data from initial geometry
    - Explore design space and aid in optimization of geometry for each design
- Determine most promising and feasible technologies for Phase 2 based on experimental and computational results

PHASE 2: Integrated SLA Vane

- Implement most promising technologies into preliminary nozzle guide vane design
- Develop computational model of preliminary vane design in high-speed cascade
- Generate flow solutions at various operating conditions
- Modify preliminary vane design per computational results
- Fabricate properly scaled plastic vanes with stereolithography (SLA) using modified design
- Test fabricated vanes in high-speed cascade
  - Characterize flow and heat transfer at various operating conditions
  - Determine compressibility effects
- Validate flow solution using experimental data
- Iterate back to low speed testing as necessary
- Generate flow solutions for final Phase 3 design at higher inlet Mach numbers and Reynolds numbers

PHASE 3: Fully Simulated NGV

- Fabricate high-temperature alloy vane using DMLS (e.g. EWI)
- Coat vane in thermal barrier coating (TBC)
- Characterize surface roughness and tolerances due to manufacturing method
- Test full material system in the TuRFR turbine test facility
  - Characterize cooling performance and pressure drop at various coolant mass flow rates
  - Characterize cooling performance at various main flow conditions
- Compare new vane design performance to conventional vane at same coolant and main flow operating conditions to determine improvement
- Develop computational model of coated NGV
  - Generate and validate flow solution in context of TuRFR testing
  - Generate simulations at higher temperatures and pressures not possible in the facility

Motivation for CFD

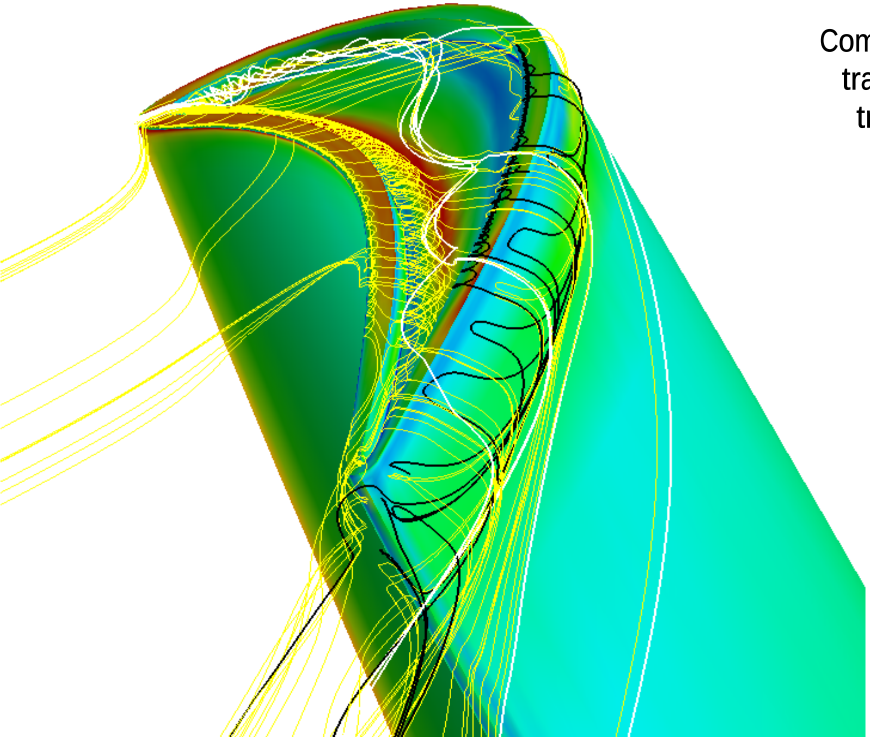
- CFD can be used to elucidate and complement experimental results and to inform the flow physics.
- Allows for extrapolation of flow outside the pressure and temperature limits of experiments.
- Understand unsteady and rotating frame of reference effects
- Allows exploration of the broader design space to find promising combinations of feasible variables for the application.
- CFD will be used at every stage of our research.

CFD Methods Utilized

- CFD is a research tool not a goal.
- The CFD, as much as possible, will be validated by the experiments to ensure accuracy.
- Our team has demonstrated capability to use various CFD methods for solving fluid flow and heat transfer problems relevant to gas turbine flows.
- Any of RANS, URANS, DES or LES will be used, as needed, with structured or unstructured or meshless methods.
- Examples follow:

Capabilities

Tip Gap Modeling



Computed flow
traces and heat
transfer in a
turbine rotor
tip clearance
gap

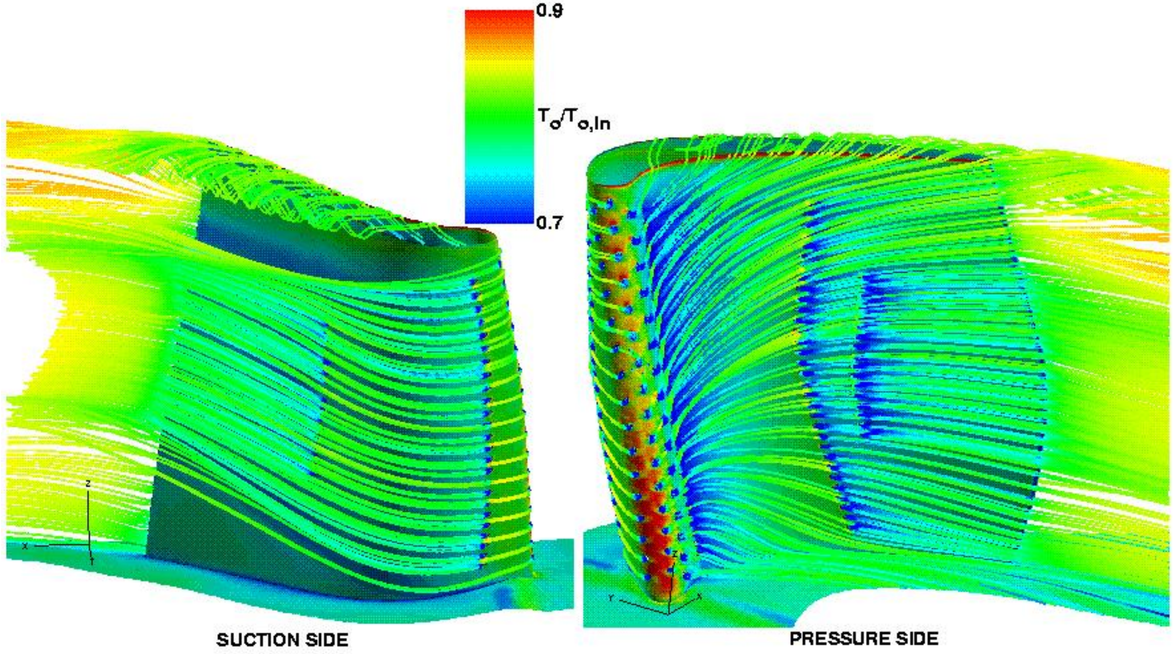
- Blade and Tip Heat Transfer

(Shyam and Ameri, 1998)

Capabilities

Film Cooled Heat Transfer Results

Three Dimensional film-cooled blade analysis



STREAMLINES, COLORED BY TEMPERATURE, EMANATING FROM HOLES OVER THE COOLED BLADE SURFACE WITH DISTRIBUTION OF h

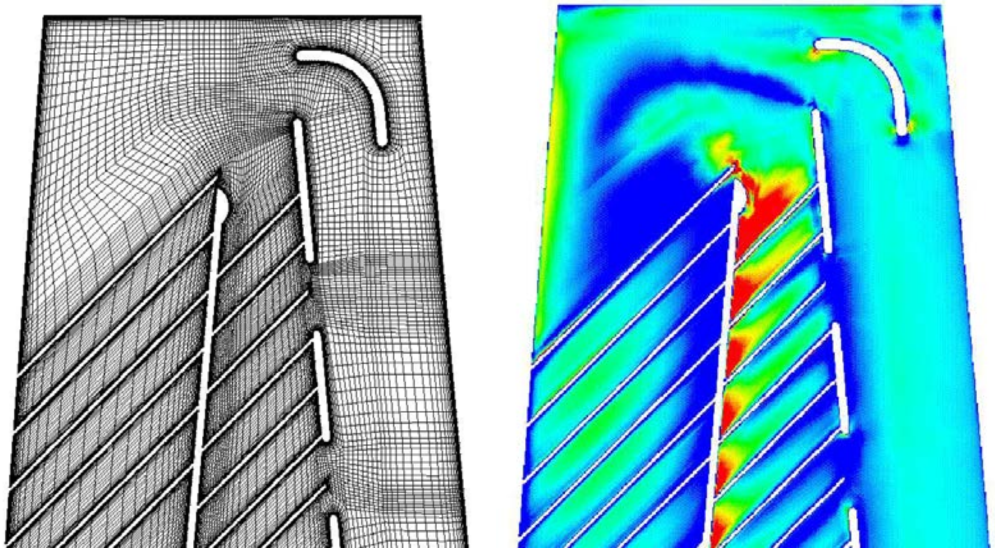
GARG

- Blade film cooling

(Garg, 1999)

Capabilities

Internal Coolant Passage Modeling



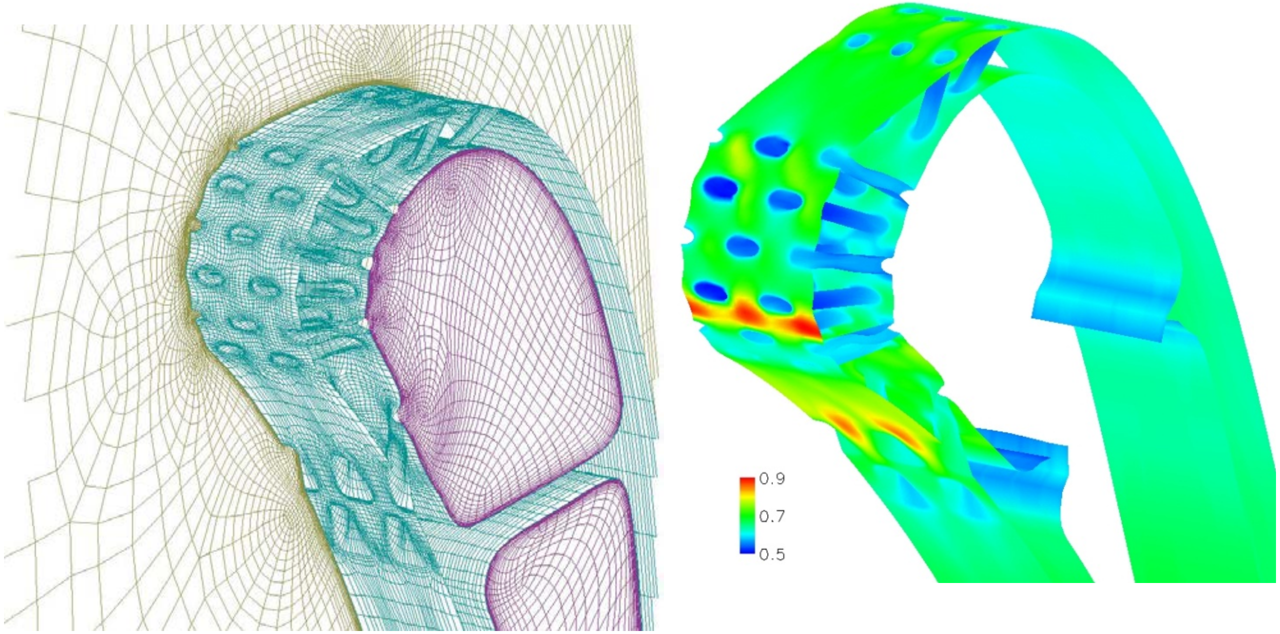
- Internal Heat Transfer

(Rigby and Bunker, 2002)

Capabilities

Conjugate Heat Transfer

wall temperatures



Grid Solution

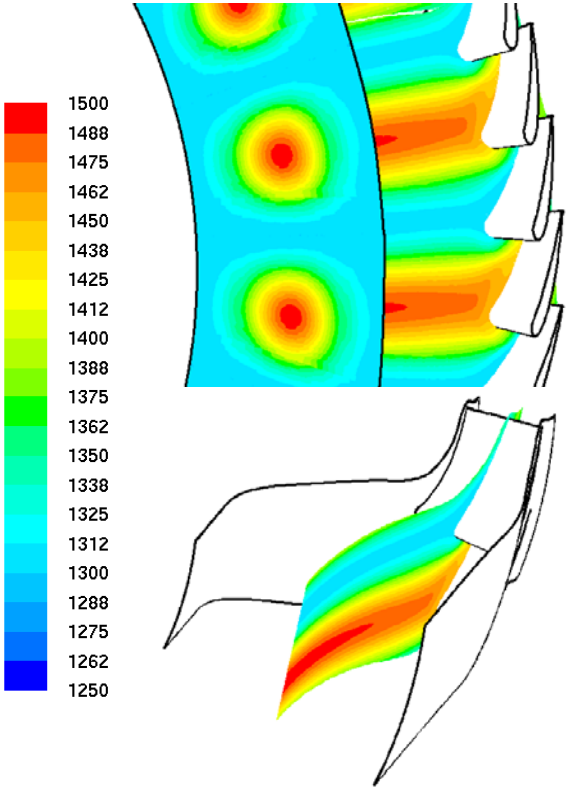
Conjugate

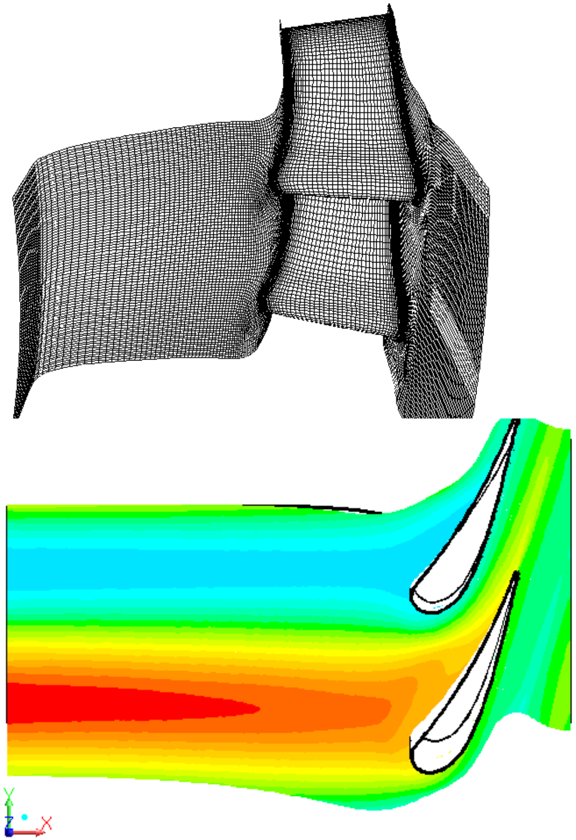
- Conjugate Heat Transfer

(Heidmann, Rigby and Ameri, 2003)

Capabilities

Hot Streak Clocking Study



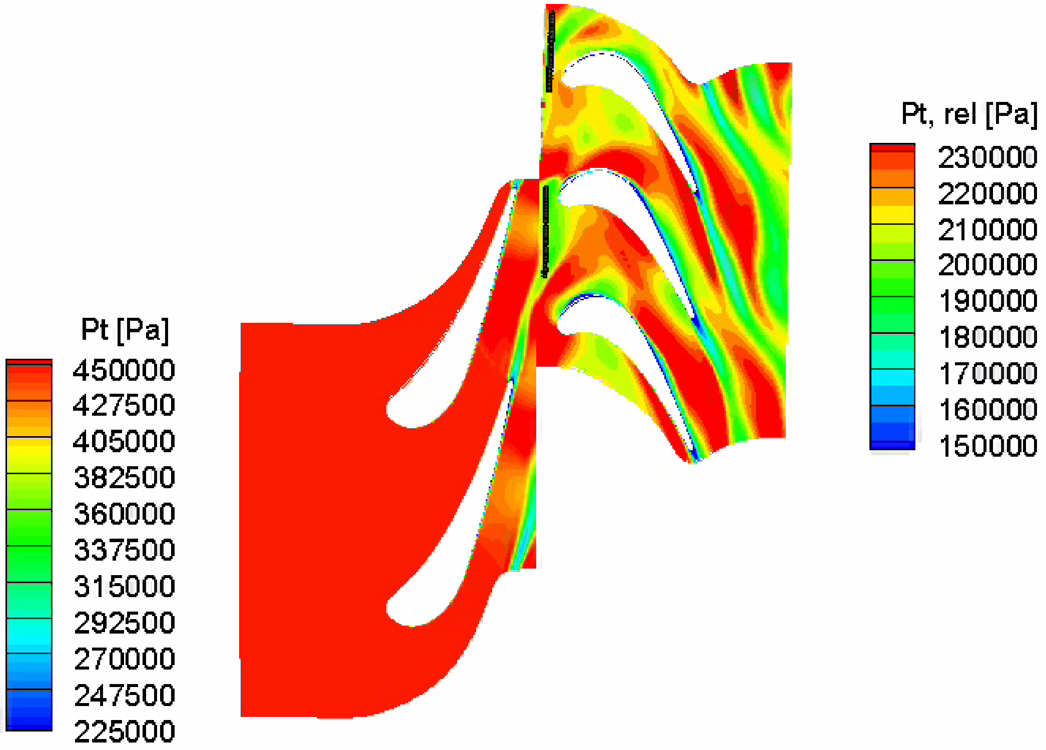


- One streak per vane doublet
- Contours of total temperature in deg K

(Casaday, Ameri, and Bons, AIAA 2012)

Capabilities

Unsteady Particle Tracking in Rotating Frame

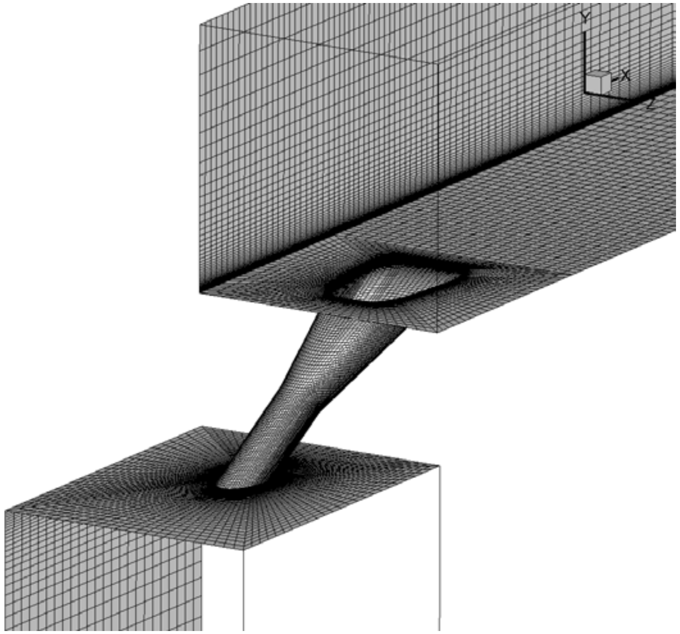


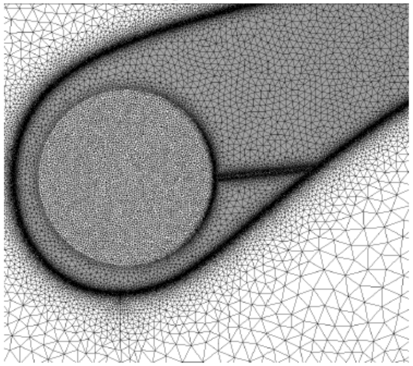
- 2 Vanes per 3 Blades
- Contours of Absolute and Relative Total Pressure

(Zagnoli, Prenter, Ameri, and Bons, IGTI 2015)

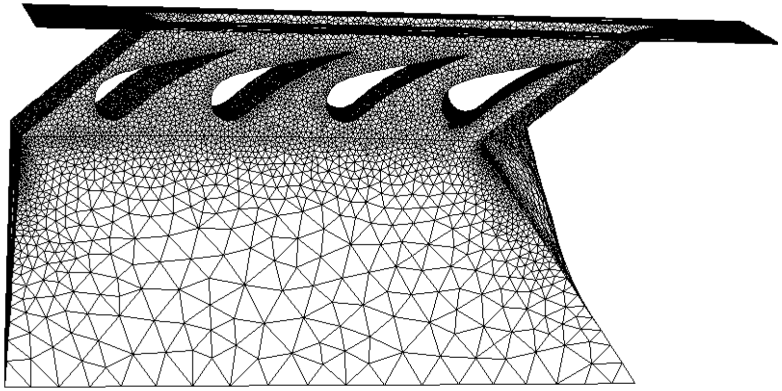
Capabilities

Representative Mesh Topologies





(b) Mesh



(Prenter and Ameri, 2013 - 2015)

Efficient Cooling

- Will seek to improve cooling by using methods that are more coolant efficient.
- Using fluidic devices can reduce blow off and the sweeping action can improve spanwise uniformity .
- Fluidic devices can be made to film cool by sweeping or impingement cool by pulsing.
- Reverse blowing may be an effective way of film cooling at high blowing-ratios.
- Internal micro-channels are shown to be capable of being more effective than impingement cooling.

CFD - Conclusions

- Validated CFD will be used, side by side, with bench top and more physically realistic configurations to extend the design space and explore more realistic physical conditions.

- We have the availability and have developed the expertise and gained the experience to perform such analyses using various steady and unsteady CFD methods to fulfil this task.

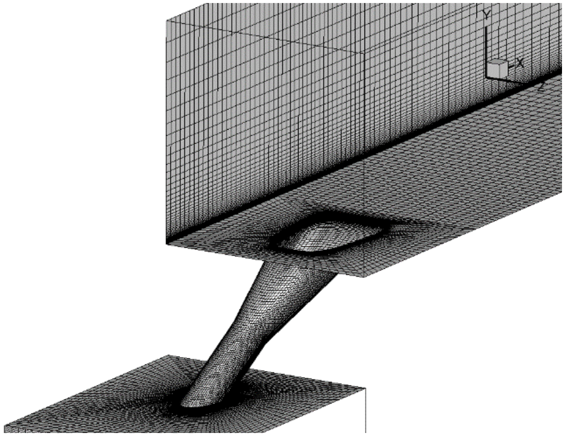
Accomplishments to Date

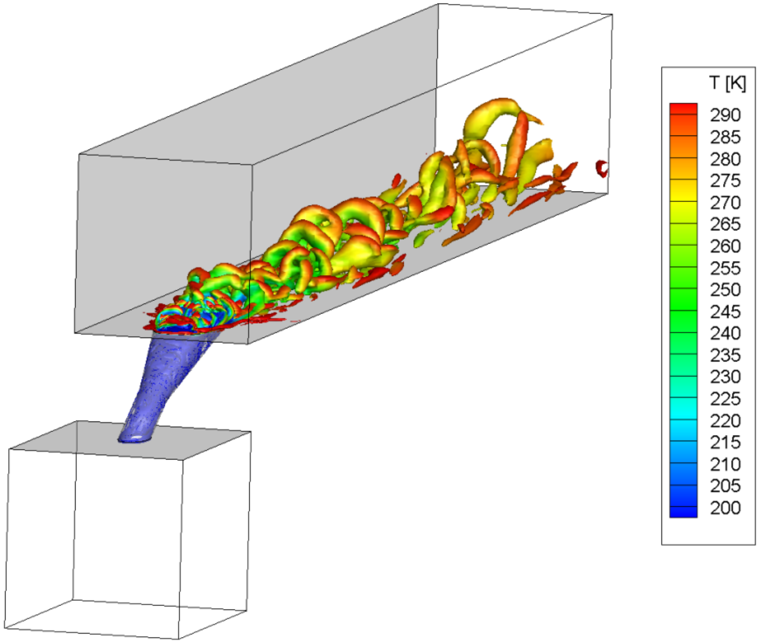
- Literature Search
- CFD Study
- Fluidic Oscillator development/preliminary study
- Reverse film cooling preliminary study

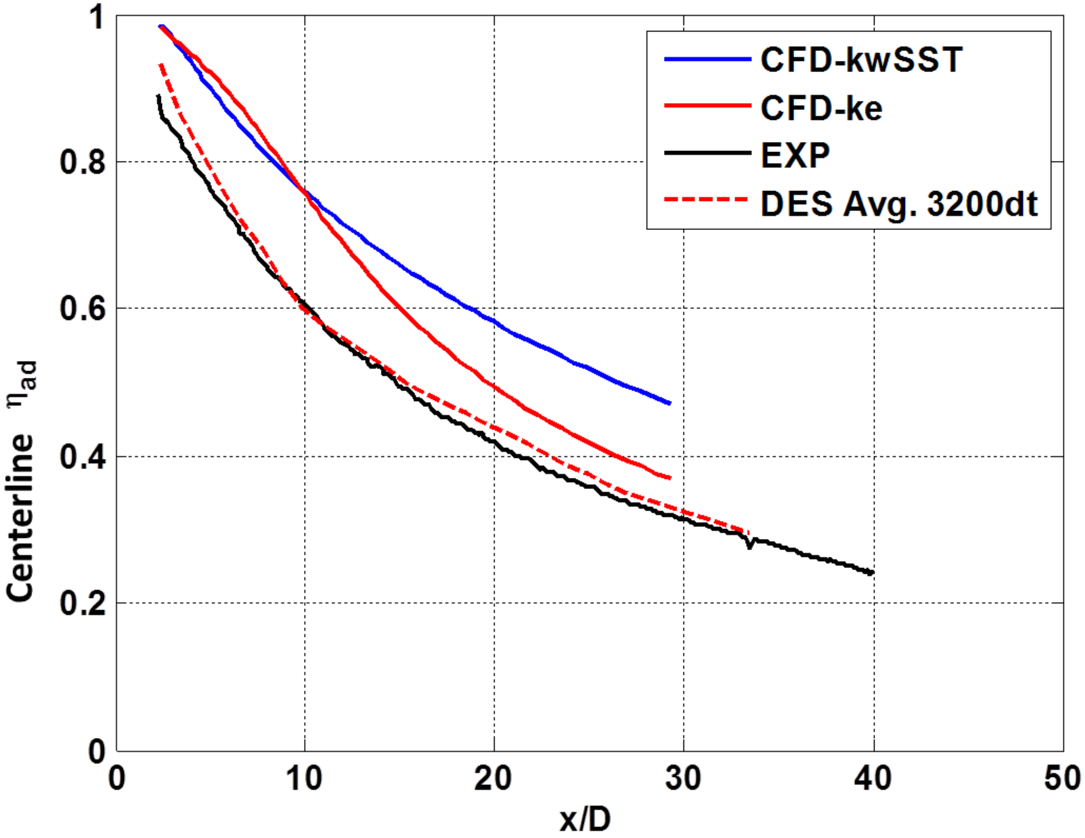
Preliminary CFD Studies

777 Hole – A DES Simulation

Tool development and validation: shaped hole film cooling via DES



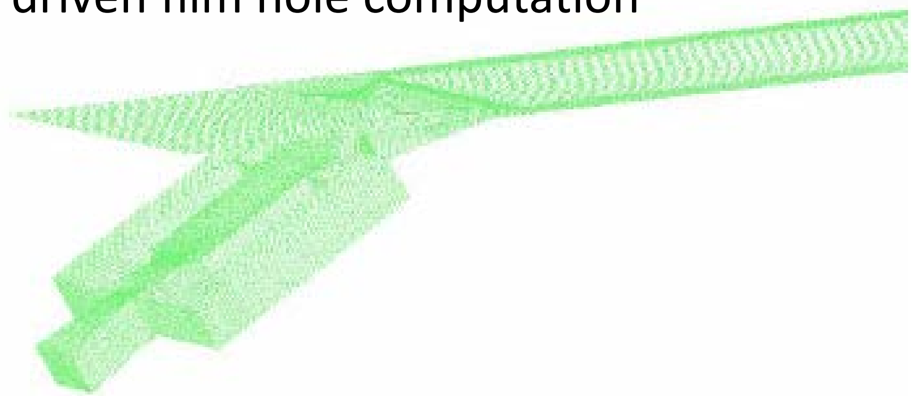




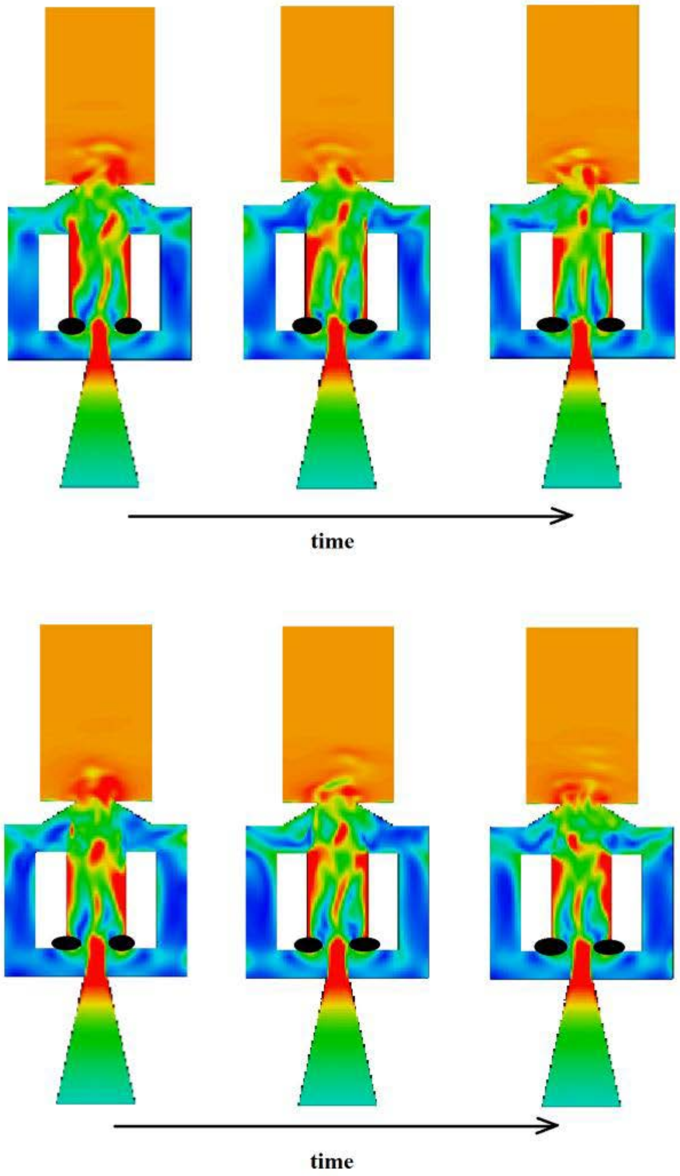
Choice of model and method is critical to accurate predictions.

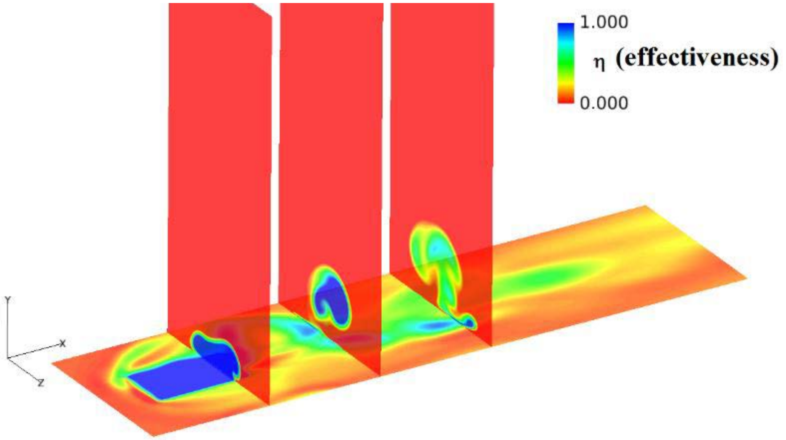
Fluidic Devices - Simulation

3D grid used for fluidic-oscillator driven film hole computation



SNAPSHOTS OF MACH NUMBER IN MID-PLANE OF FLUIDIC HOLE FROM UNSTEADY 3D CFD AT BR=2.0 (BLUE=0, RED=0.45)





Thurman et al. IGTI2015

Preliminary Testing Oct. 2015

Reverse Film Cooling

Preliminary Testing – Reverse Film Cooling

Test Conditions and Scaling Parameters:

$$L_{h,model} = 1.625\text{m}$$

$$D_{model} = 1.75\text{cm}$$

$$u_{\infty} = 4.5\text{m/s}$$

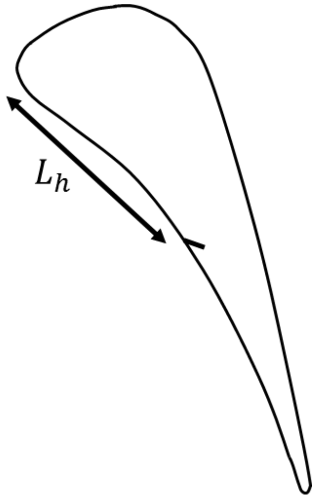
$$T_{\infty} = 22°\text{C}$$

$$\Rightarrow$$

$$Re_{d,model} = \frac{u_{\infty} D_{model}}{\nu} \cong 5800$$

$$Re_{L,model} = \frac{u_{\infty} L_{h,model}}{\nu} \cong 4.5e^{5}$$

$$\frac{Re_{L,model}}{Re_{L,turb,exit}} = \frac{4.5e^{5}}{1e^{6}}$$ (45% of total chord length)



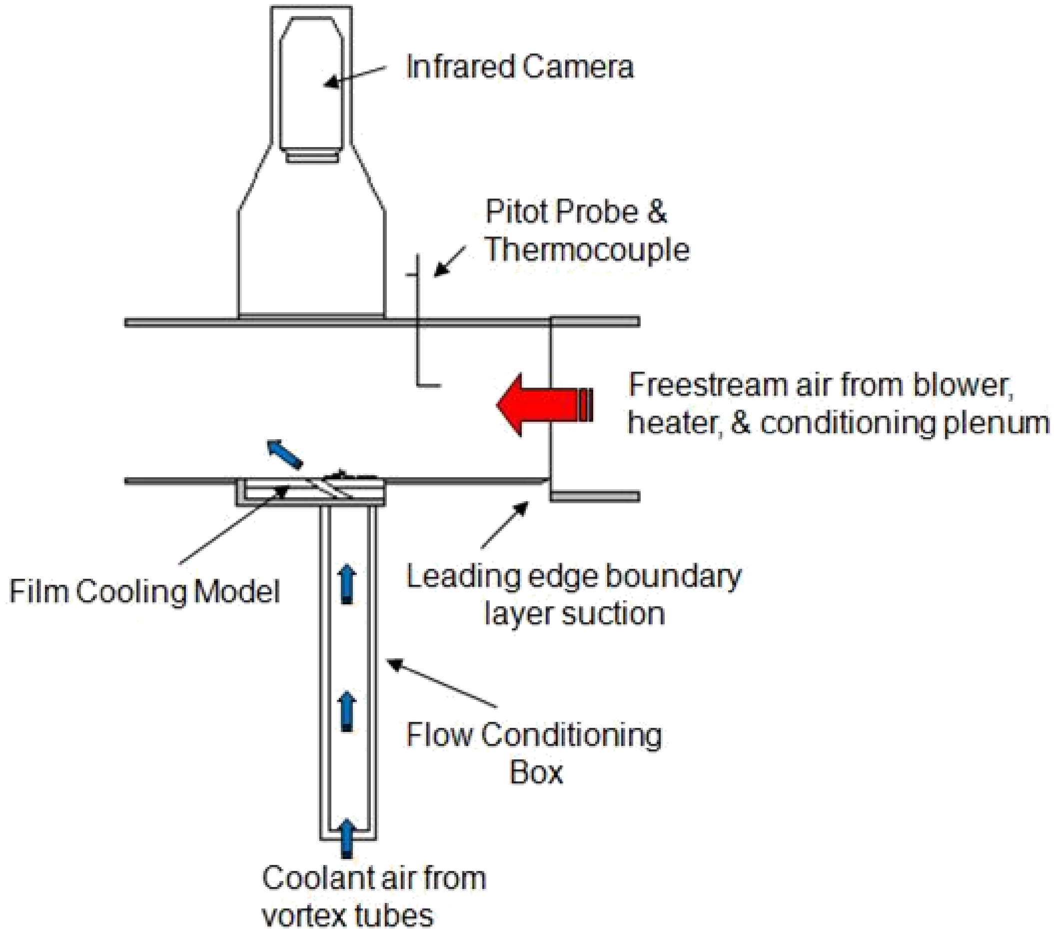
Boundary layer:

$$\frac{\delta}{D} = 1.4$$

$$H = \frac{\delta^{*}}{\theta} = 1.38$$ Suggests turbulent boundary layer

Preliminary Testing – Reverse Film Cooling

Experimental Facility



Freestream conditions:

$u_\infty = 4.5\text{m/s}$ (can increase to 20m/s)

$T_\infty = 22°\text{C}$ (can be heated up to 60°C)

Coolant conditions:

$$M = \frac{\rho_c u_c}{\rho_\infty u_\infty} = 0.5, 0.75, 1, 1.4$$

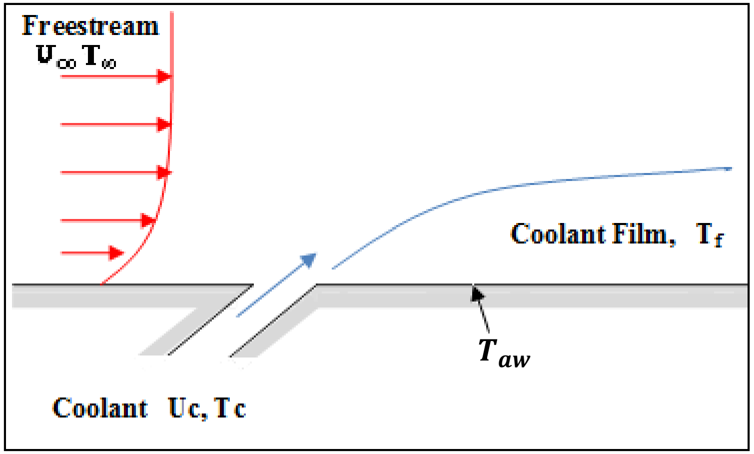
$$DR = \frac{\rho_c}{\rho_\infty} \approx 1.065$$

Infrared camera: Cedip SILVER 480M

- 320x256 pixel Indium Antimonide (InSb) sensor
- Accuracy: ± 1°C
- Sensitivity: ± 0.02°C
- Max frame rate: 400Hz

Preliminary Testing – Reverse Film Cooling

Analysis – η (steady state test)



$$\eta = \frac{T_\infty - T_f}{T_\infty - T_c} \approx \frac{T_\infty - T_{aw}}{T_\infty - T_c}$$

$$\eta_{\min} = 0$$

$$\eta_{\max} = 1$$

T_∞ (Freestream temperature) - Measured with thermocouple

T_c (Coolant temperature) – Measured at exit of film cooling holes with thermocouple.

T_{aw} (Surface temperature) – Measured using infrared camera.

Preliminary Testing – Reverse Film Cooling

Analysis – h (transient test)

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

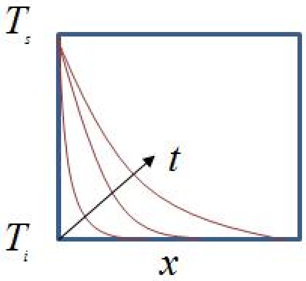
1D heat equation

$$\frac{\partial^2 T}{\partial \eta^2} = -2\eta\frac{\partial T}{\partial \eta} \qquad \eta \equiv \frac{x}{(4\alpha t)^{1/2}}$$

Boundary conditions (semi-infinite solid)

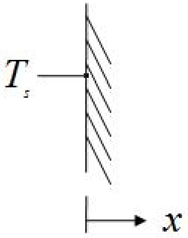
$T(x,0) = T_{init}$ and $\lim\limits_{x \to \infty} T(x,t) = T_{init}$

$$\frac{T(x,t) - T_{init}}{T_s - T_{init}} = erf\left(\frac{x}{2\sqrt{\alpha t}}\right)$$



Boundary condition (step change in T_surface)

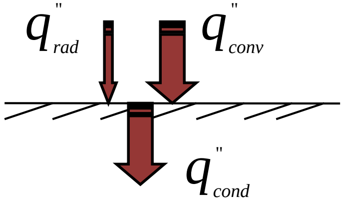
$$T(0,t) = T_s$$



$$q''_{s,cond}(t) = -\kappa\left.\frac{dT}{dx}\right|_{x=0} = \frac{\kappa}{\sqrt{\pi\alpha}}\frac{(T_s - T_{init})}{\sqrt{t}}$$

Duhamel's Superposition

$$q''_{s,cond}(t) = \frac{\kappa}{\sqrt{\pi\alpha}}\sum_{i=1}^{n}\frac{T_s(\tau_i) - T_s(\tau_{i-1})}{\frac{1}{2}\left[\sqrt{t-\tau_i} - \sqrt{t-\tau_{i-1}}\right]}$$



$$q''_{cond} = q''_{rad} + q''_{conv}$$

$$q''_{conv} = h(T_\infty - T_s)$$

$$h_n = \frac{1}{T_\infty - T_{s\,n}}\left[\frac{2\kappa}{\sqrt{\pi\alpha}}\sum_{m=1}^{n}\frac{T_{s\,m}(\tau_i) - T_{s\,m-1}(\tau_{i-1})}{\sqrt{t_n - \tau_i} + \sqrt{t_n - \tau_{i-1}}}\right]$$

Preliminary Testing – Reverse Film Cooling

Analysis – Heat Load

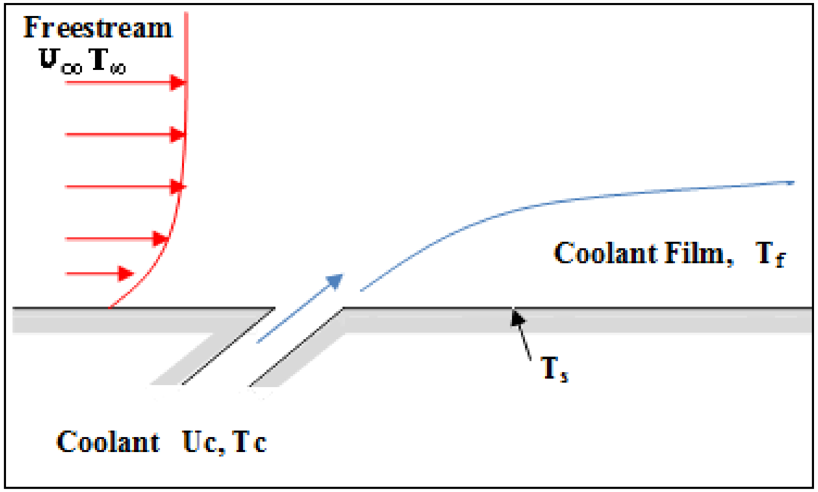
$$q_0'' = h_0(T_\infty - T_s)$$ **Without film cooling**

$$q'' = h(T_f - T_s)$$ **With film cooling**

$$\left(\frac{q''_{with.\,film.\,cooling}}{q''_{without.\,film.\,cooling}}\right) \qquad \frac{q''}{q_0''} = \frac{h}{h_0}\frac{\left(T_f - T_s\right)}{\left(T_\infty - T_s\right)}$$

$$\Rightarrow \quad \frac{q''}{q_0} = \frac{h}{h_0}\left\{1 - \eta\frac{\left(T_\infty - T_c\right)}{\left(T_\infty - T_S\right)}\right\}$$

$$\Rightarrow \quad \boxed{\frac{q''}{q_0} = \frac{h}{h_0}\left\{1 - \frac{\eta}{\Phi}\right\}}$$



Overall cooling effectiveness

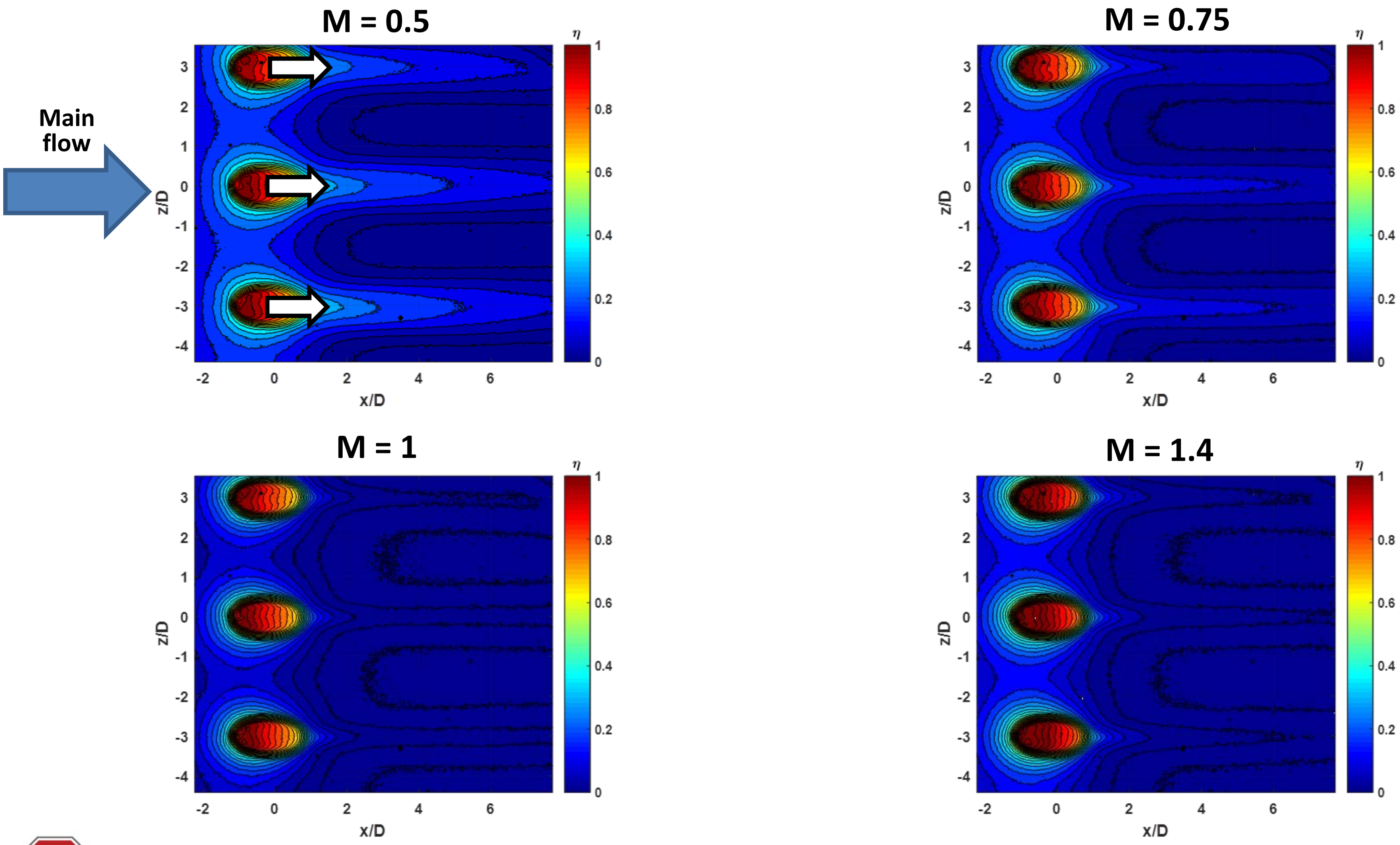
$$\eta = \frac{T_\infty - T_f}{T_\infty - T_c} \qquad \Phi = \frac{T_\infty - T_S}{T_\infty - T_c} \approx 0.6$$

$$\frac{q''}{q_0''} < 1$$ **Net cooling benefit**

$$\frac{q''}{q_0''} > 1$$ **Net cooling loss**

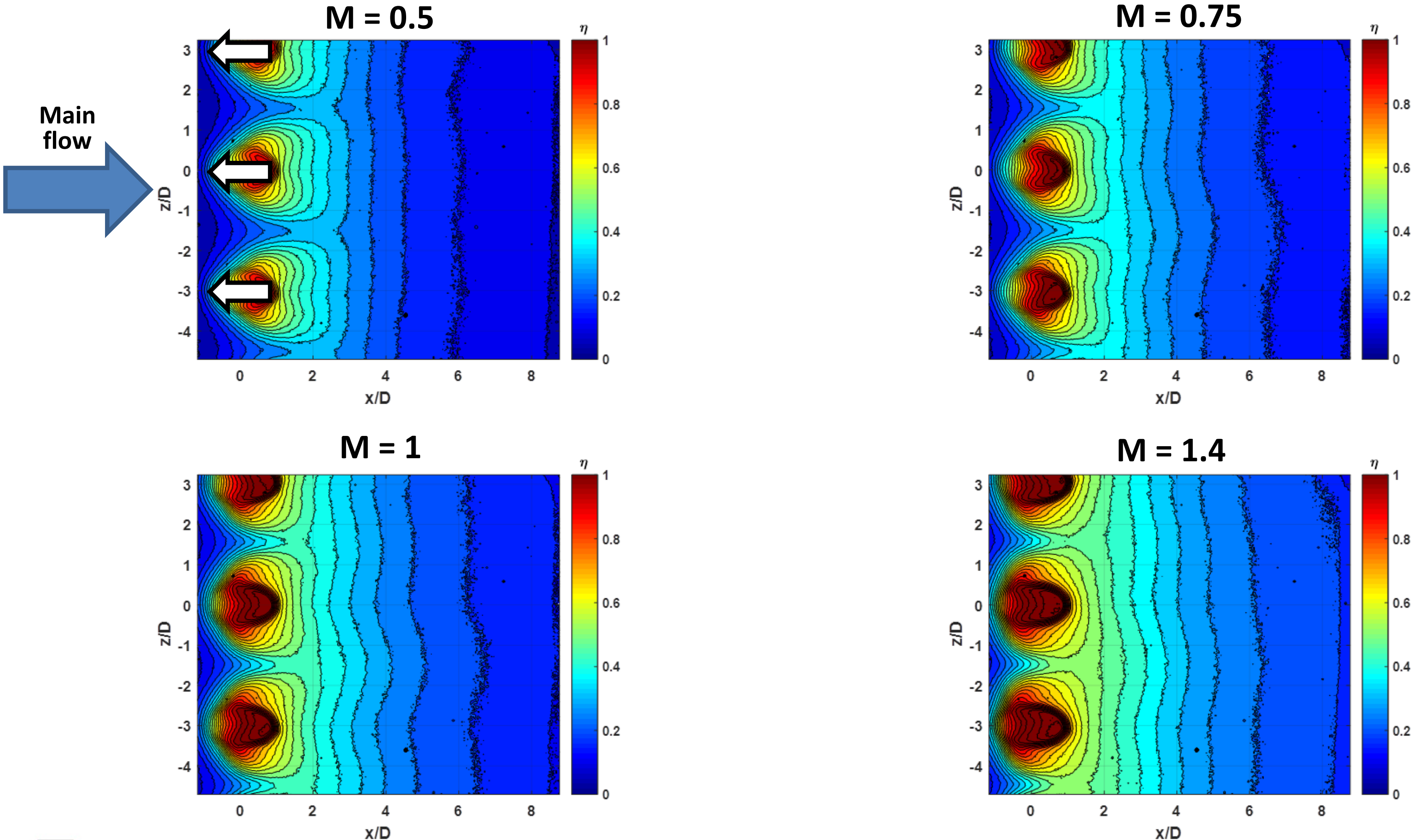
Preliminary Testing

Results – Conventional Blowing (P/D = 3, α = 30°)



Preliminary Testing

Results – Reversed Blowing (P/D = 3, α = 30°)


M = 0.5

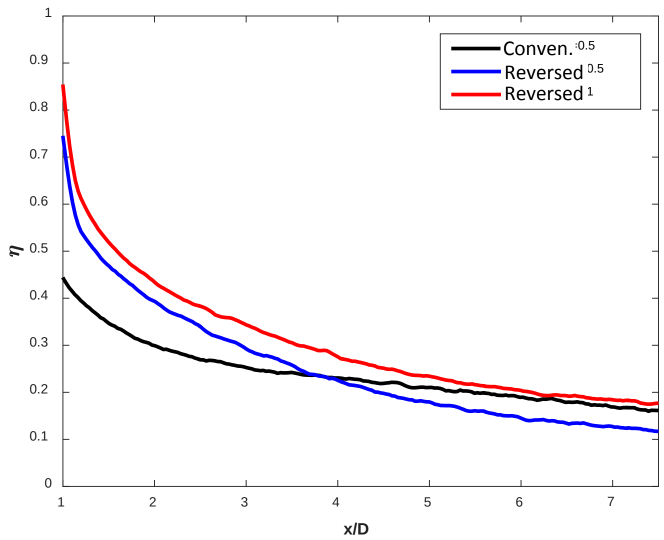
M = 0.75

M = 1

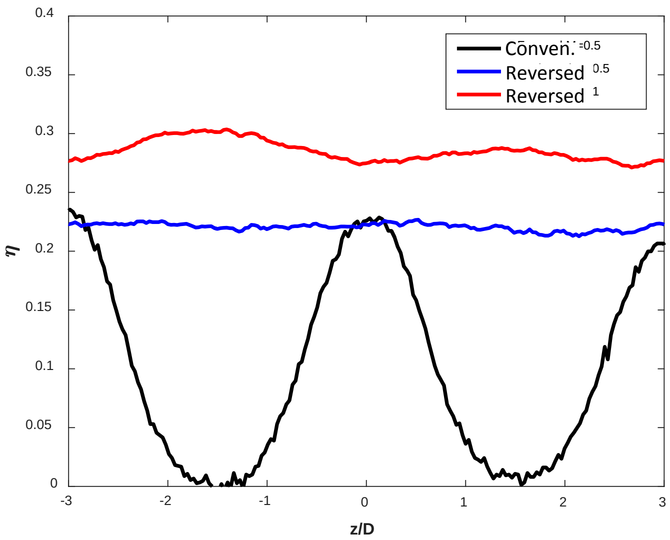
M = 1.4

Preliminary Testing

Results – Comparison M = 0.5



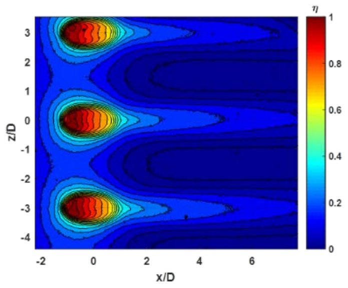
Centerline Traces

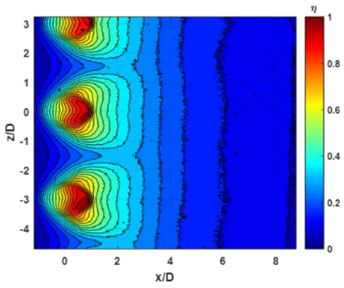


Lateral Traces at x/D = 4

Promising initial comparison, however:

- h/h_0 is likely augmented
- Compare to more representative geometries (e.g. 777 Hole)
- Effects of higher FST levels
- Effects of pressure gradient





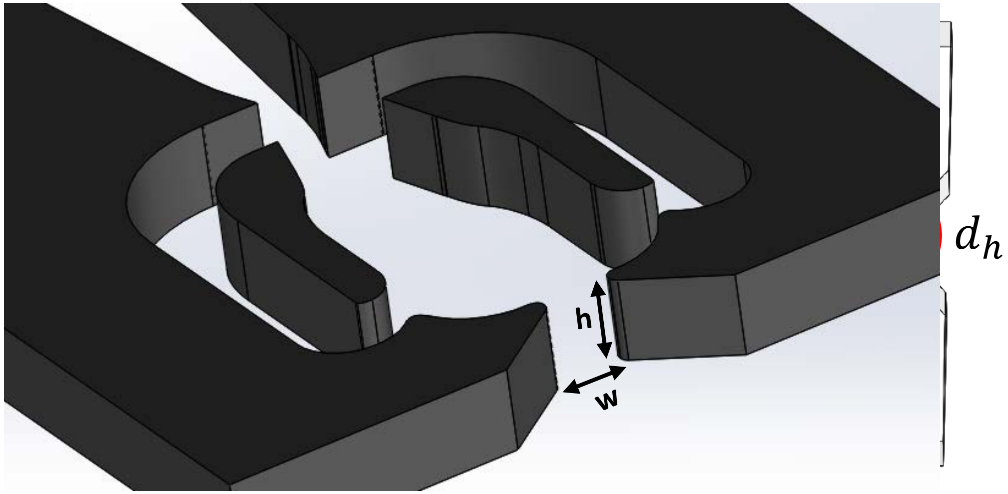
Preliminary Testing

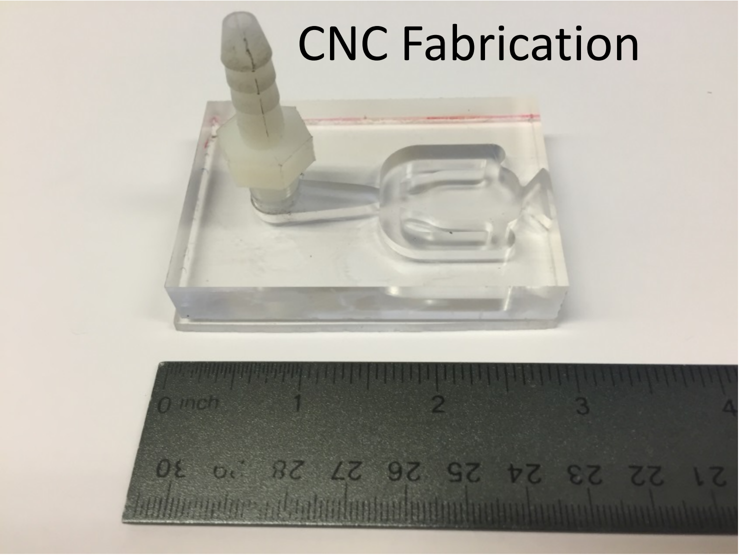
Oscillating Impingement Jets

Preliminary Testing – Oscillating Jets

Initial Design:

- Geometry from literature (Raman et al., 1999)
- $D = d_h = 4.5\text{mm}$
- AR = w/h = 0.82
- Fabricated test article from acrylic using CNC

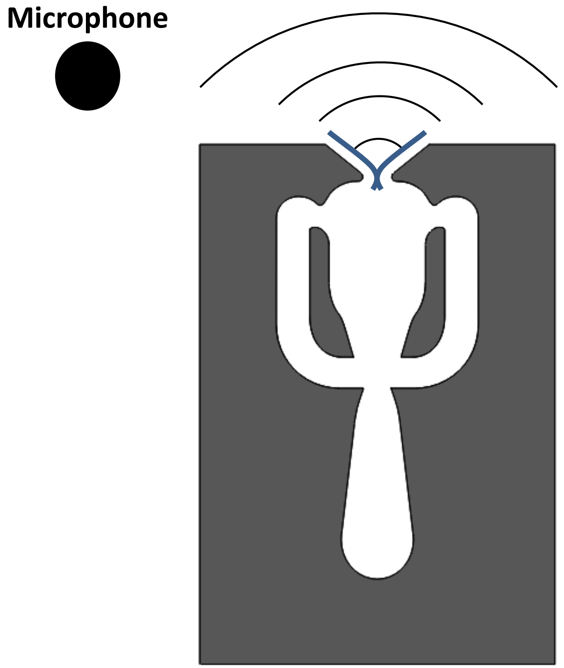



CNC Fabrication

Preliminary Testing – Oscillating Jets

Fluidic Oscillator Characterization:

- Determine frequency-mass flow rate relationship
- Place microphone outside of the hydrodynamic field
- Use FFT to determine frequency of oscillations at different mass flow rates

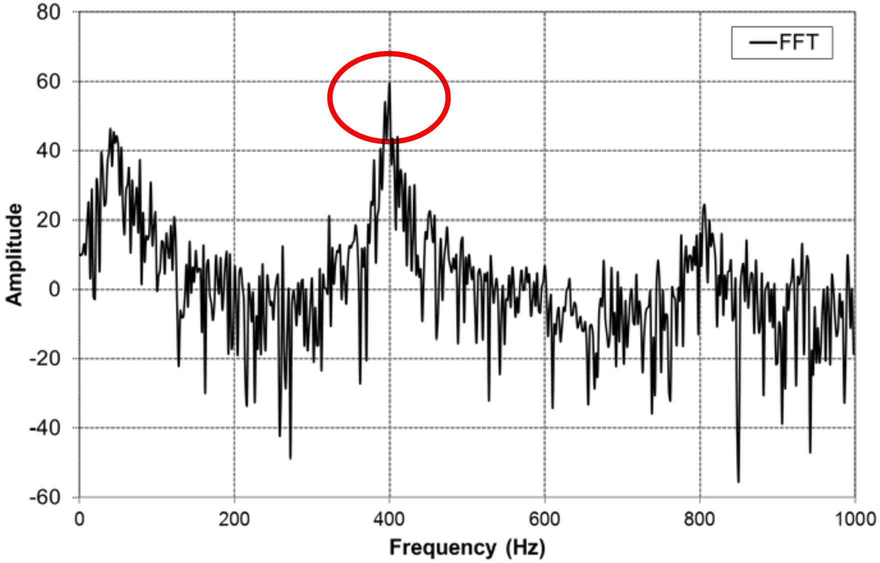


Fluidic Oscillator

Preliminary Testing – Oscillating Jets

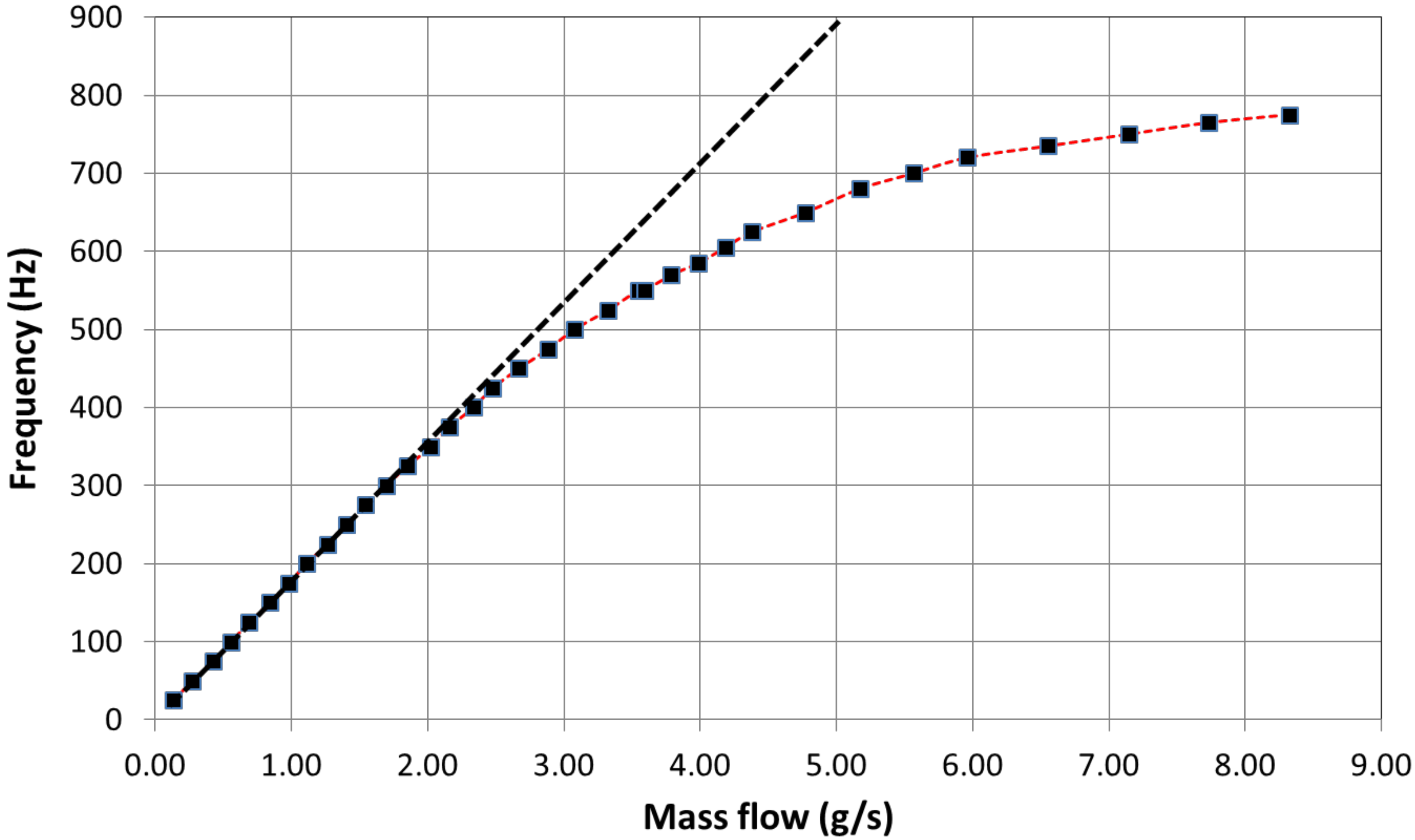
Fluidic Oscillator Characterization:

- Determine frequency-mass flow rate relationship
- Place microphone outside of the hydrodynamic field
- Use FFT to determine frequency of oscillations at different mass flow rates



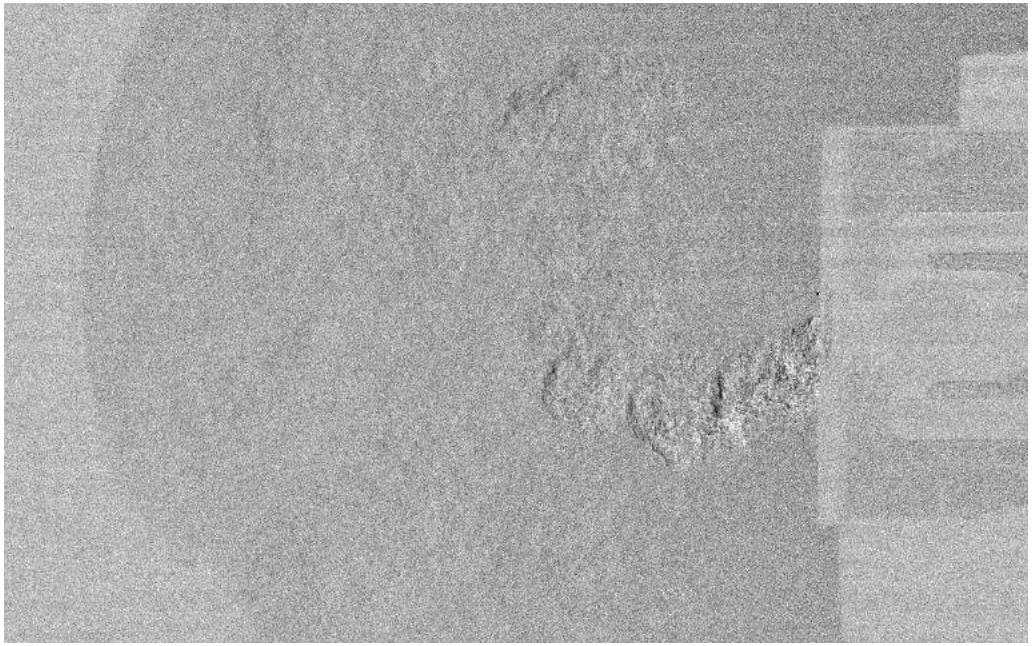
Preliminary Testing – Oscillating Jets

Fluidic Oscillator Characterization:



Preliminary Testing – Oscillating Jets

Fluidic Oscillator Characterization:



Schlieren of oscillator operating at 430Hz

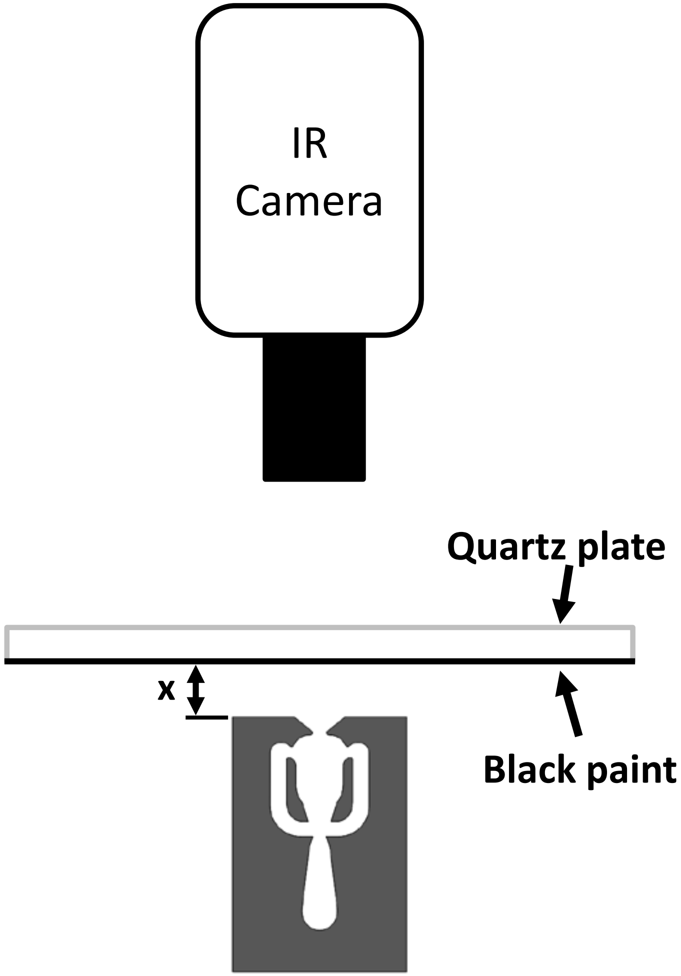
Preliminary Testing – Oscillating Jets

Impingement Heat Transfer

- Initial testing includes:
  - Fluidic oscillator vs. straight jet
  - A single mass flow rate
  - x/D = 1.5 and 2.0

- There are several parameters to explore:
  - Jet aspect ratio
  - x/D
  - Frequency
  - Mass flow rate
  - Pressure drop

} Fluidic oscillator design



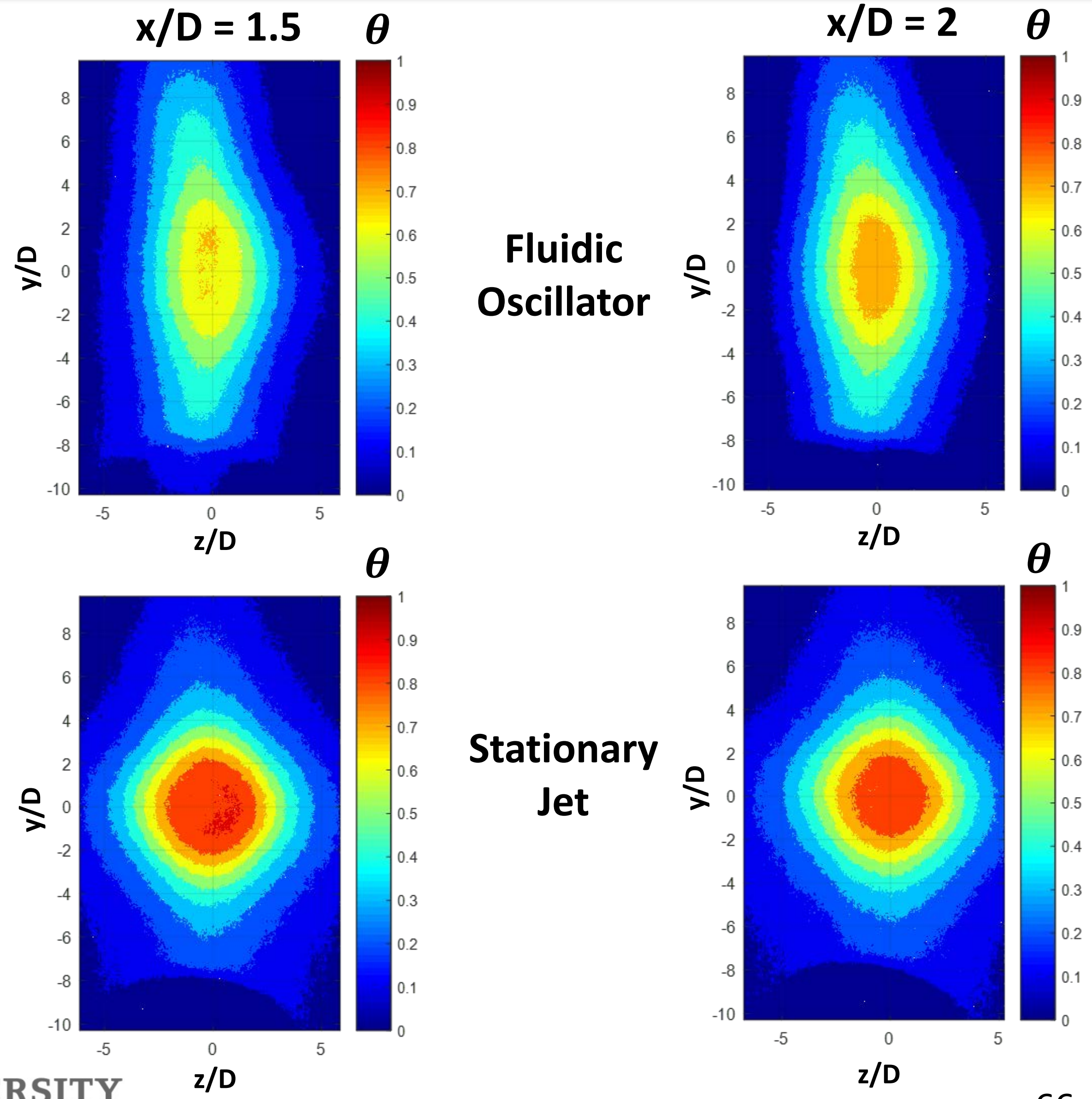
Preliminary Testing – Oscillating Jets

Initial Results:

- Mass flow rate: 2.96 g/s
- *f* = 480 Hz

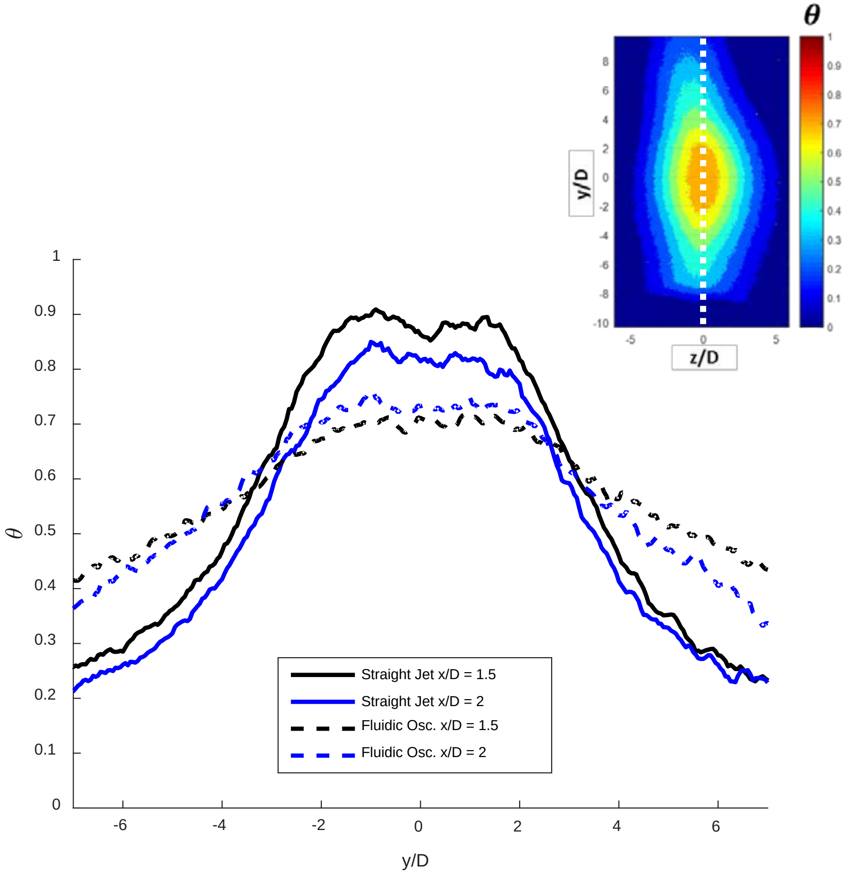
$$\theta = \frac{T_\infty - T}{T_\infty - T_c}$$

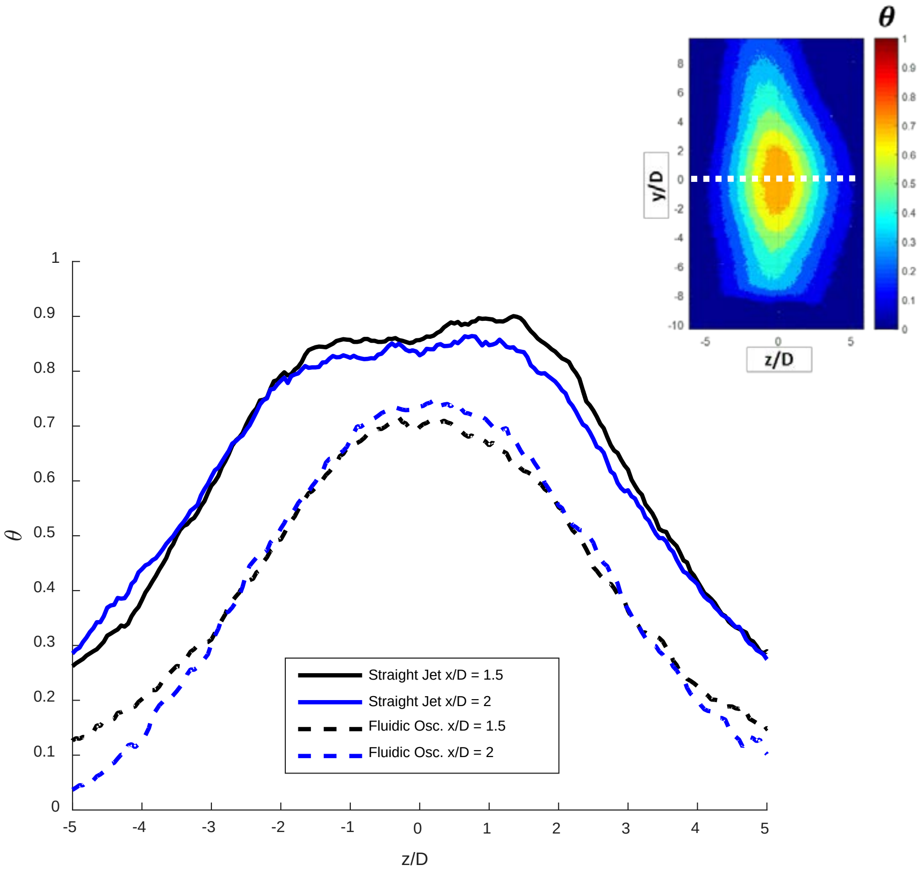
- For oscillating jets, augmentation of *h* may be the real advantage



Preliminary Testing – Oscillating Jets

Initial Results:



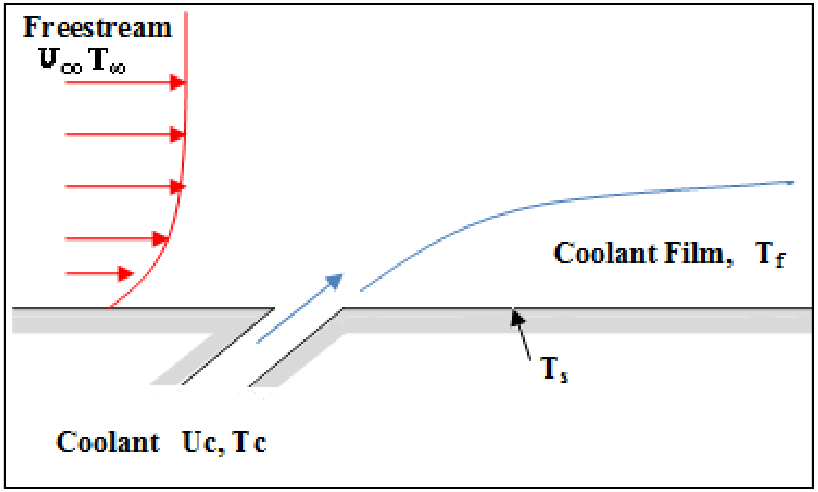


Preliminary Testing – Backward Blowing

Analysis – Heat Load

$$q_0'' = h_0(T_\infty - T_s)$$ **Without film cooling**

$$q'' = h(T_f - T_s)$$ **With film cooling**



$$\left(\frac{q''_{with.\,film.cooling}}{q''_{without.\,film.cooling}}\right) \qquad \frac{q''}{q_0''} = \frac{h}{h_0}\frac{(T_f - T_s)}{(T_\infty - T_s)}$$

$$\Rightarrow \frac{q''}{q_0} = \frac{h}{h_0}\left\{1 - \eta\frac{(T_\infty - T_c)}{(T_\infty - T_S)}\right\}$$

Overall cooling effectiveness

$$\eta = \frac{T_\infty - T_f}{T_\infty - T_c} \qquad \Phi = \frac{T_\infty - T_S}{T_\infty - T_c} \approx 0.6$$

$$\Rightarrow \boxed{\frac{q''}{q_0} = \frac{h}{h_0}\left\{1 - \frac{\eta}{\Phi}\right\}}$$

$$\frac{q''}{q_0''} < 1$$ **Net cooling benefit**

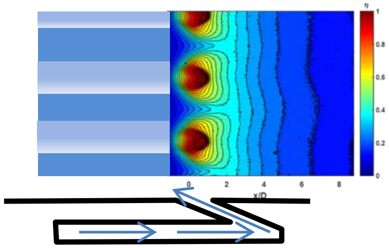
$$\frac{q''}{q_0''} > 1$$ **Net cooling loss**

Next Steps

Eventual Integration of Promising Designs

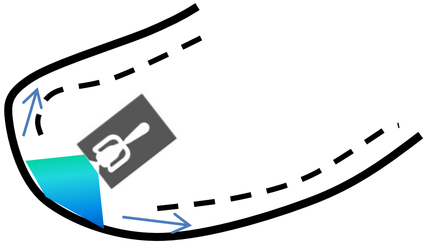
Reverse Cooling on PS:

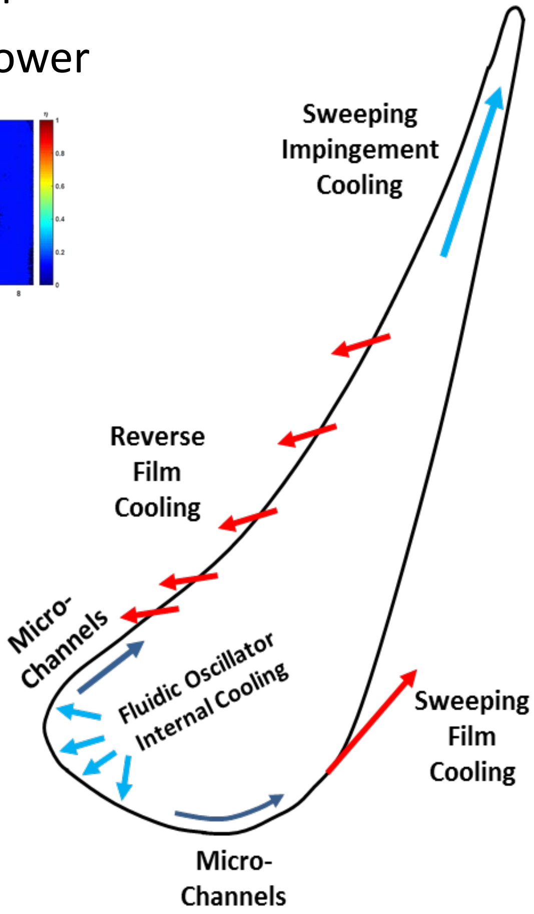
- Fed by upstream microchannel
- Better surface coverage with lower massflow?



Fluidic Oscillator Impingement Cooling on LE:

- Eliminate showerhead
- Lower massflow required?
- Microchannel exhaust



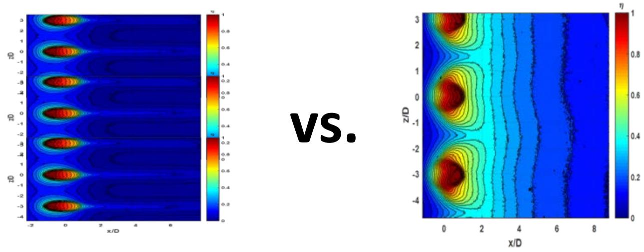


Sweeping Fluidic Oscillator in TE:

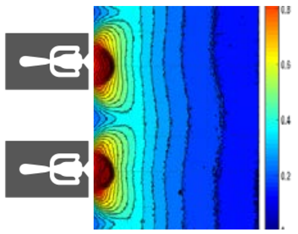
- Improved coverage with lower massflow required?
- Lower pressure drop than pedastels?

Sweeping Fluidic Oscillator Film Cooling:

- Improved coverage with lower massflow required?

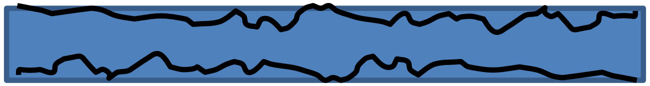


vs.



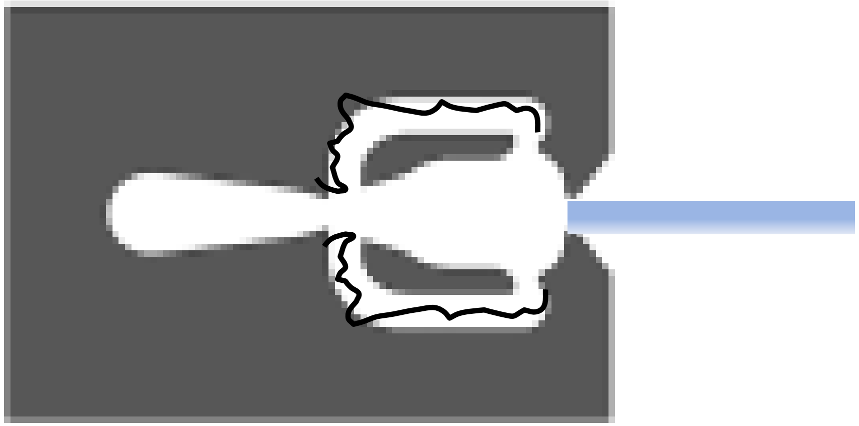
Manufacturing Challenges with DMLS

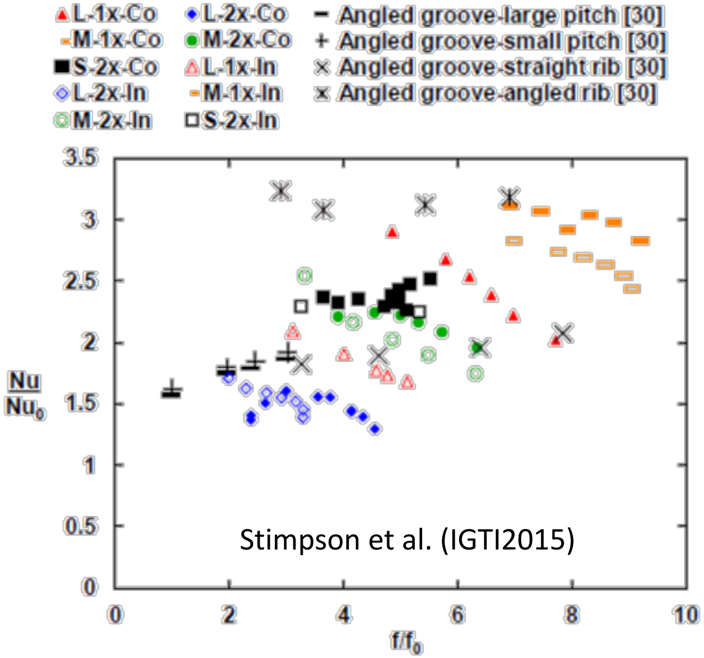
- Surface finish could…
  - Enable technology



naturally roughened microchannel

  - Or disable technology

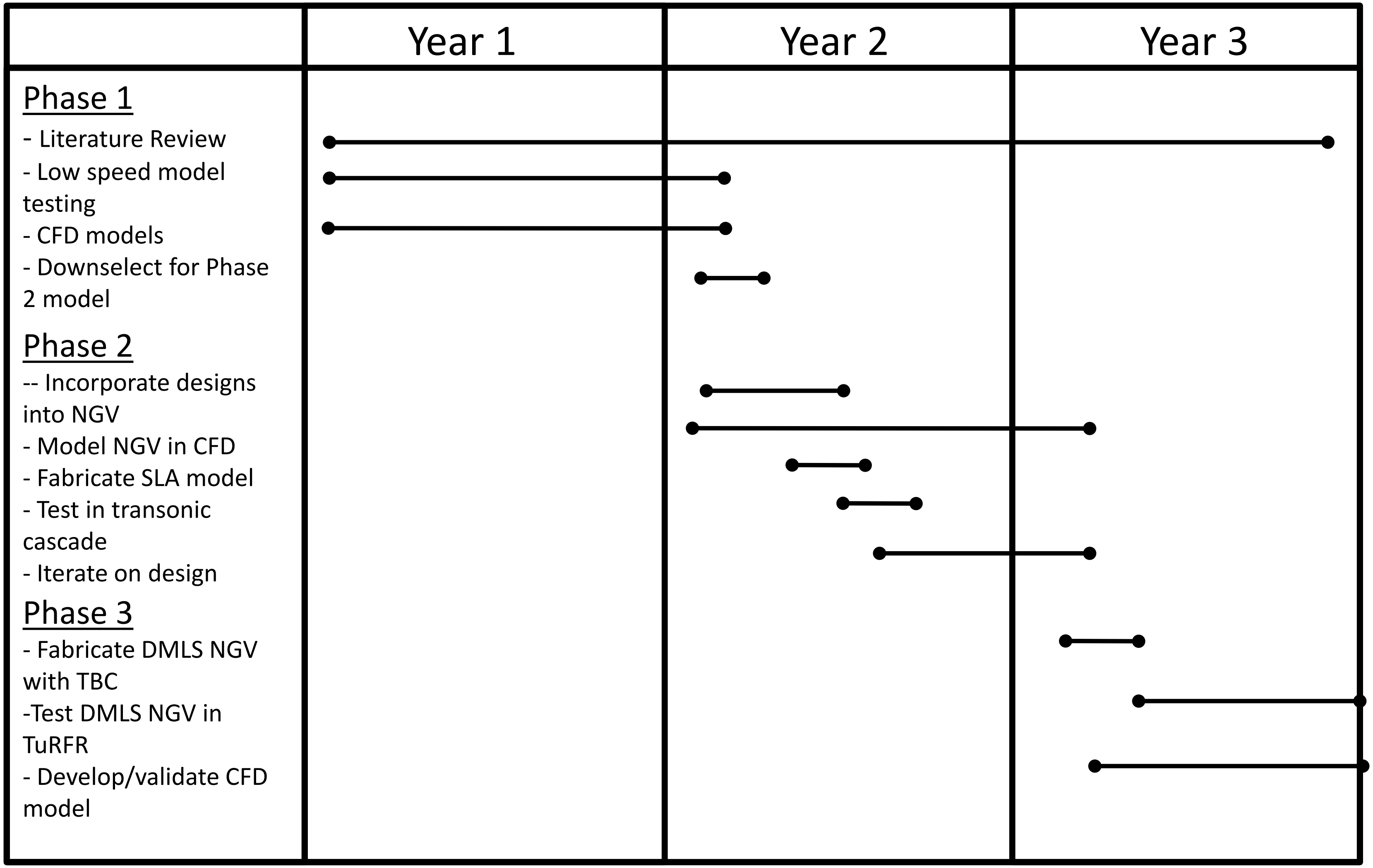




Stimpson et al. (IGTI2015)

- DMLS is still on a steep learning curve.
- Design for “tomorrow’s” level of improved geometric tolerance.

Gantt Chart



Phase 1

- Literature Review
- Low speed model testing
- CFD models
- Downselect for Phase 2 model

Phase 2

-- Incorporate designs into NGV
- Model NGV in CFD
- Fabricate SLA model
- Test in transonic cascade
- Iterate on design

Phase 3

- Fabricate DMLS NGV with TBC
-Test DMLS NGV in TuRFR
- Develop/validate CFD model