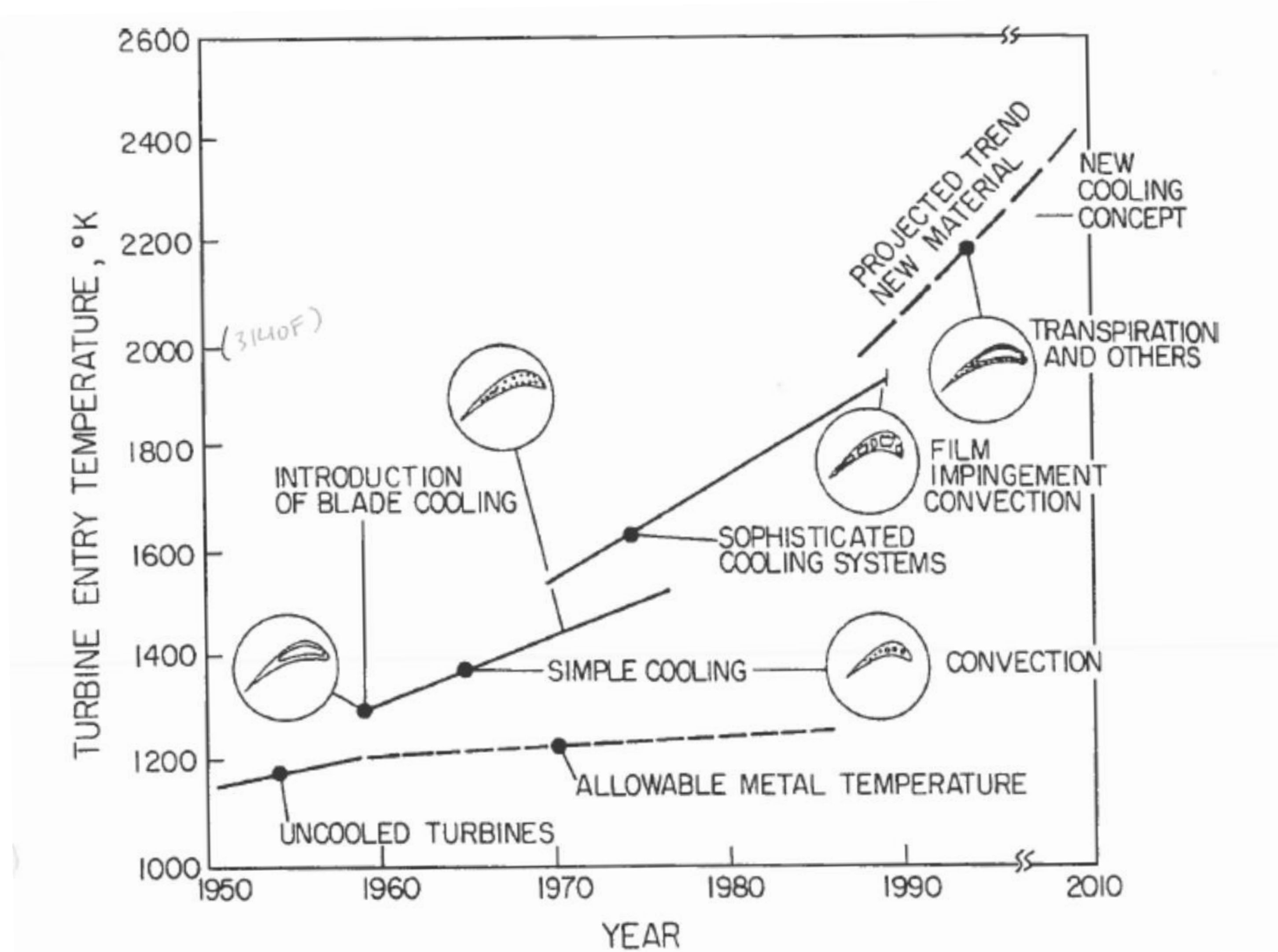
Revolutionizing Turbine Cooling with Micro-Architectures Enabled by Direct Metal Laser Sintering

THE OHIO STATE UNIVERSITY

(5 Oct 2015 - NETL Kick-Off Presentation)

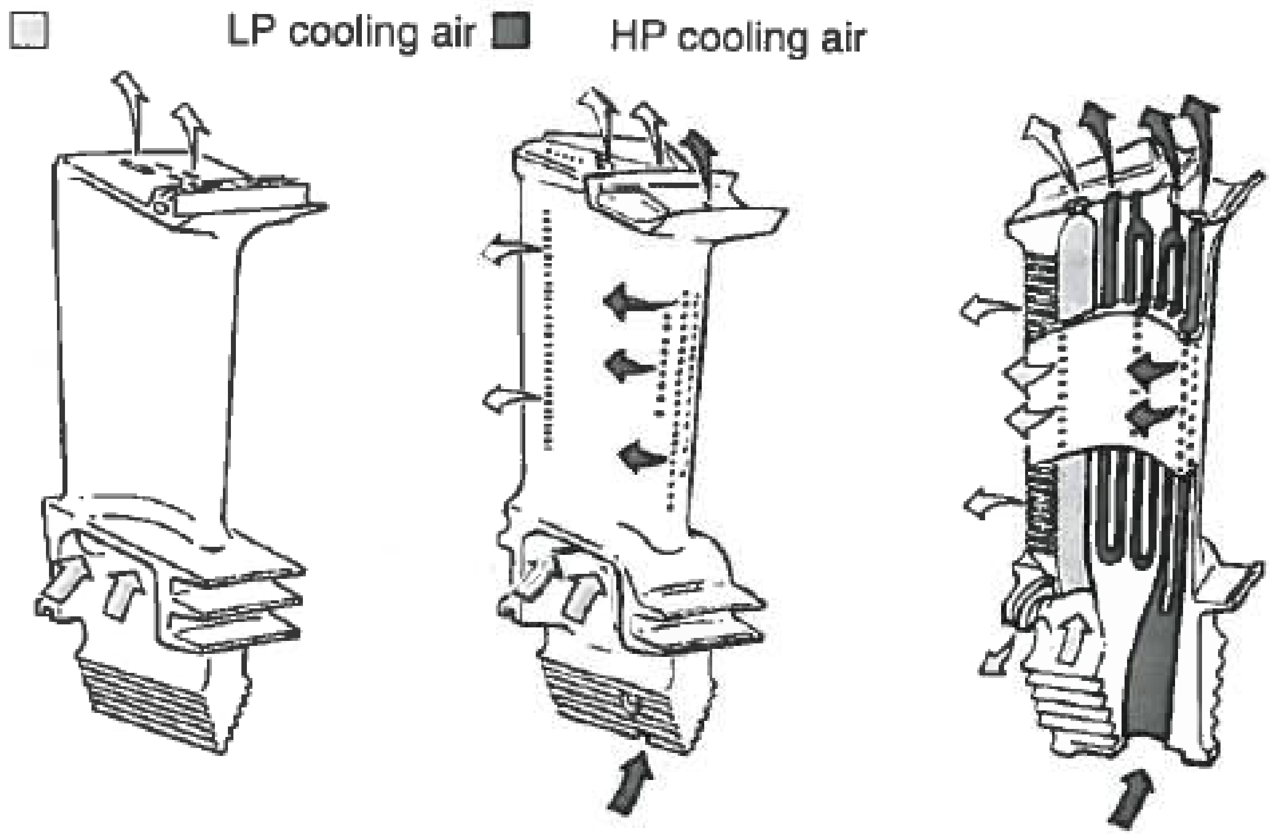
MOTIVATION

Turbine Cooling – Where did we come from?



MOTIVATION

Turbine Cooling – Where did we come from?



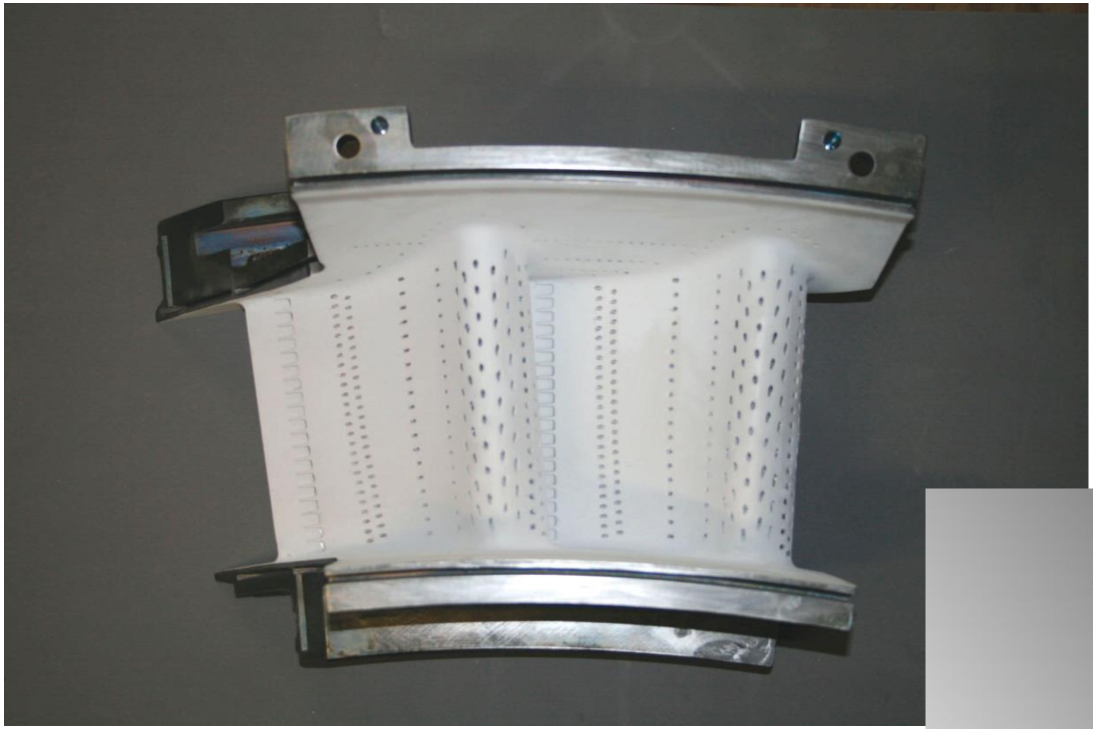
Convection Single pass (1960)

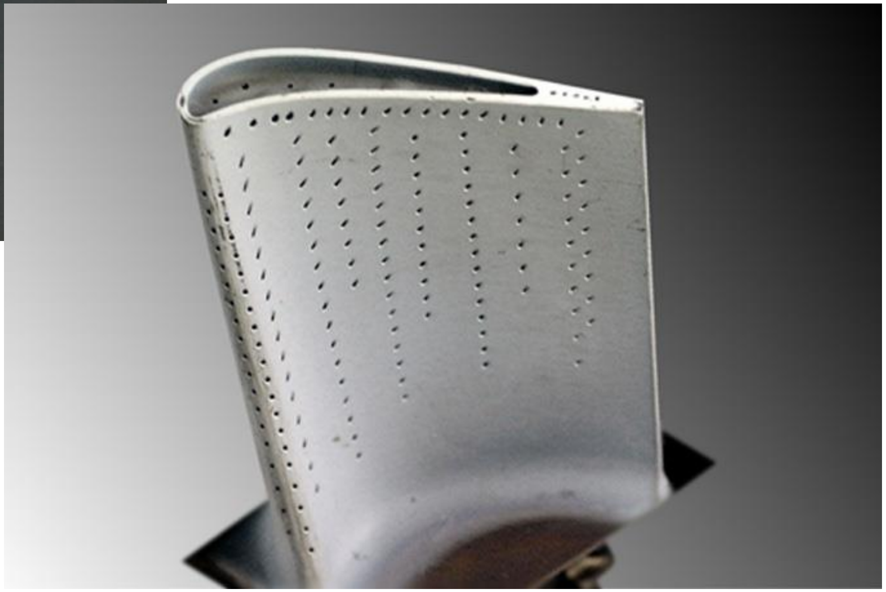
Convection (single pass-multiple feed) and film (1970)

Convection (Quintuple pass-multifeed) and film cooling

MOTIVATION

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

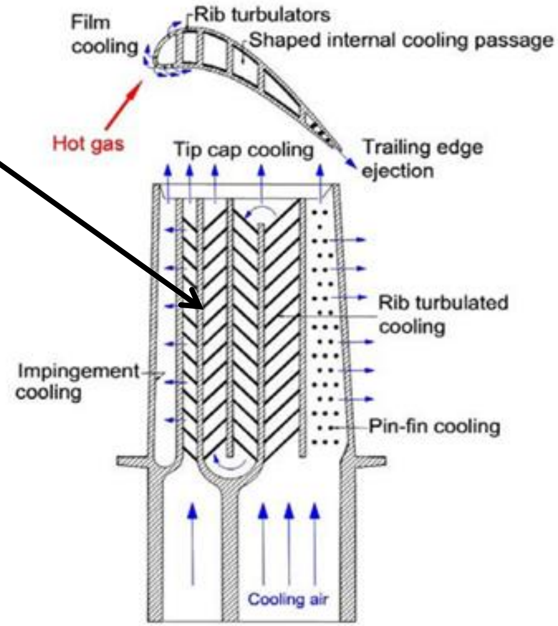




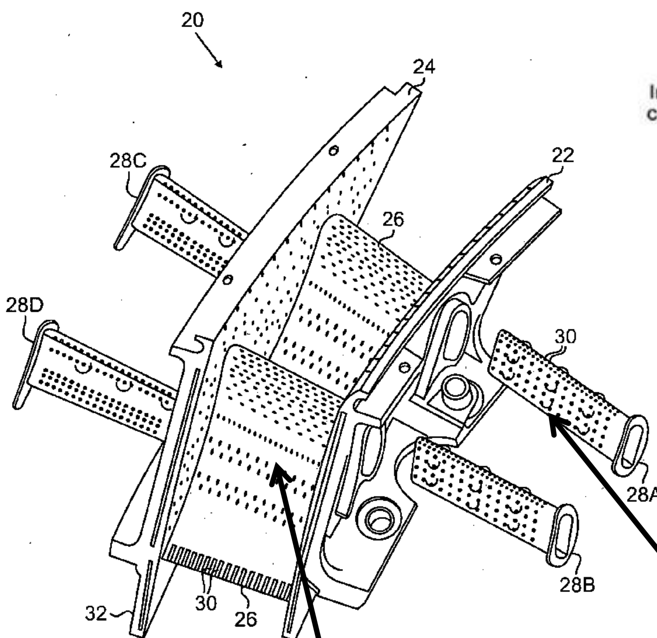
MOTIVATION

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

Turbulated serpentine internal cooling passages

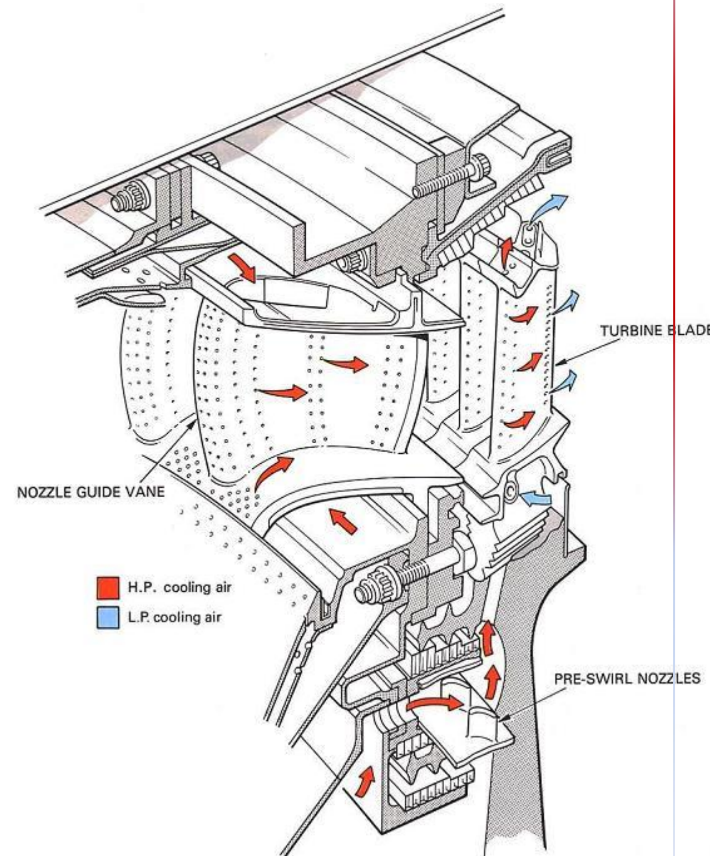


(Gupta et al., 2012)



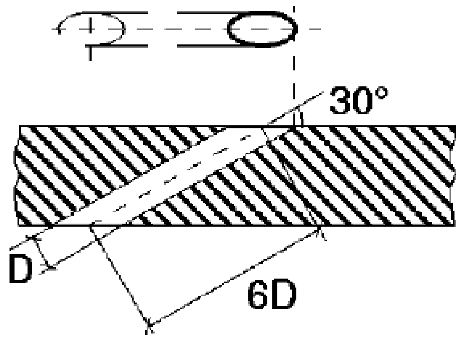
Film Cooling.

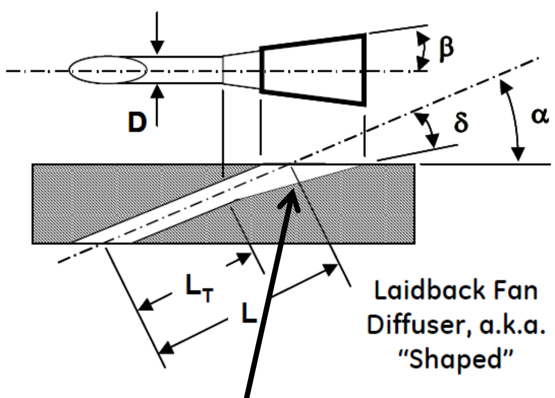
Double walled impingement cooling.



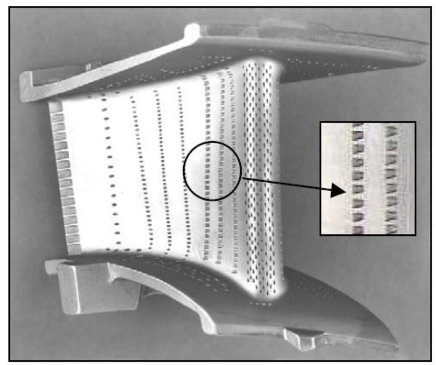
MOTIVATION

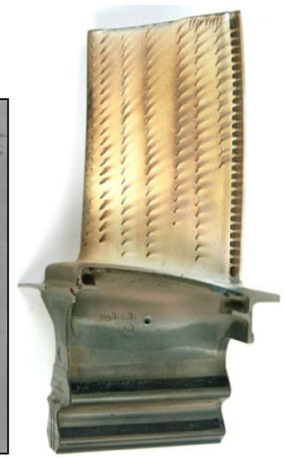
State-of-the-Art in Turbine Cooling – Where are we now?

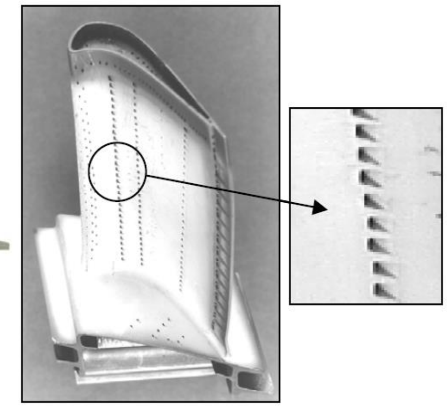




Shaped film holes

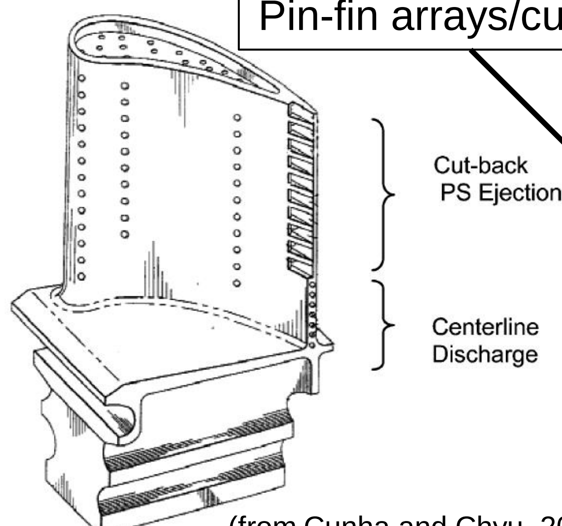


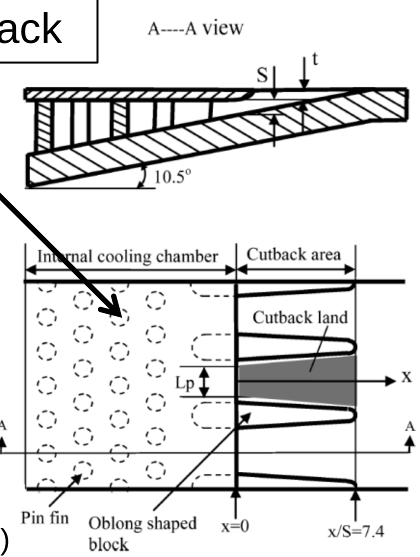




(from Bunker, IGTI2010)

Pin-fin arrays/cutback





(from Cunha and Chyu, 2006)

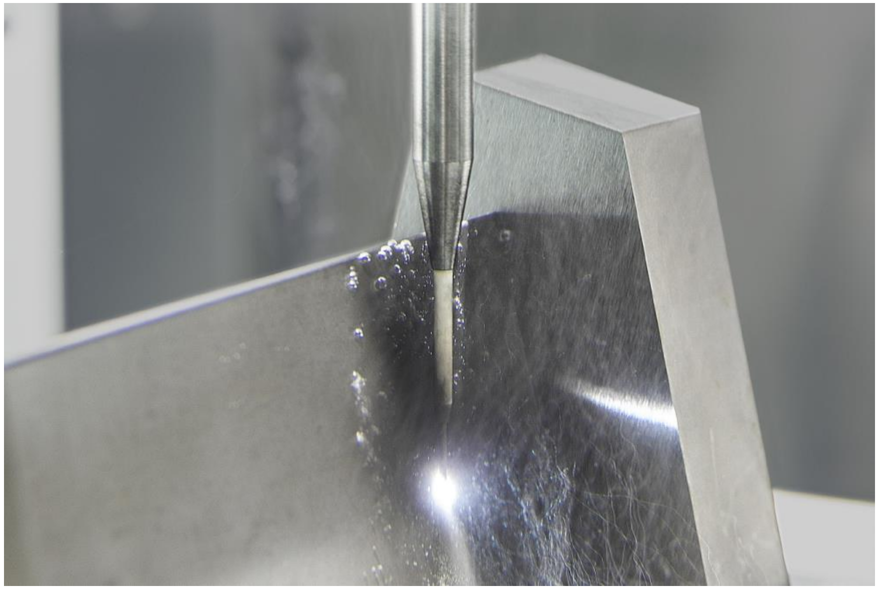
MOTIVATION

Manufacturing Process – Investment Casting

MOTIVATION

Manufacturing Process – Laser Drilling and plunge EDM

Photo courtesy PRIMA/Laserdyne



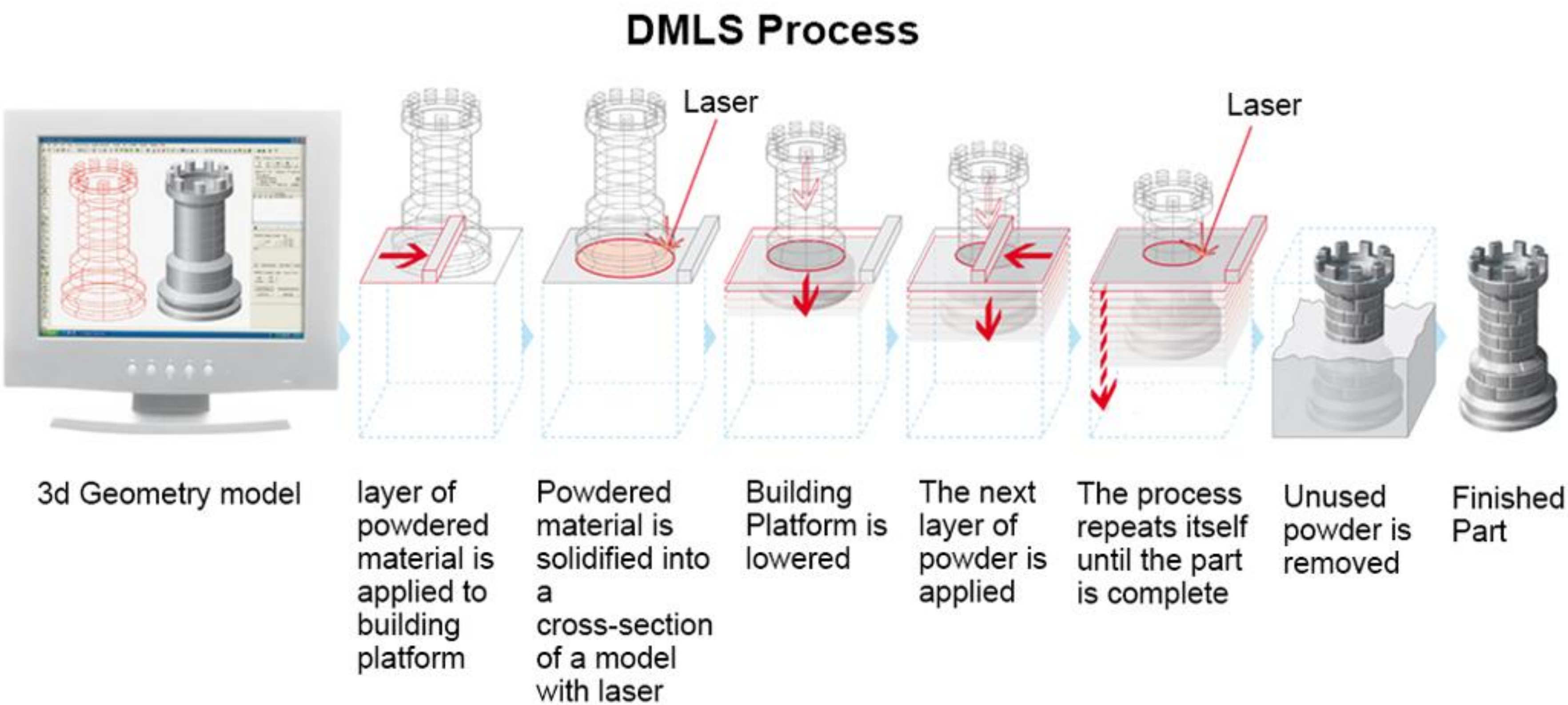
CRITICAL NEED

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 [illegible] impingement for airfoil cooling and advanced near wall cooling techniques. … The increased turbine inlet temperatures 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

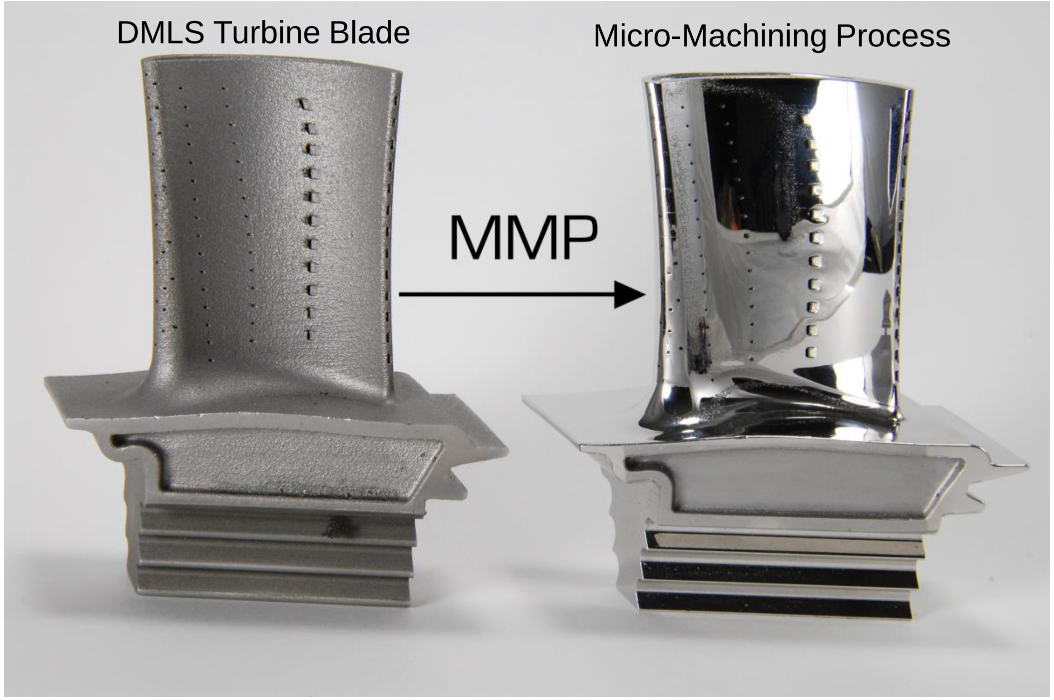
Where will these advances come from…

Direct Metal Laser Sintering

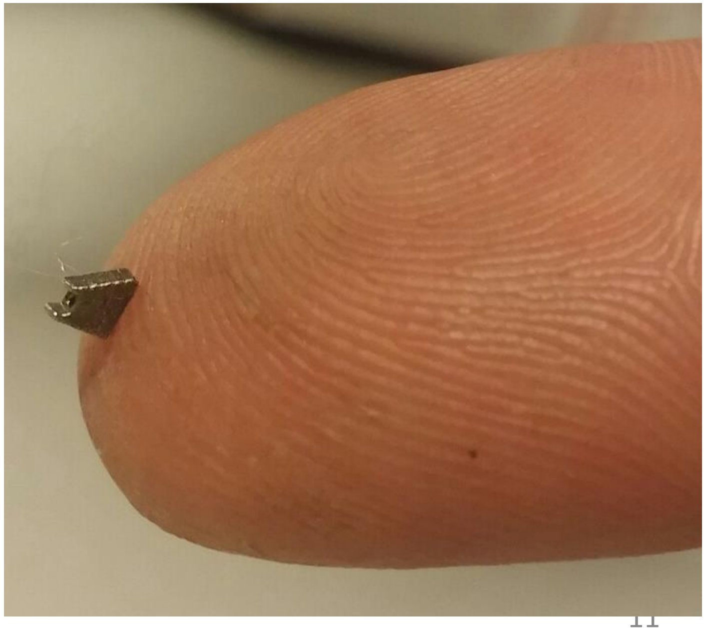


Direct Metal Laser Sintering

Can you fabricate a cooled turbine blade with DMLS?



Just how small can the features be?



INDUSTRY NEWS › LOGISTICS & TRANSPORTATION

Here's what soon-to-be-built high-tech plant in Findlay will mean to GE

Oct 2, 2015, 2:40pm EDT

INDUSTRIES & TAGS Logistics & Transportation, Manufacturing, Aerospace, Automotive, Metals, Innovation, TechFlash, Public Companies

Justine Coyne
Reporter
Pittsburgh Business Times

The investment General Electric Co. is making in its Pittsburgh-area additive manufacturing facility speaks to the level of interest and dedication the company has in 3-D printing technology, according to Greg Morris, general manager for additive technologies at GE Aviation.

The whole idea behind the 125,000-square-foot research center the company is in the process of building in Findlay Township is to be a testing ground for different businesses to tap into additive technologies being in developed in areas like aviation to spread the technology throughout GE (NYSE: GE) businesses.

Greg Morris, speaking Oct. 1 at a conference hosted by Catalyst Connection.

SCOTT DIETZ

It is the largest center of its kind focused on additive in GE's operations, according to Morris. The facility represents a $32 million investment over three years and will create 50 high-tech engineering jobs initially, the company said when the for the facility's opening.

"From prototyping to tooling there are many opportunities to use additive throughout GE's business to make us more efficient and reduce overall costs," Morris said in an interview with the Pittsburgh Business Times.

GE Aviation already has made a big bet in additive manufacturing. The company's CFM LEAP jet engine features a 3-D printed fuel nozzle that took a part that required 20 different components to be manufactured and assembled, and replaced it with a single printed part. GE is y in the process of scaling up for production at its facility in Auburn, Ala., and expects to produce the nozzles at a rate of 40,000 per year, according to Morris.

Morris, who is based in Cincinnati, said his group is one of several that will work with the researchers and engineers at the new facility.

"I think it's going to allow for a more fundamental look as an emerging capability to think about how we can design parts differently," he said.

With additive manufacturing on the brink of becoming mainstream and playing such an emerging role in Pittsburgh, it's important for manufacturers of all sizes to take notice, said Petra Mitchell, president and CEO of Catalyst Connection.

"If you look at Alcoa's investment, GE's investment, and the fact that the National Additive Manufacturing Institute, America Makes, is so close by, this region becoming a hub for additive manufacturing," she said.

On Sept. 3 Alcoa Inc. announced it would be investing $60 million in its Pittsburgh-area research and development facility in order to expand the company's additive manufacturing capabilities.

For the companies her organization works with, which are largely small and mid-size manufacturers, Mitchell said most are still trying to figure out how additive is going to impact their business.

"I think the initial investment is in learning and evaluating what this means for their particular business," she said.

Morris joined GE in 2012 when the company acquired two of his companies, Morris Technologies and Rapid Quality Manufacturing. He said that from a creative aspect, additive should be challenging companies of all sizes.

"Additive is another tool in the toolbox that allows for greater creativity, whether you're leveraging the technology to launch or start a small company, or it's enabling the largest of corporate entities rethink they way they do things," he said.

Justine Coyne covers manufacturing and higher education.

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

Dr. Jeffrey Bons
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Ohio State University
Columbus, OH

Robin Prenter
PhD Candidate

Co-PI
Focus: Computational Fluid Dynamics and Heat Transfer

Dr. Ali Ameri
Research Scientist
Department of Mechanical and Aerospace Engineering
Ohio State University
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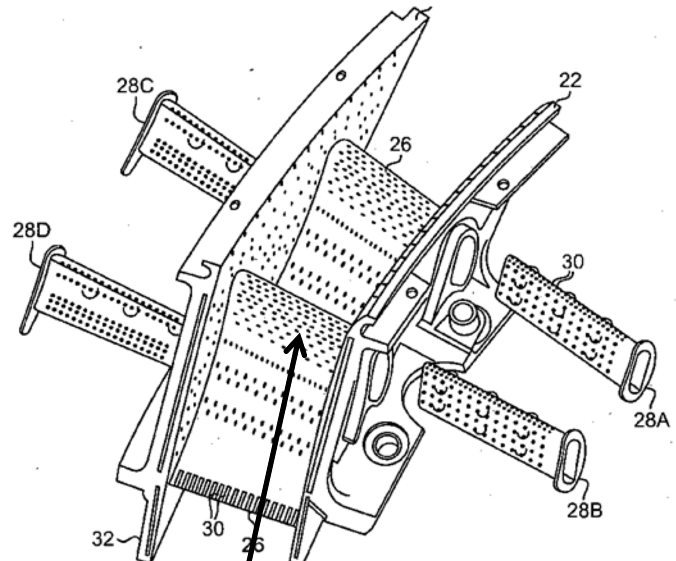
Arif Hossain
PhD Candidate

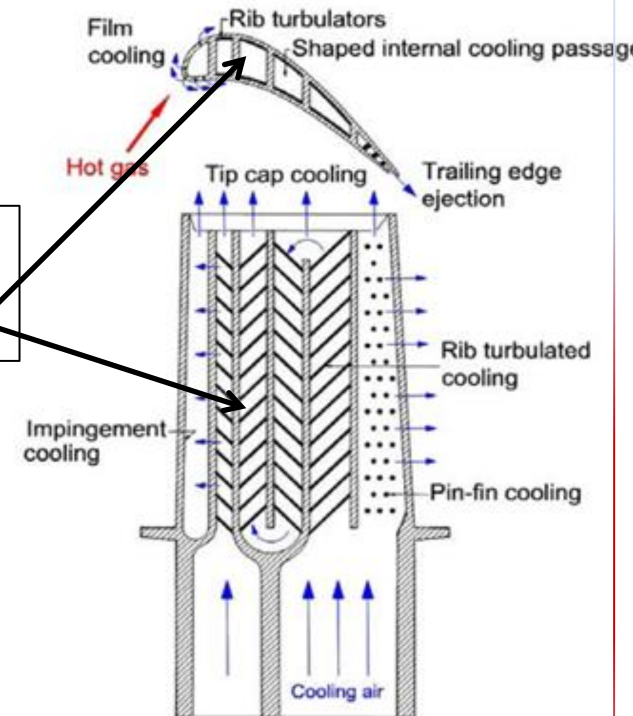
Co-PI
Focus: Experimental Fluid Mechanics, Fluidic Oscillator Development

Dr. Jim Gregory
Associate Professor
Department of Mechanical and Aerospace Engineering
Ohio State University
Columbus, OH

Cooling Designs Enabled by DMLS



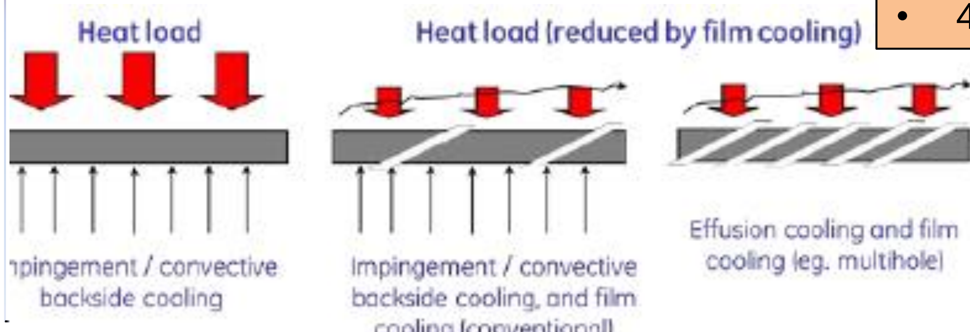
All film cooling holes fed from the same reservoir – YET not all regions NEED the same coolant flowrate!

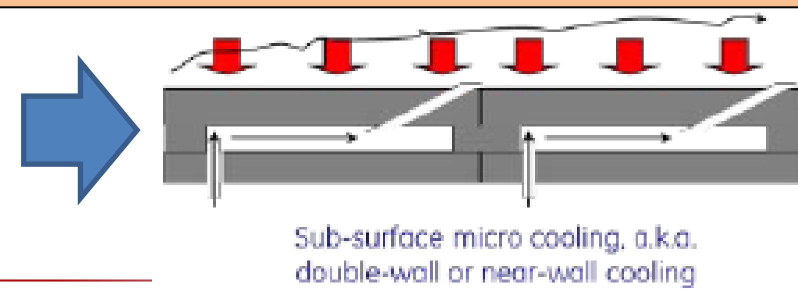


Blade is cooled from the center – YET only surface needs cooling!

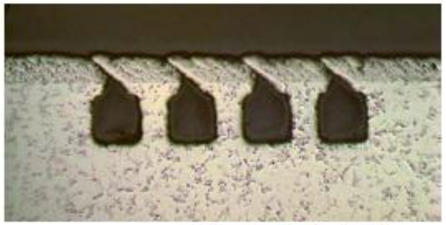
Bunker (IGTI 2013) showed that "skin cooling" could yield

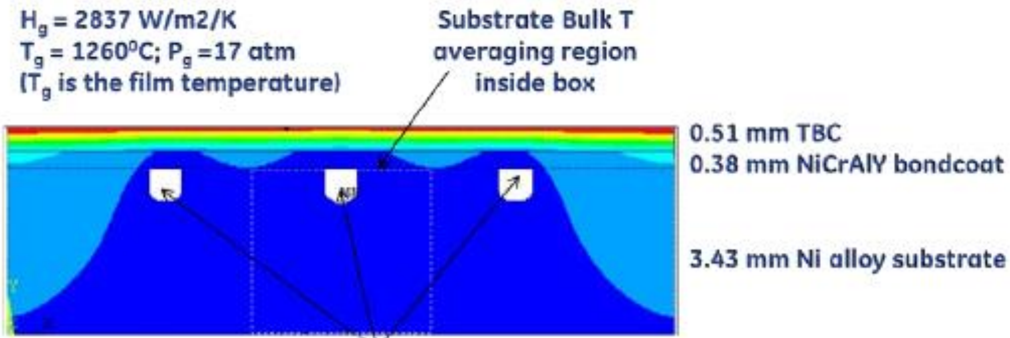
- 25% cooling flow reductions
- 50% thermal gradient (stress) reductions.
- 40% coolant savings.

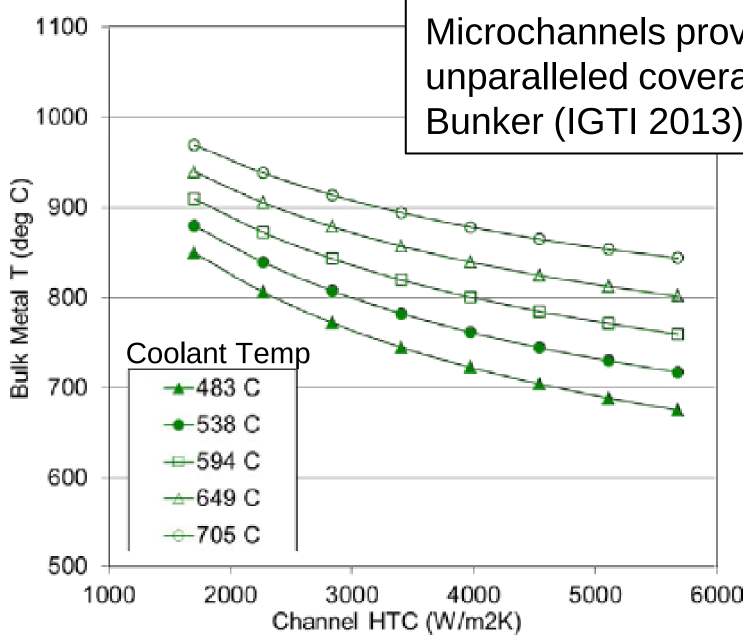




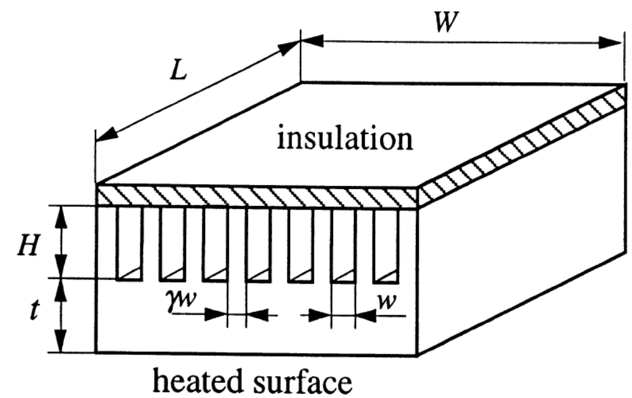
Cooling Designs Enabled by DMLS

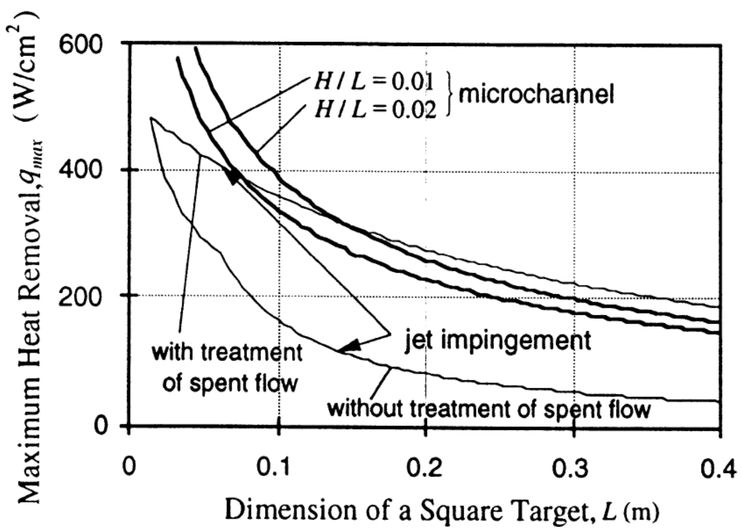






Microchannels provide unparalleled coverage. Bunker (IGTI 2013)

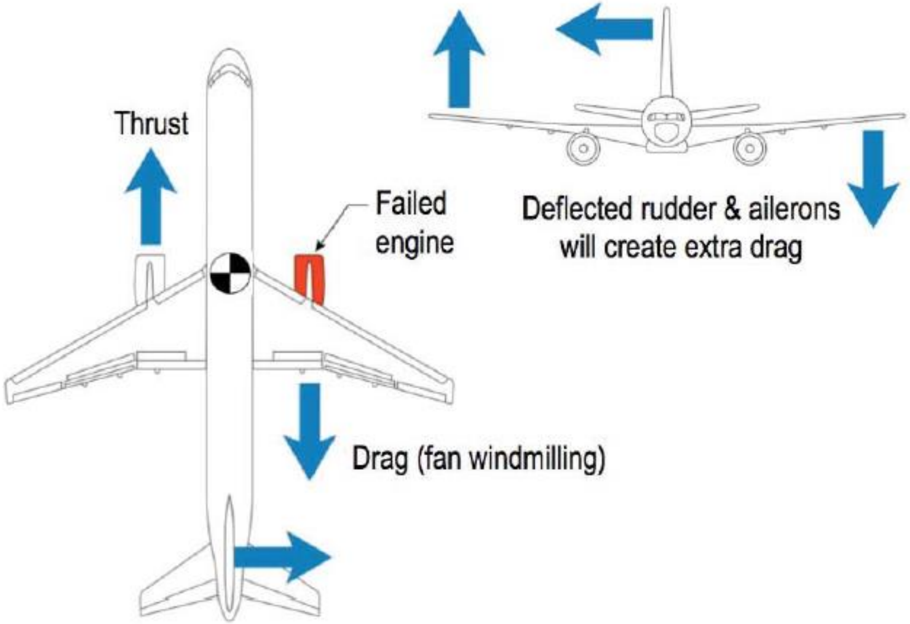


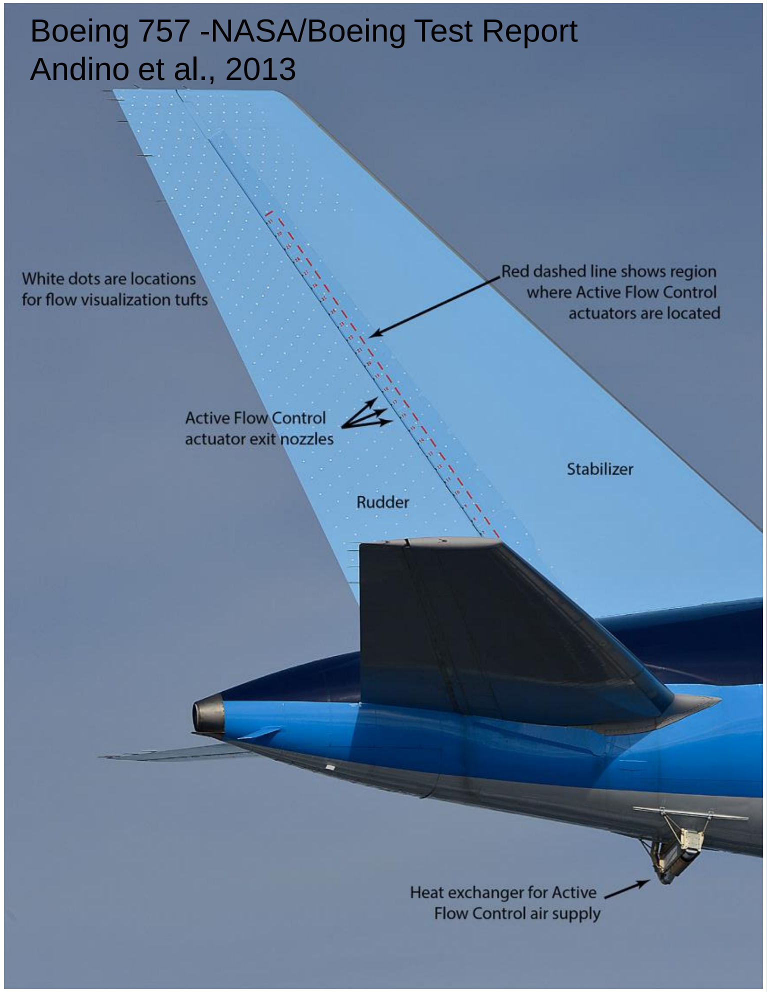


Lee and Vafai (IJHMT 1999) showed microchannel cooling is superior to backside jet impingement cooling

Cooling Designs Enabled by DMLS

Sweeping Fluidic Oscillators for flow control

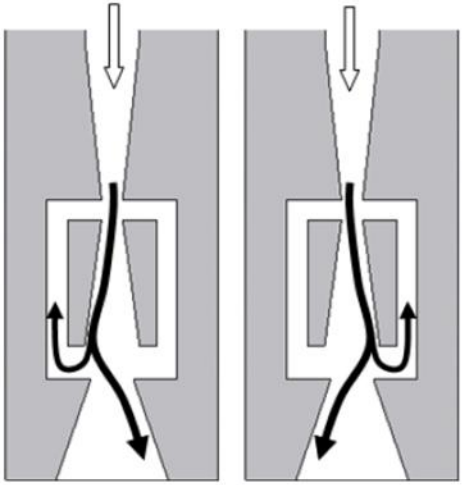


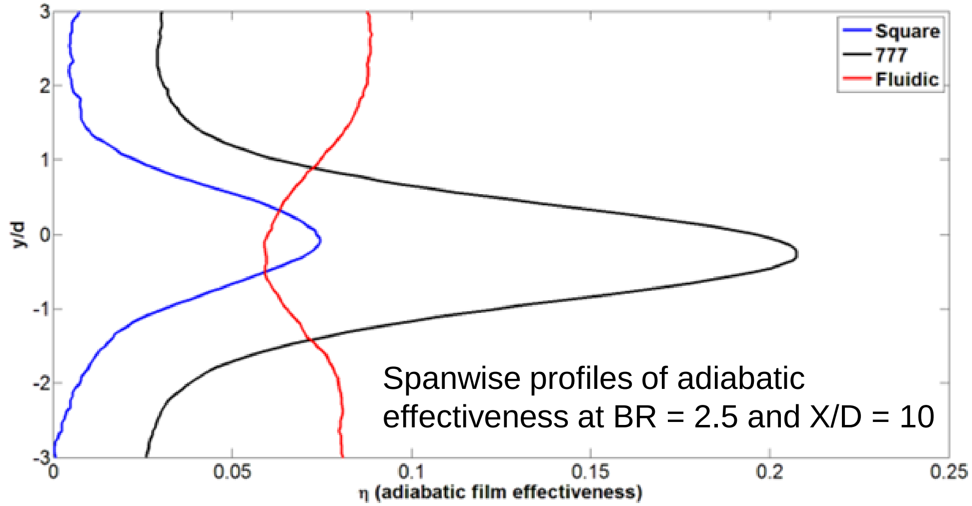


…and many other applications…

Cooling Designs Enabled by DMLS

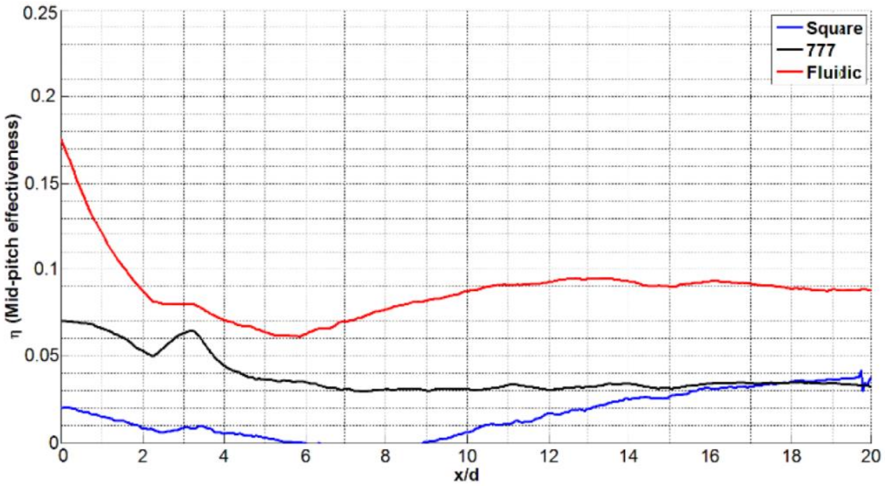
Sweeping Fluidic Oscillators
(Thurman et al. IGTI2015)

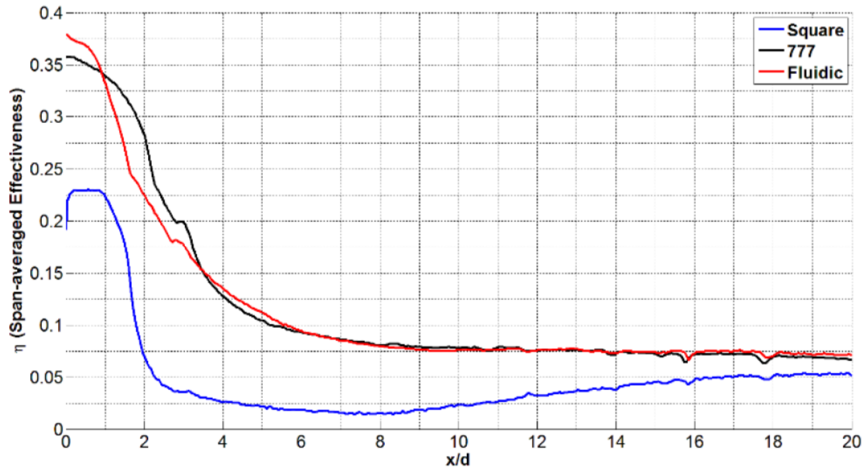




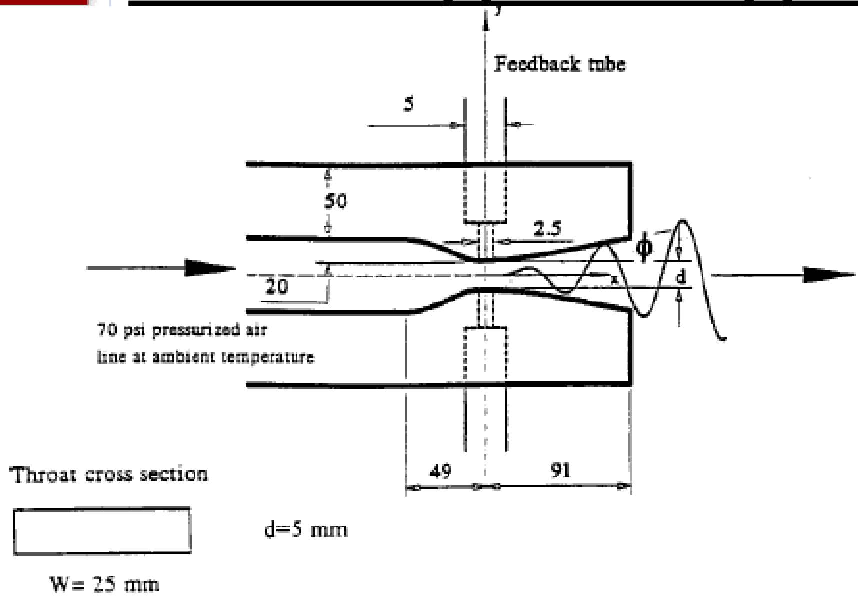
Spanwise profiles of adiabatic effectiveness at BR = 2.5 and X/D = 10

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



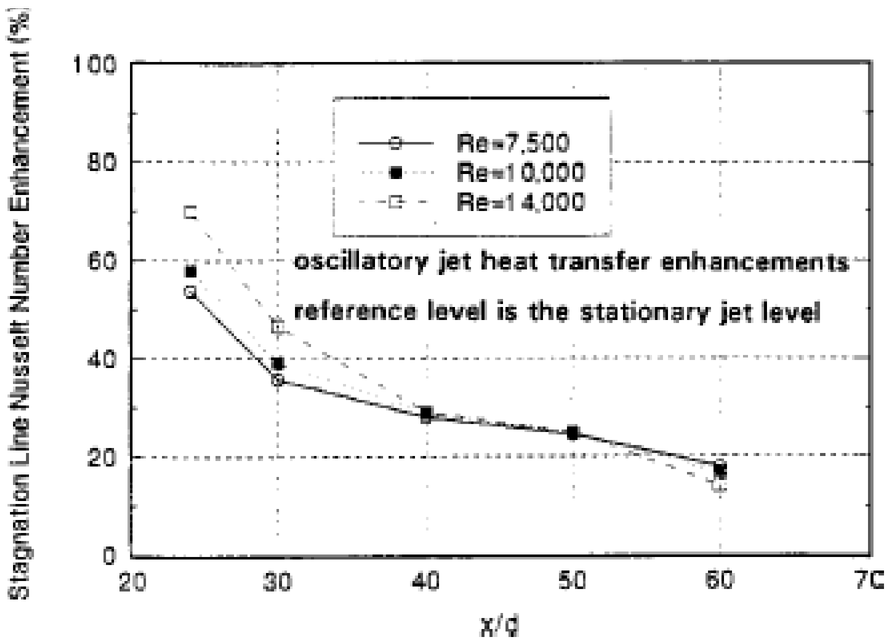


Cooling Designs Enabled by DMLS

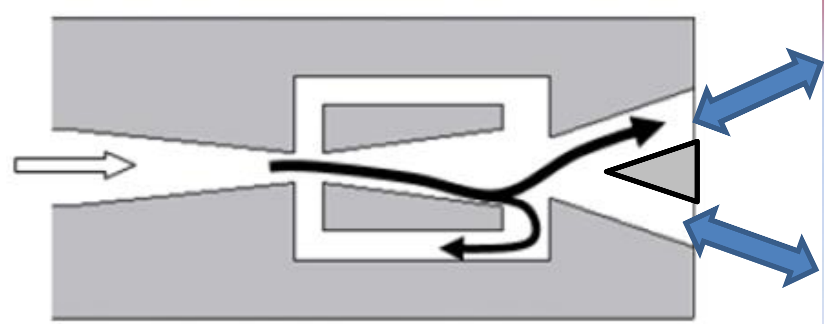


Pulsed impingement cooling jet (Camci & Herr, JHT 1999)

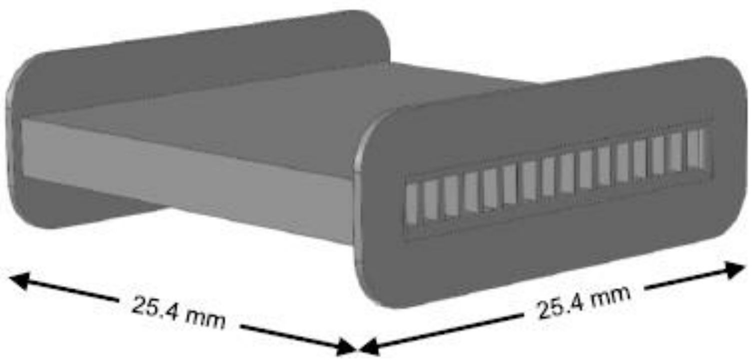
- 40-60% heat transfer enhancement compared to steady jets for x/d<30
- No external input required to produce oscillation



Pulsing Fluidic Oscillators (Gregory)



Potential Concerns with DMLS



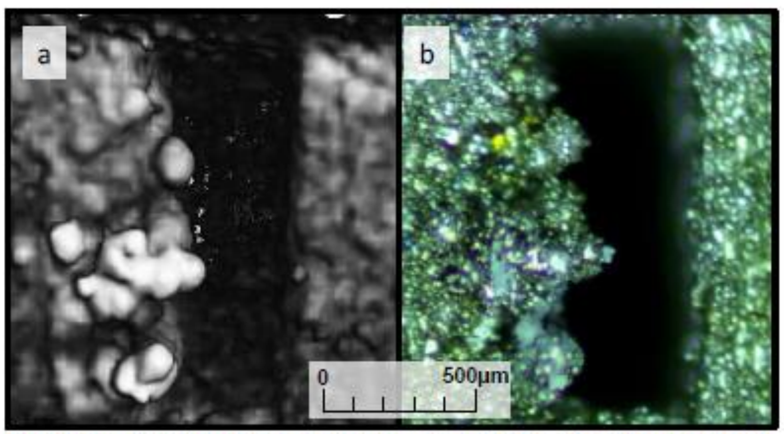
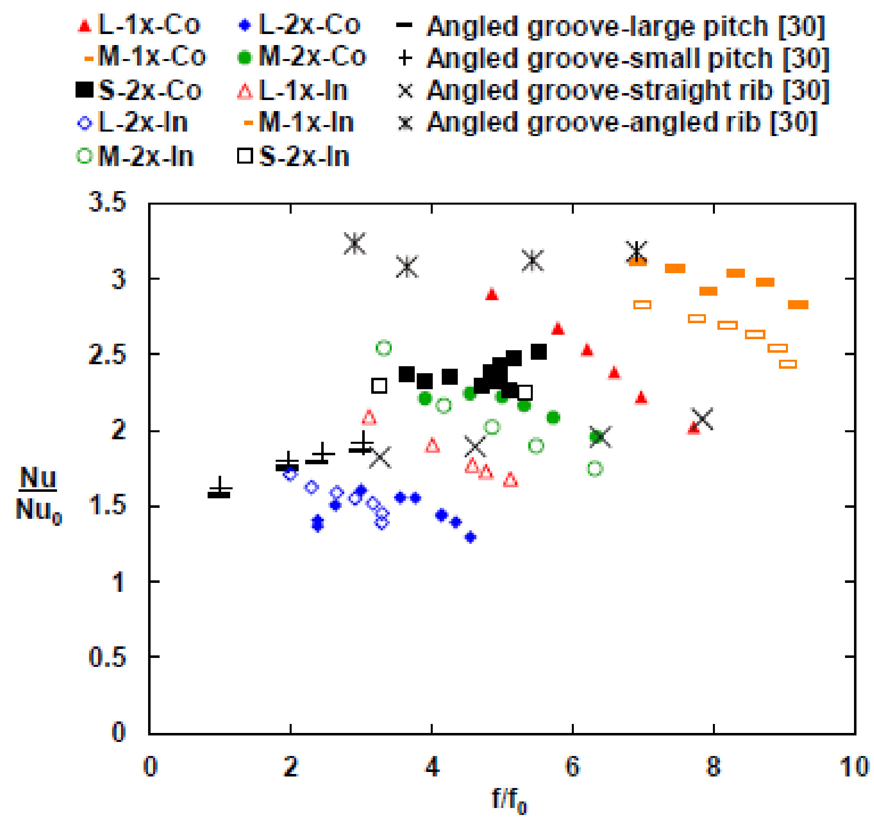


Figure 5. Image of the opening of a single channel of the M-2x-Co coupon a) digitally reconstructed from CT scan data and b) collected with a light microscope.

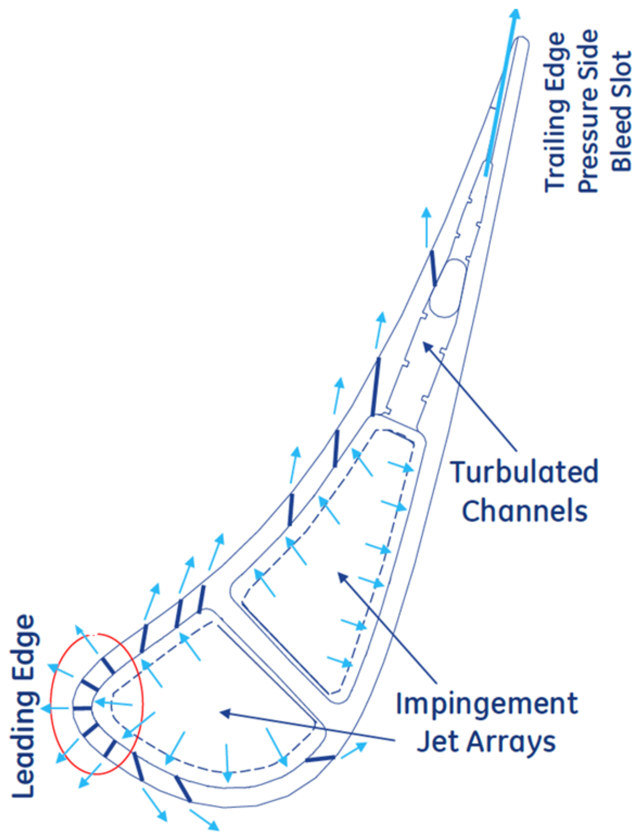
Stimpson et al. (IGTI2015)

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



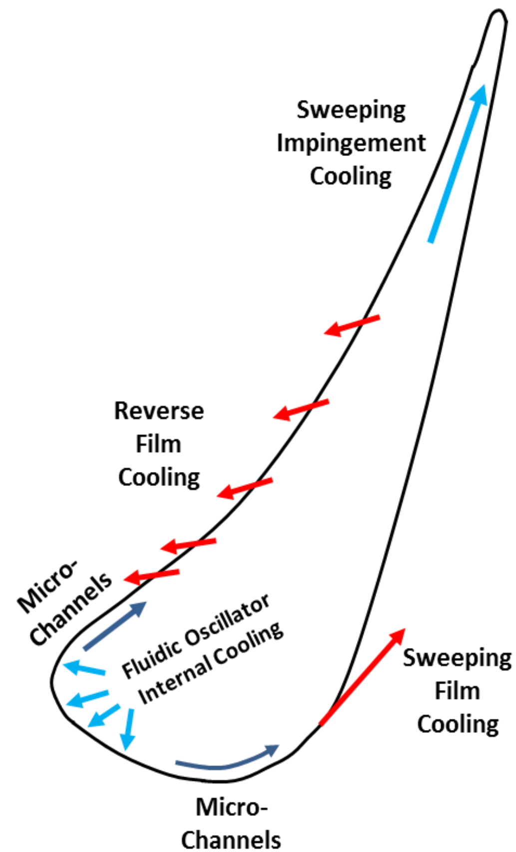
Innovative Cooling Designs

Combine all technologies on single NGV.



(a)

(Bunker, IGTI 2013)



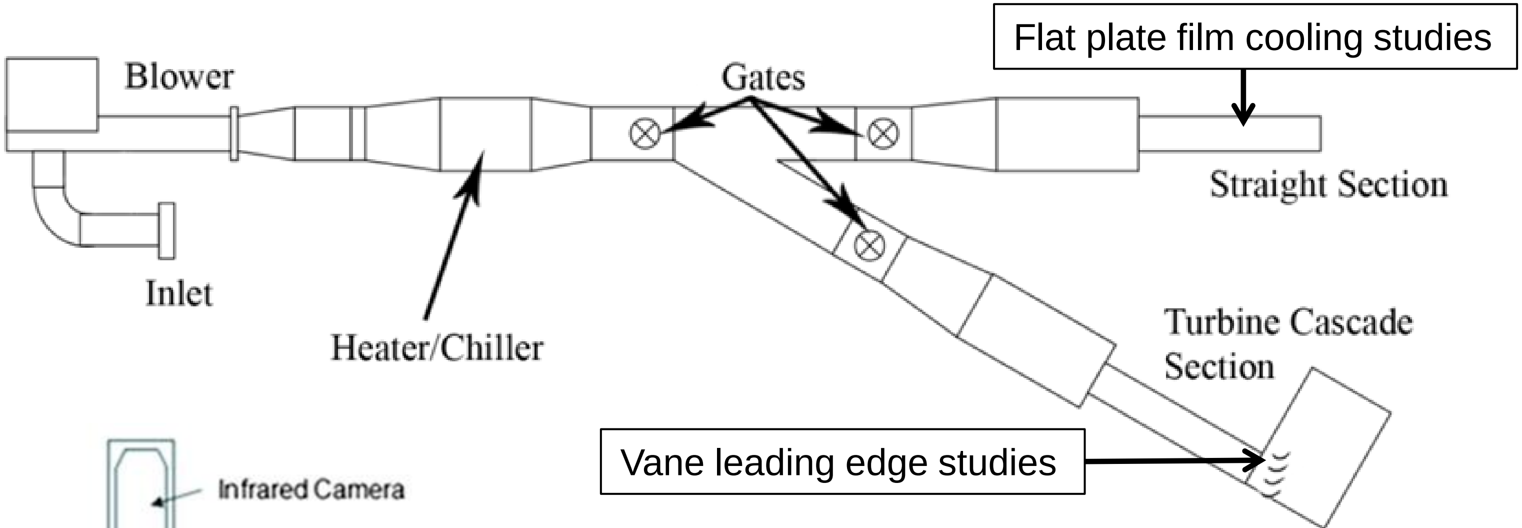
(b)

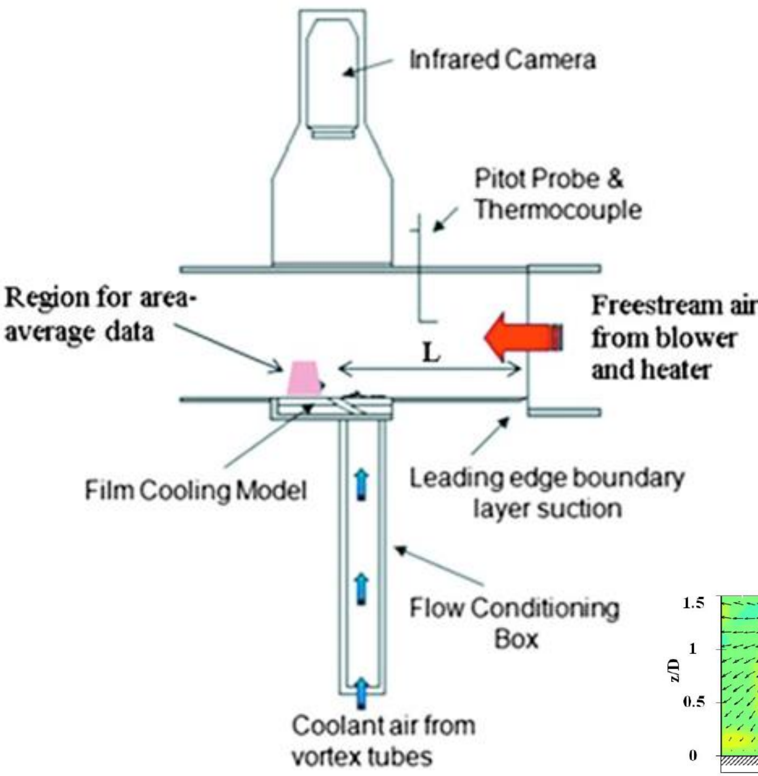
(Notional DMLS NGV Model)

Turbine Heat Transfer Facilities

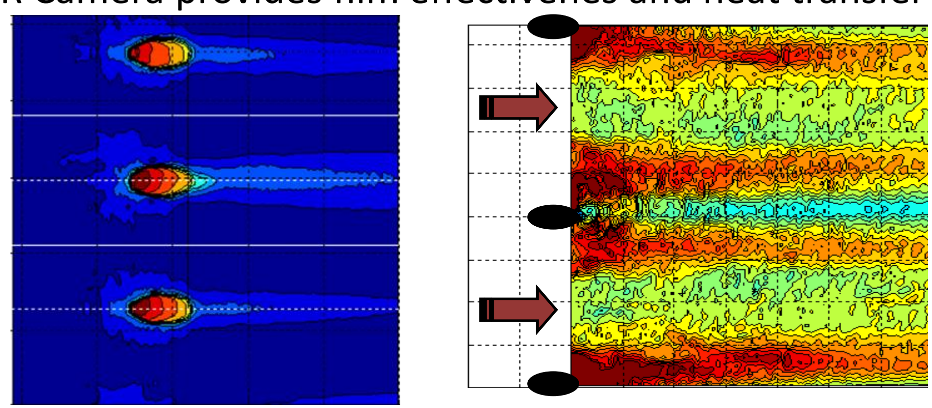
- For innovative concepts to be viable, must be vetted in facilities that simulate the real operating environment
- Graduated complexity
  - Low speed, large scale
  - High speed, smaller scale
  - High speed, high temperature, small scale

Low Speed Large Scale Tunnel

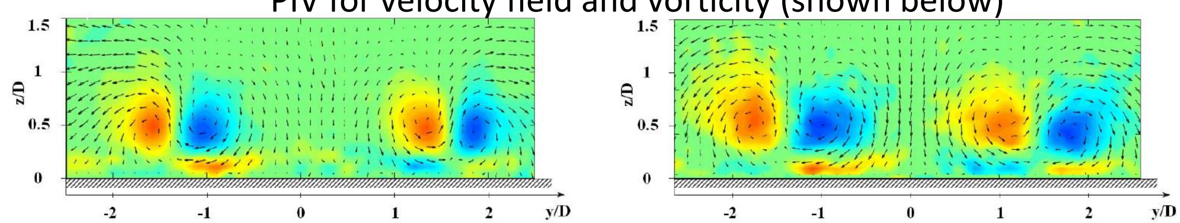




IR Camera provides film effectivenes and heat transfer



PIV for velocity field and vorticity (shown below)

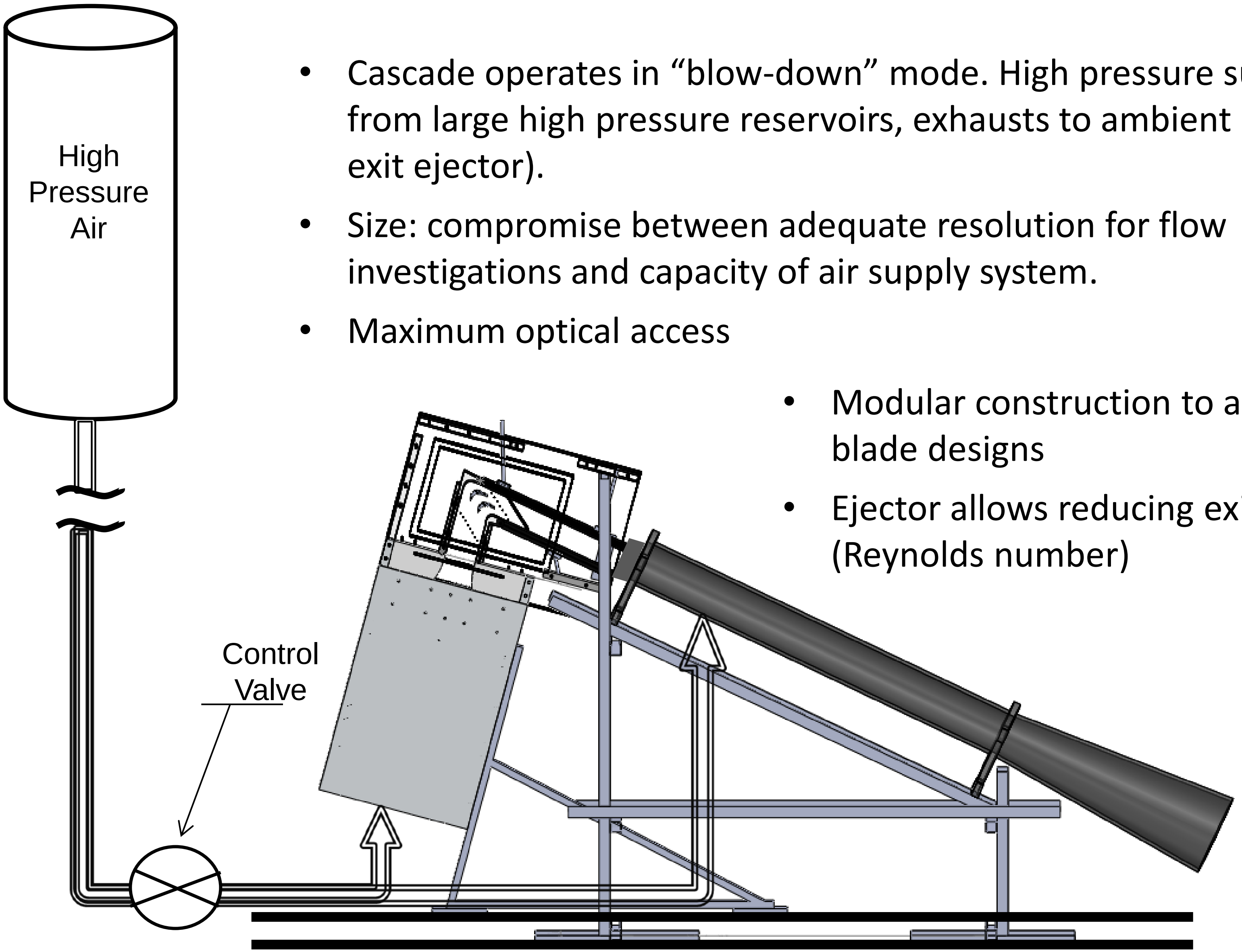


(c) $Tu = 0.7, x/D = 7$

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

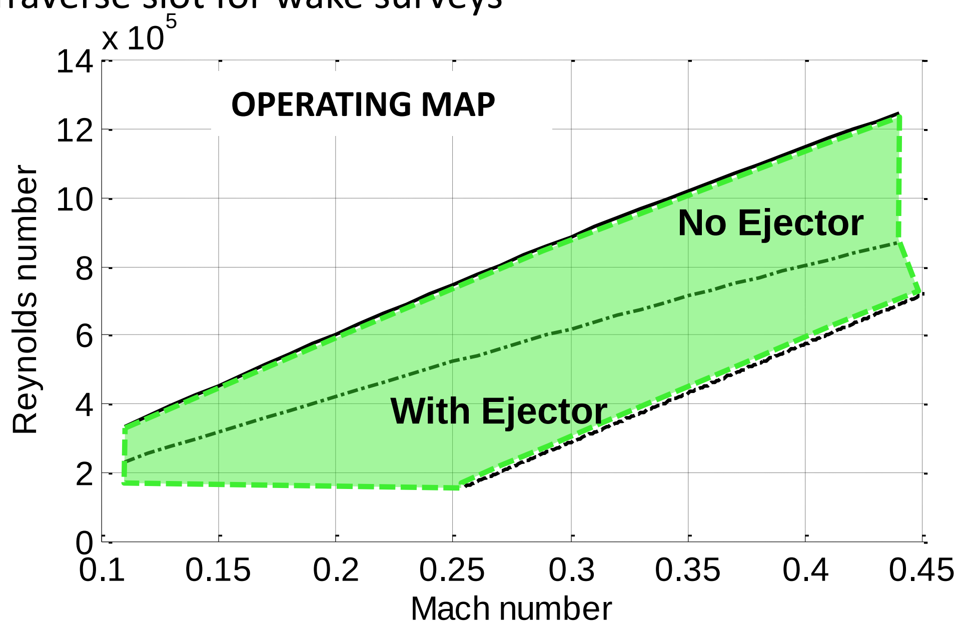
Transonic Turbine Cascade

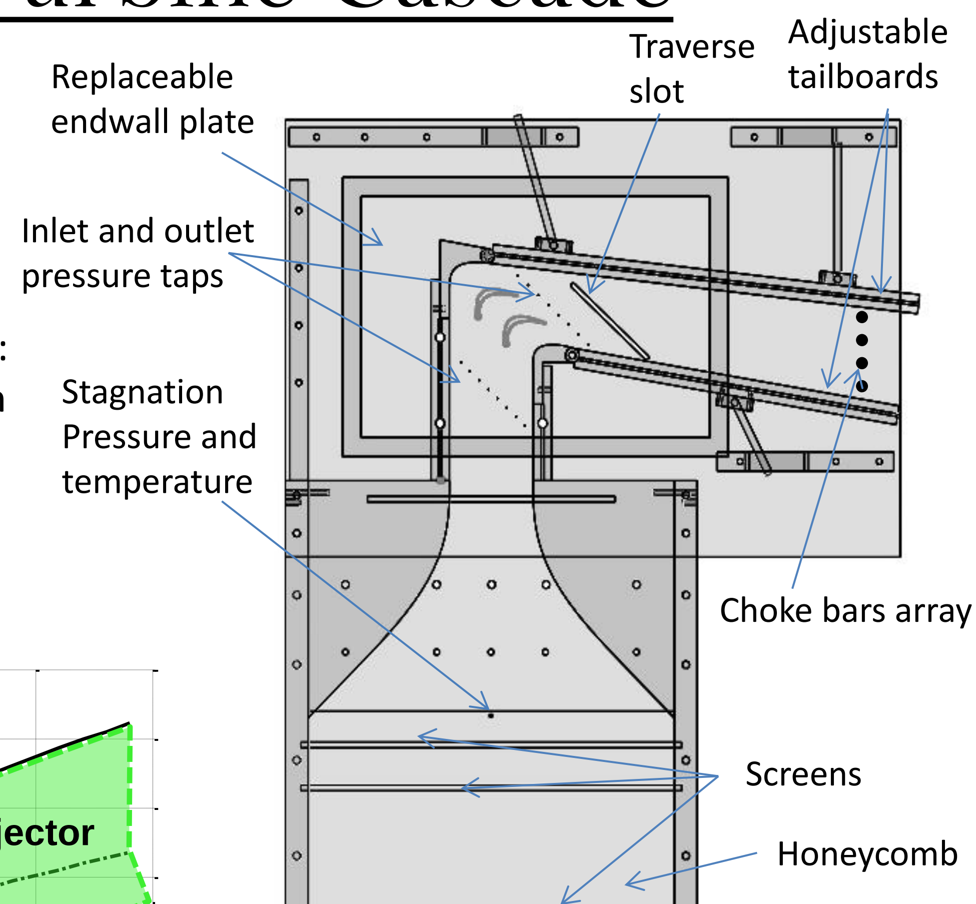
- Cascade operates in “blow-down” mode. High pressure supplied from large high pressure reservoirs, exhausts to ambient (without exit ejector).
- Size: compromise between adequate resolution for flow investigations and capacity of air supply system.
- Maximum optical access
- Modular construction to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

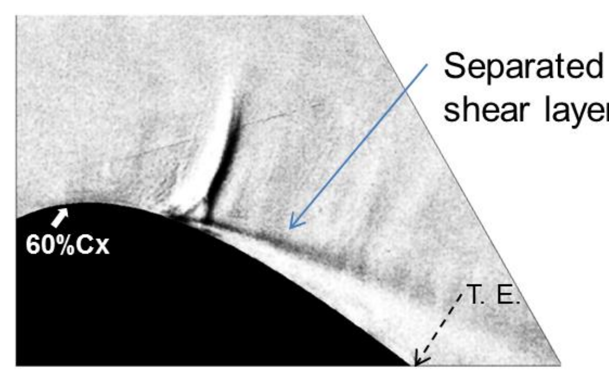


Transonic Turbine Cascade

- 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 within 1.5%. Tu = 1%
- Inlet and exit wall pressure taps
- Traverse slot for wake surveys

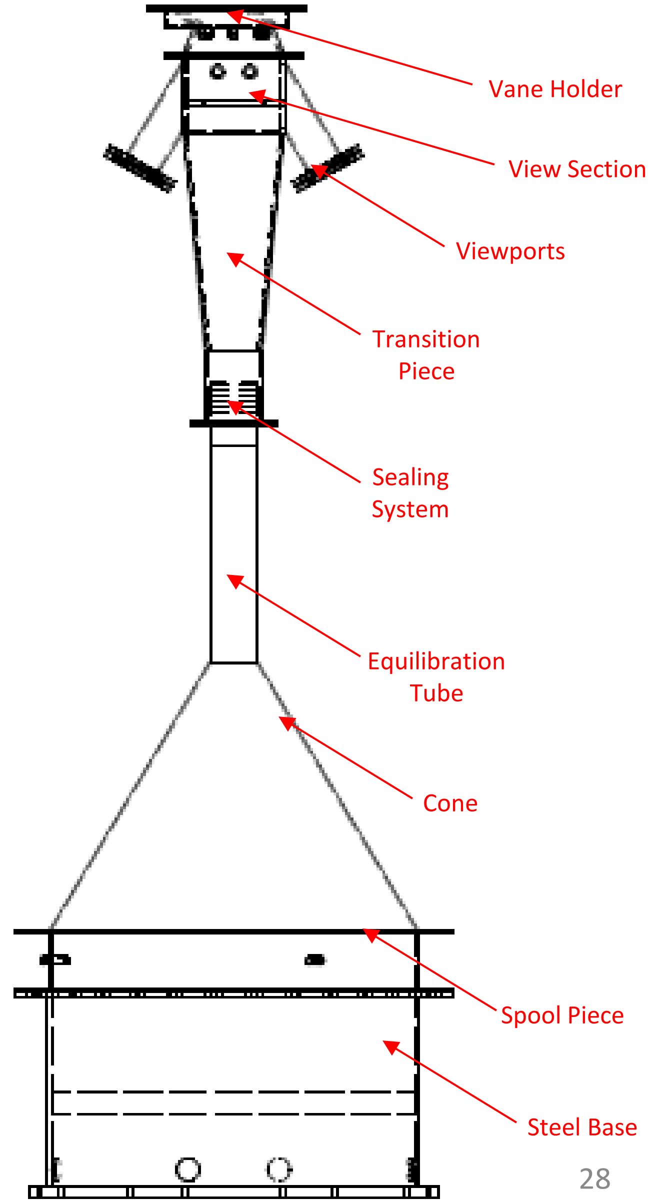




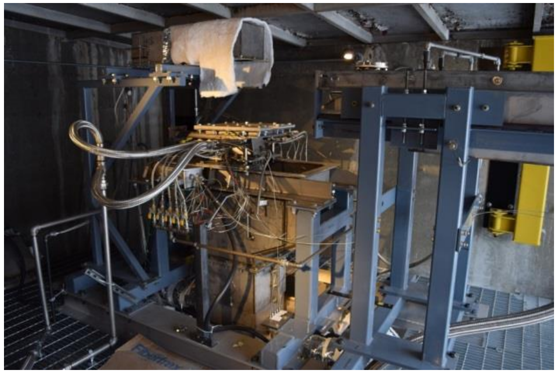


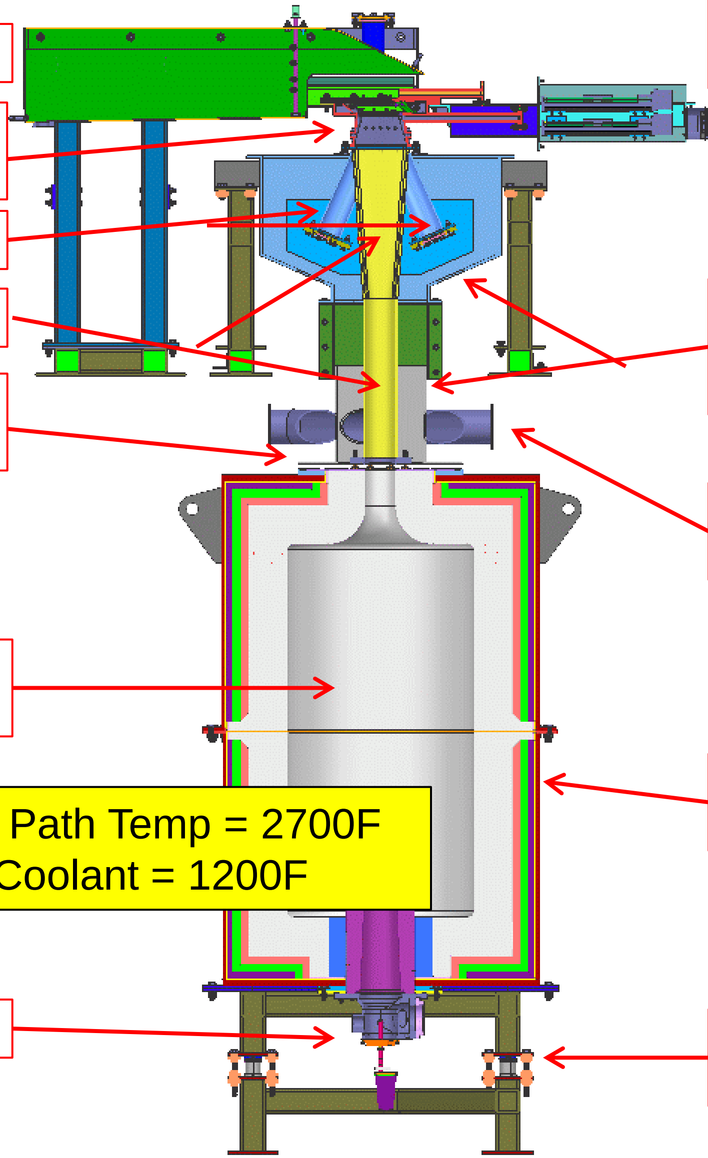
OSU's Turbine Reacting Flow Rig (TuRFR)

- 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)

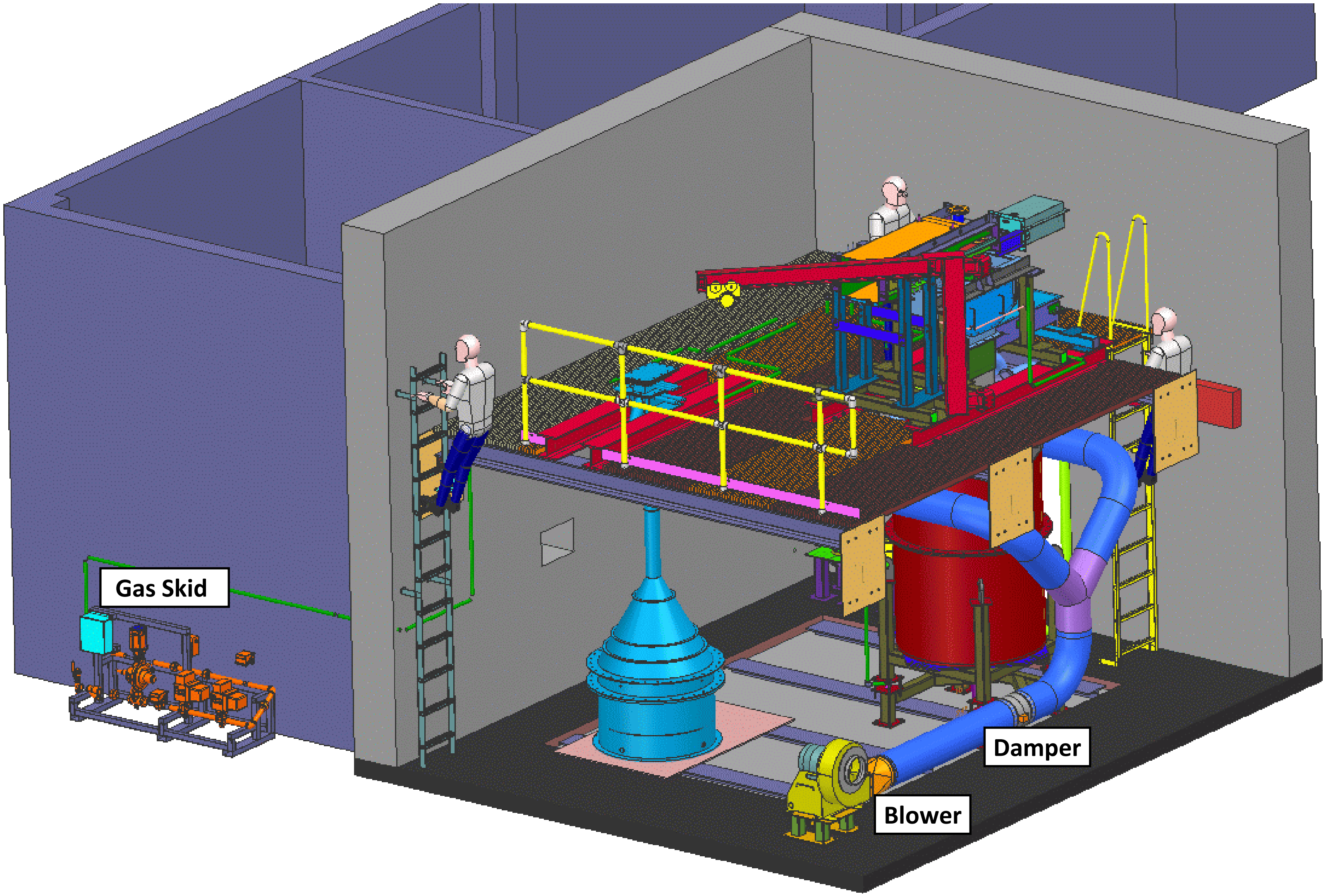


TuRFR II

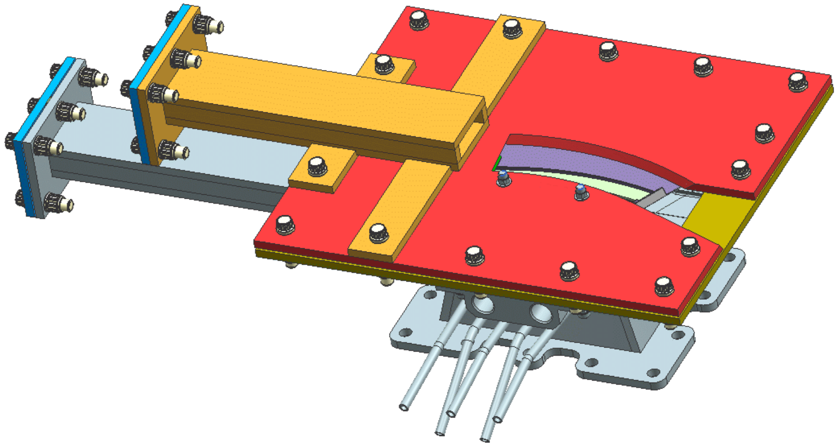


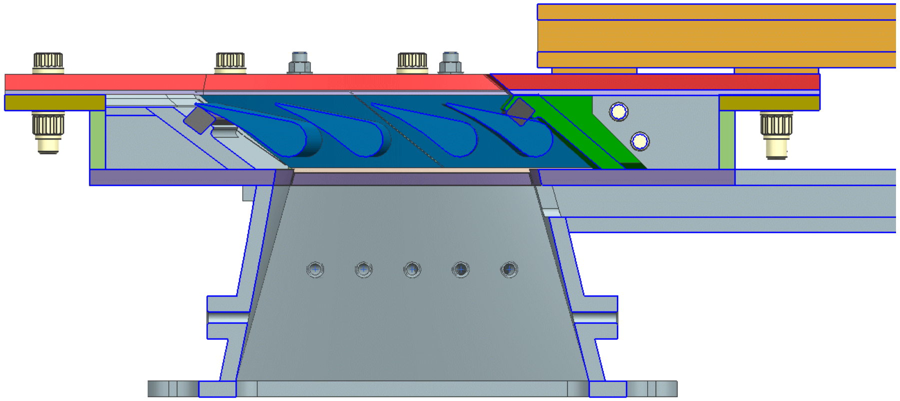


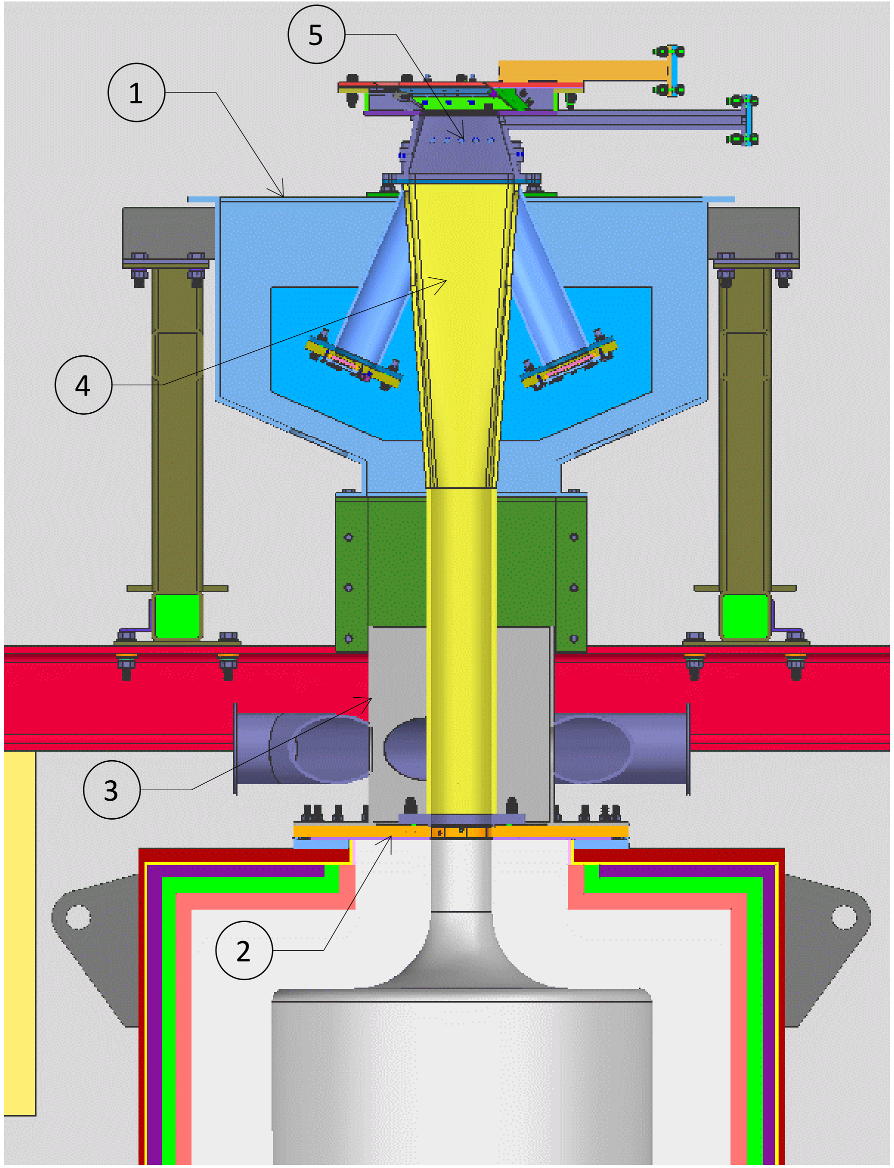
Max Gas Path Temp = 2700F
Max Coolant = 1200F


Gas Skid
Damper
Blower

TuRFRll Test Section

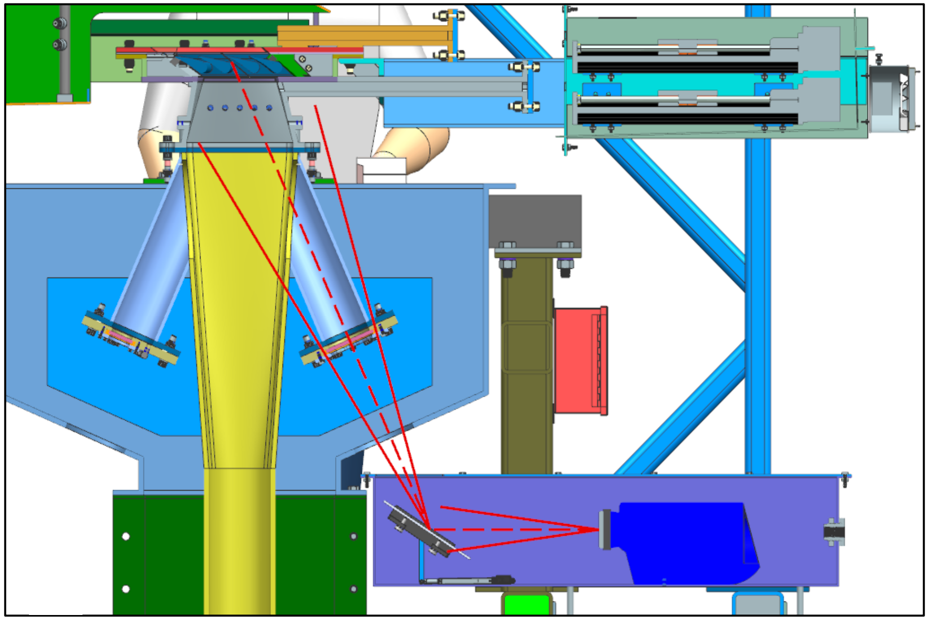




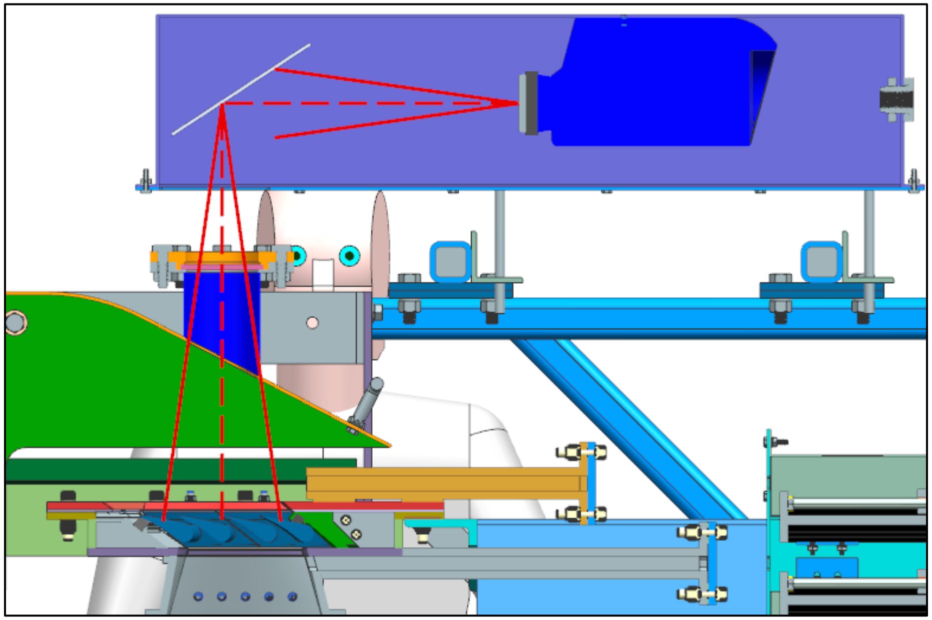


Optical Access

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 for pressure surface
  - Microcooling circuits
- 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
- 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

Accomplishments to date

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

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.
- Allows exploration of the broader design space to find promising combinations of feasible variables for the application.
- We plan to use CFD at every stage of our research.

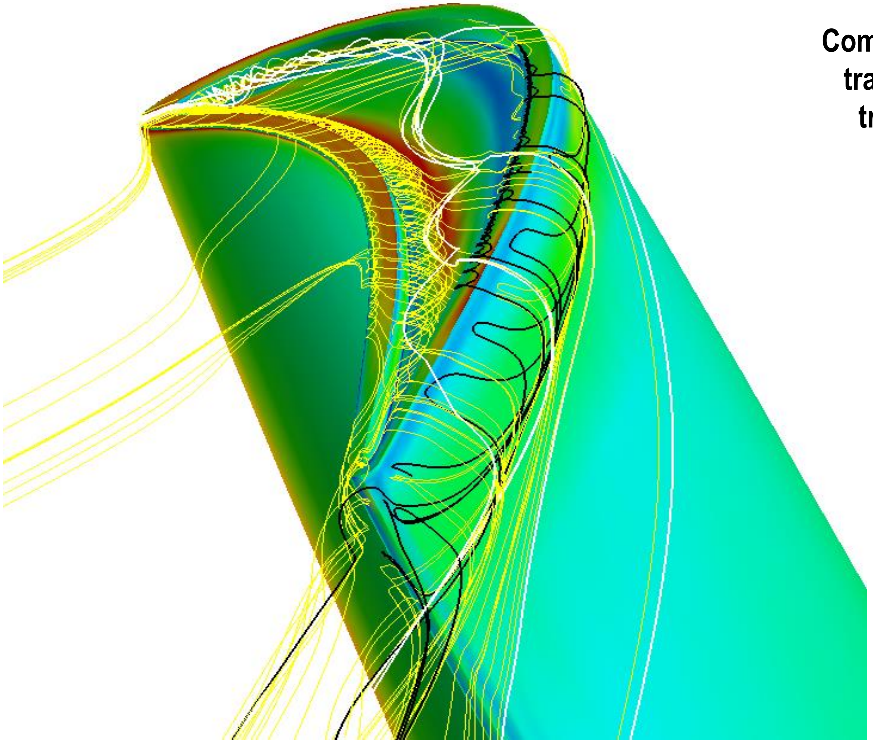
CFD Methods Utilized

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

Capabilities

- The team has been engaged in computational analysis of many types of flows and heat transfer analyses both steady and unsteady.
- Examples follow:

CAPABILITIES



Tip Gap Modeling

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

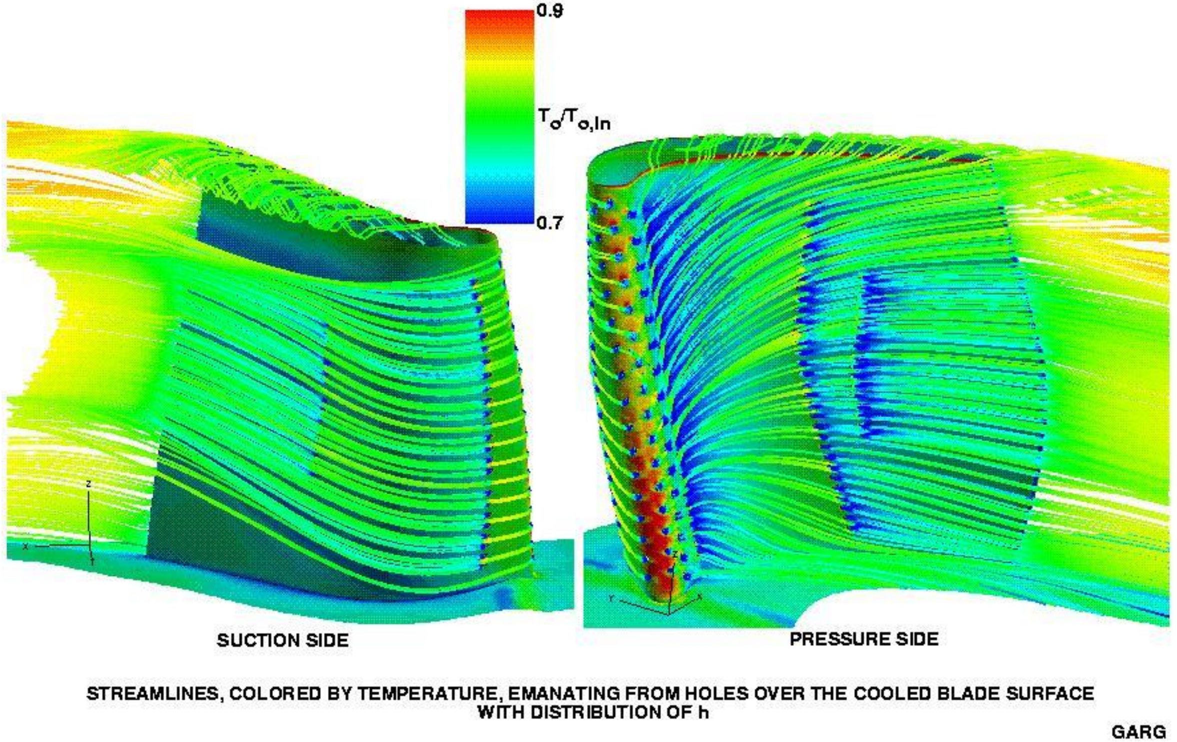
•Blade and Tip Heat Transfer

(Shyam and Ameri, 1998)

CAPABILITIES

Film Cooled Heat Transfer Results

Three Dimensional film-cooled blade analysis



- Blade film cooling

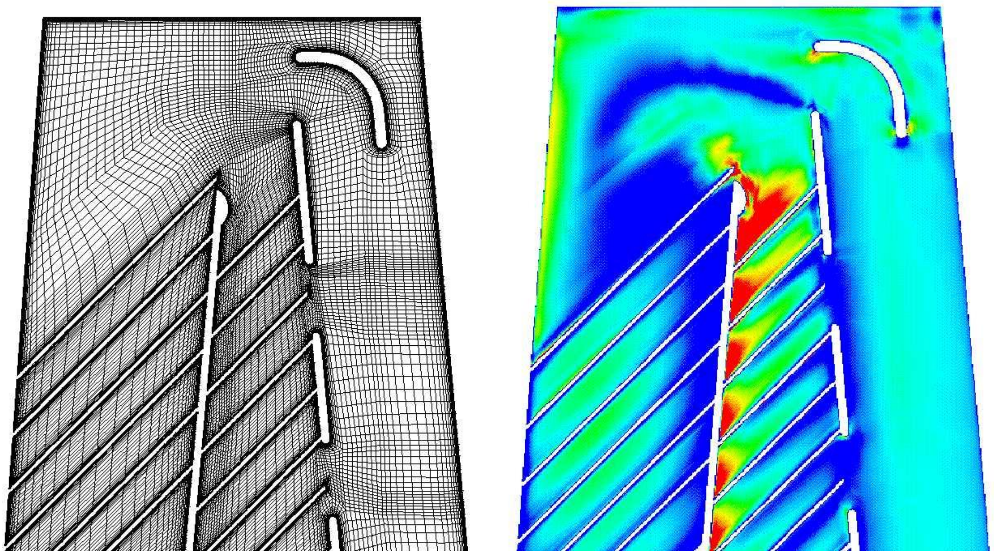
(Garg, 1999)

CAPABILITIES

Internal Coolant Passage Modeling

computed
heat transfer
in internal passages

Grid



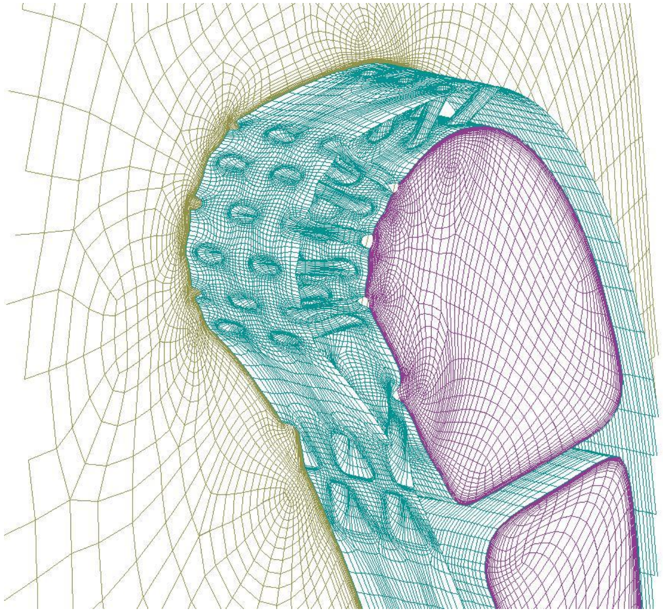
•Internal Heat Transfer

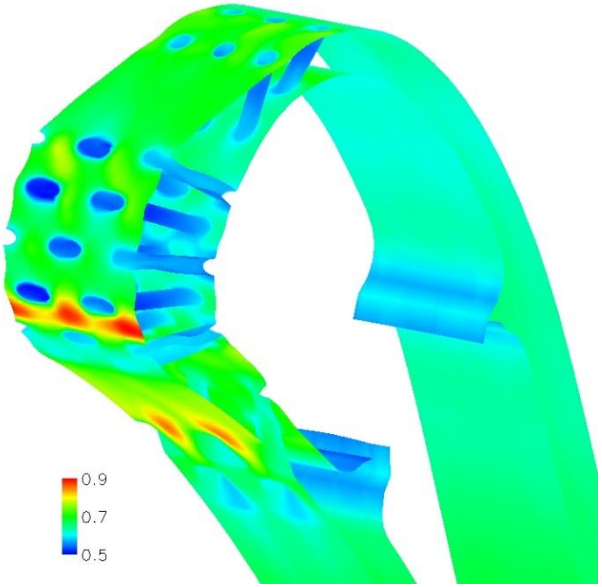
(Rigby and Bunker, 2002)

CAPABILITIES

Conjugate Heat Transfer

wall temperatures





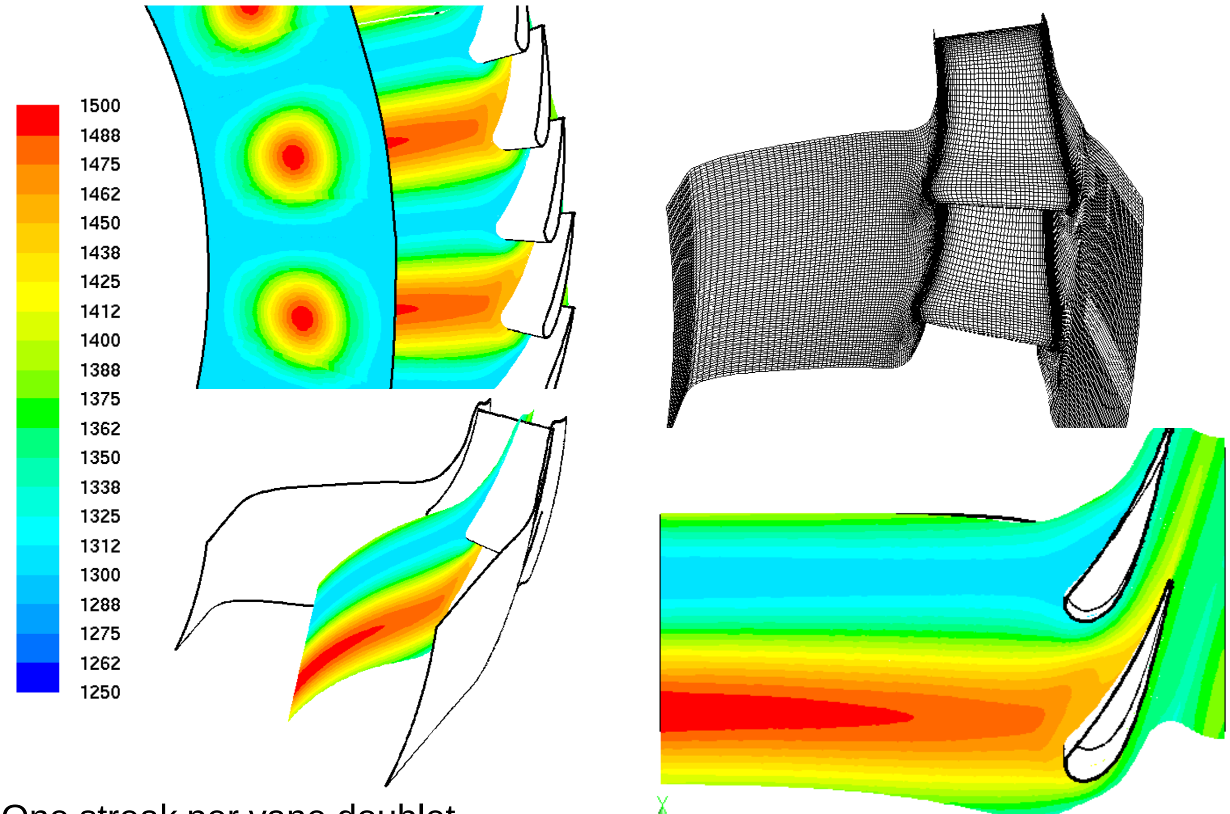
Grid
Solution

Conjugate

• Conjugate Heat Transfer

(Heidmann, Rigby and Ameri, 2003)

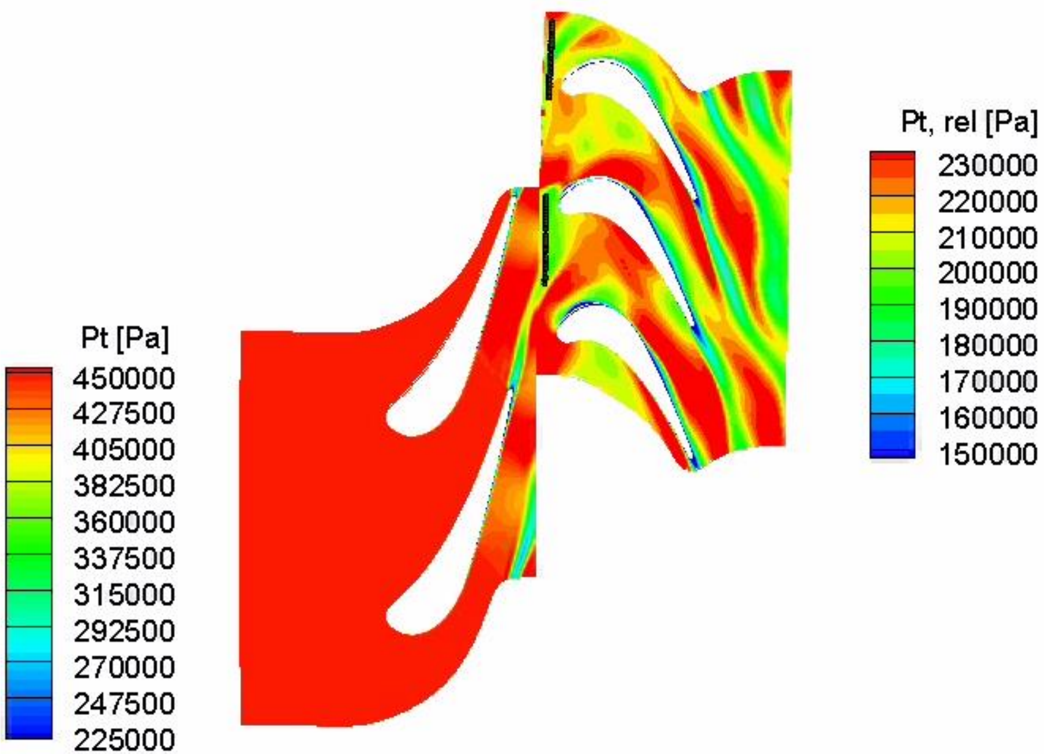
Hot Streak Clocking Study



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

(Casaday, Ameri, and Bons, AIAA 2012)

CAPABILITIES Rotor/Stator Interaction and Deposition

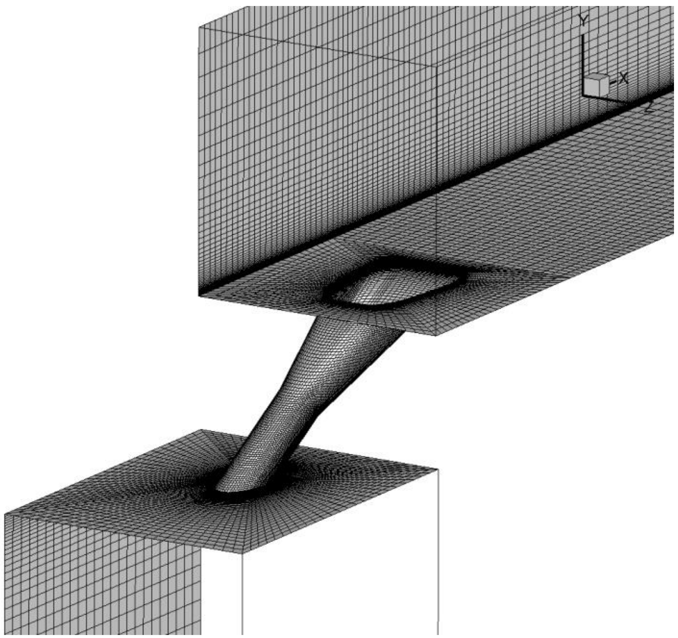


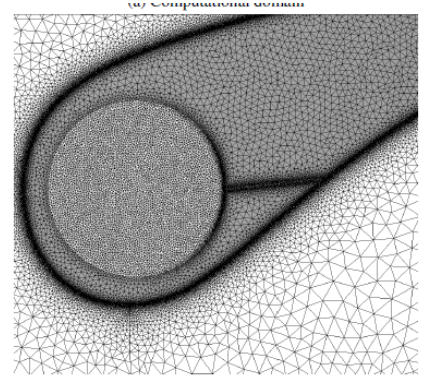
- 2 Vanes per 3 Blades
- Contours of Relative Total Pressure

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

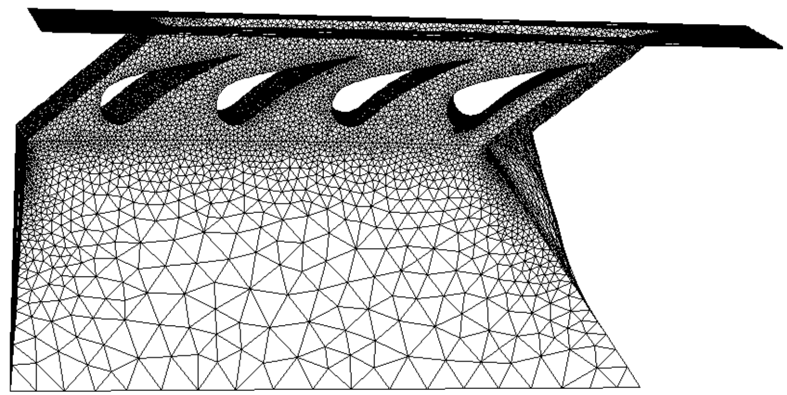
Mesh Topologies

CAPABILITIES





(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.

Square, 777 and Fluidic Methods

Sweeping Fluidic Oscillators
(Thurman, Poinsatte, Ameri,
Culley, Raghu, Shyam IGTI2015)

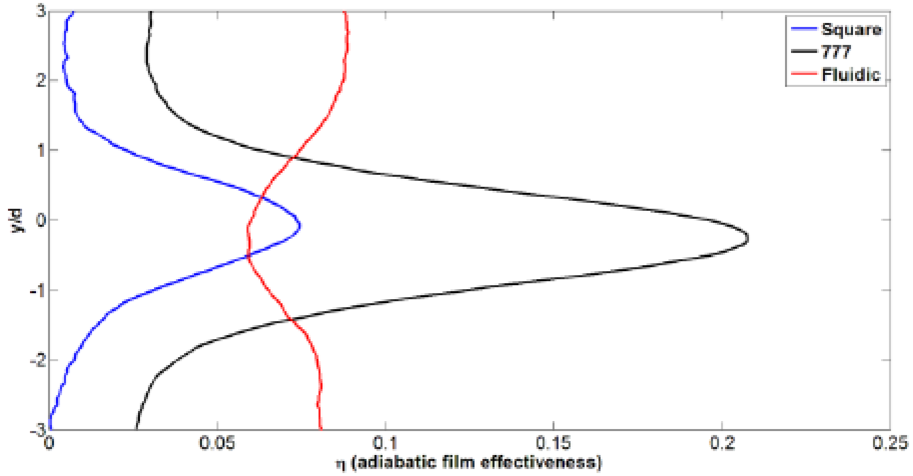
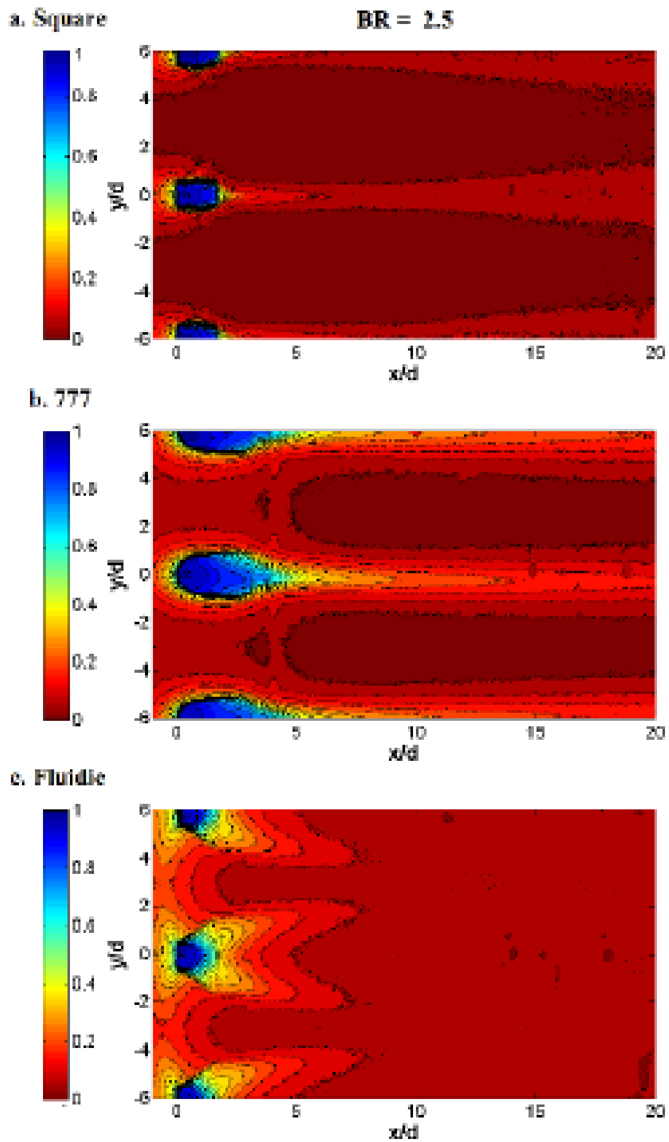
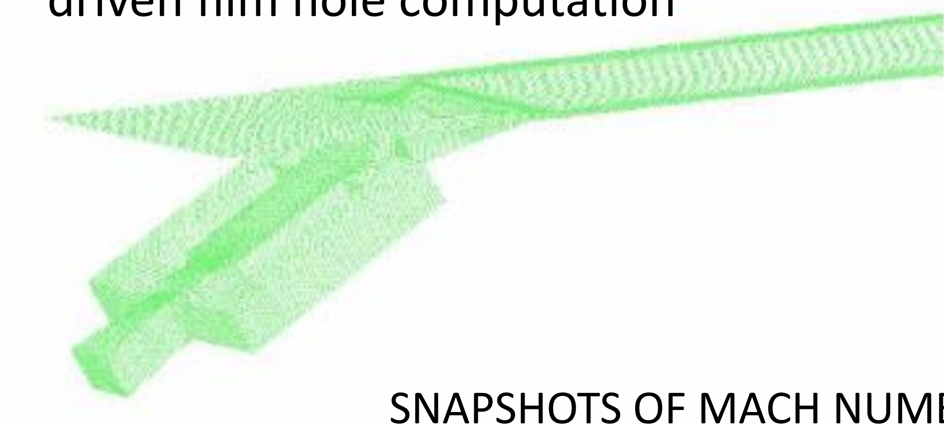


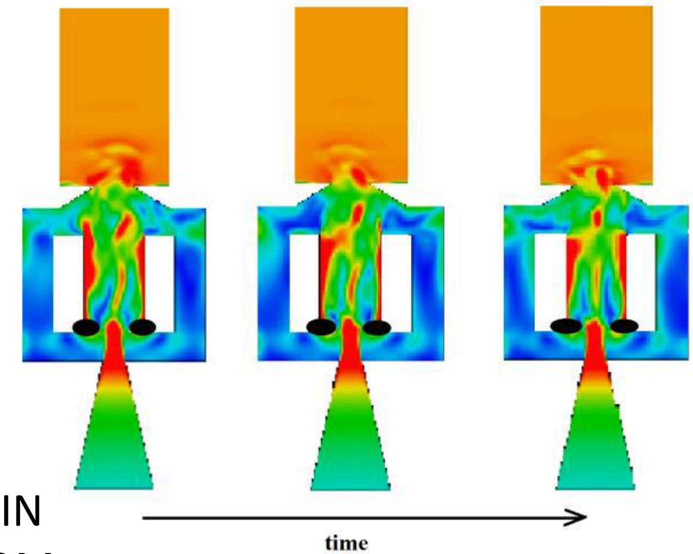
FIGURE 19. SPANWISE PLOTS OF ADIABATIC EFFECTIVENESS AT *BR*=2.5 AT *X/D*=10.



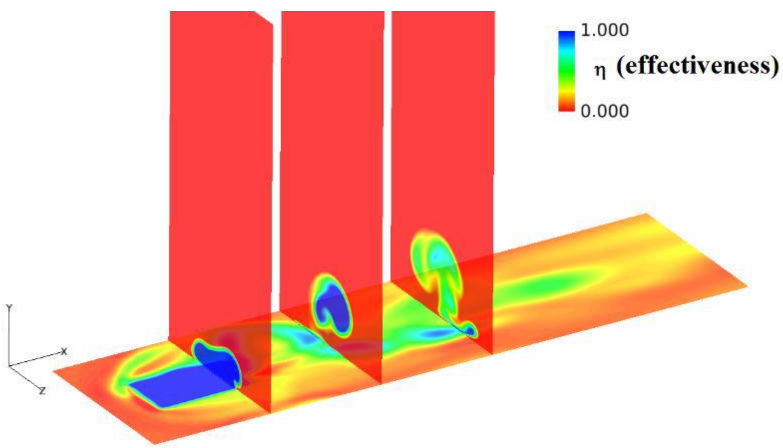
Fluidic Devices –Simulation

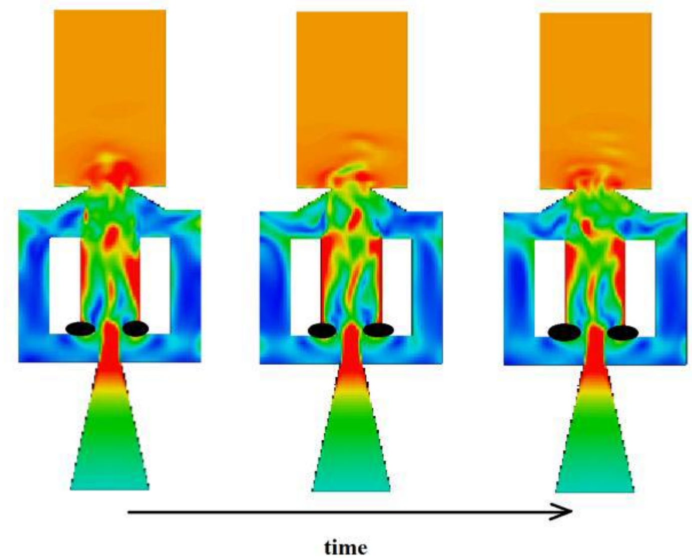
3D grid used for fluidic-oscillator driven film hole computation



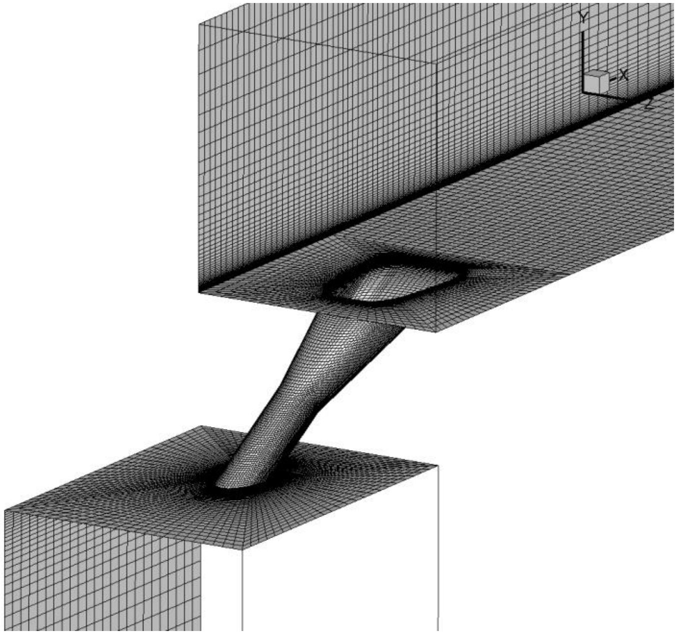


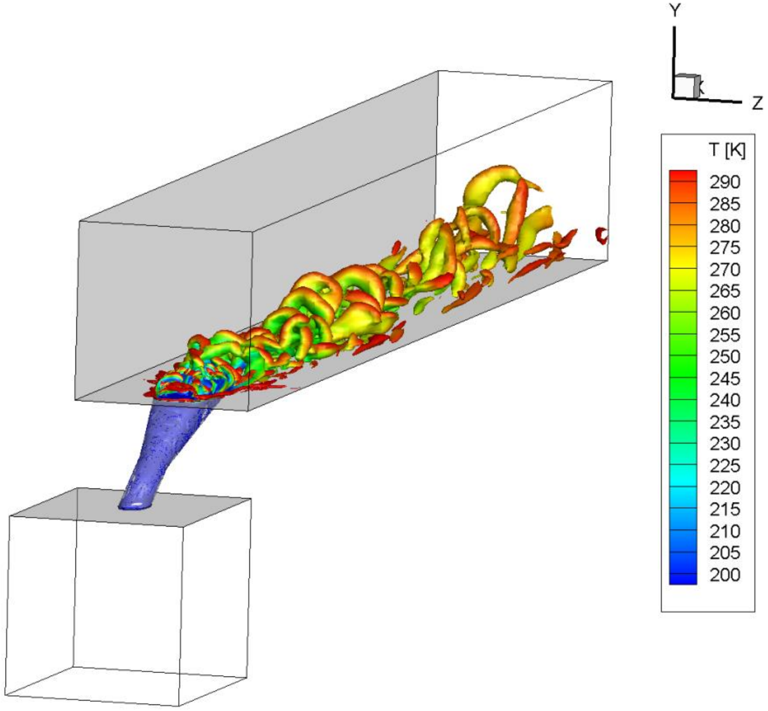
SNAPSHOTS OF MACH NUMBER IN MID-PLANE OF FLUIDIC HOLE FROM UNSTEADY 3D CFD AT BR=2.0 (BLUE=0, RED=0.45)



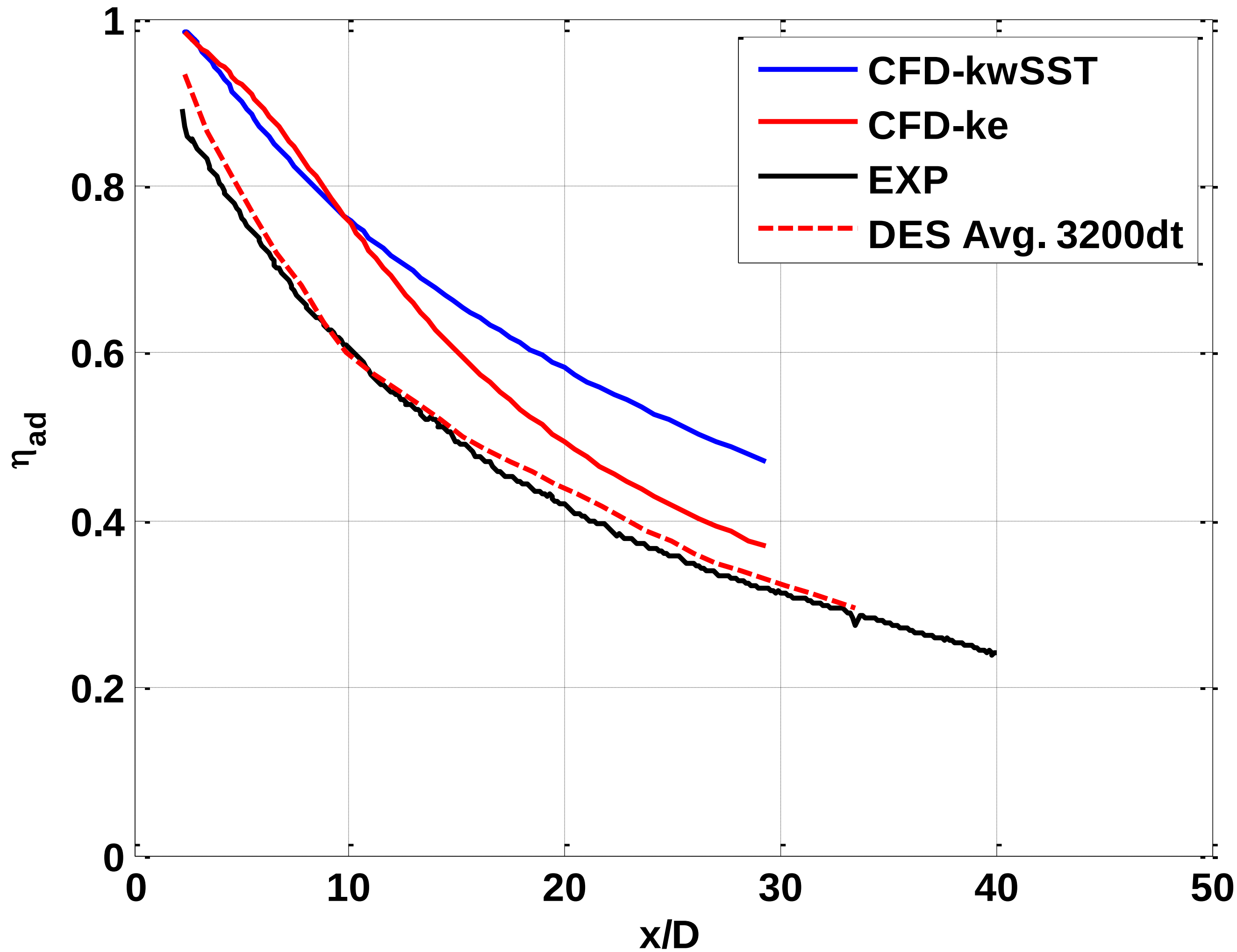


777 – A DES Simulation





Film Cooling (777 Hole)



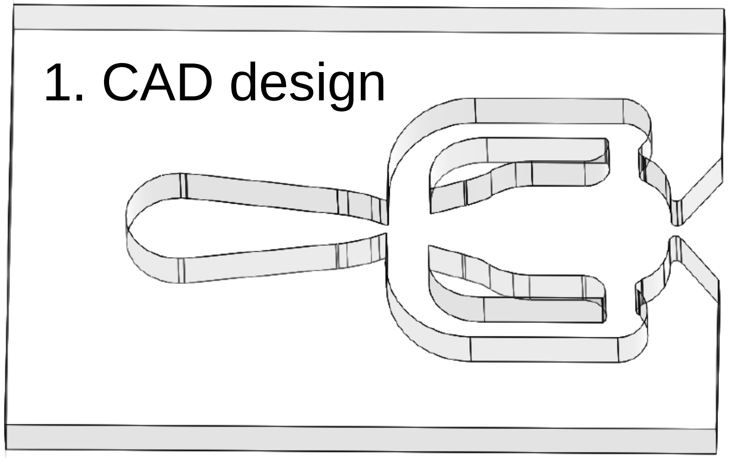
Choice of model and method determines the outcome.

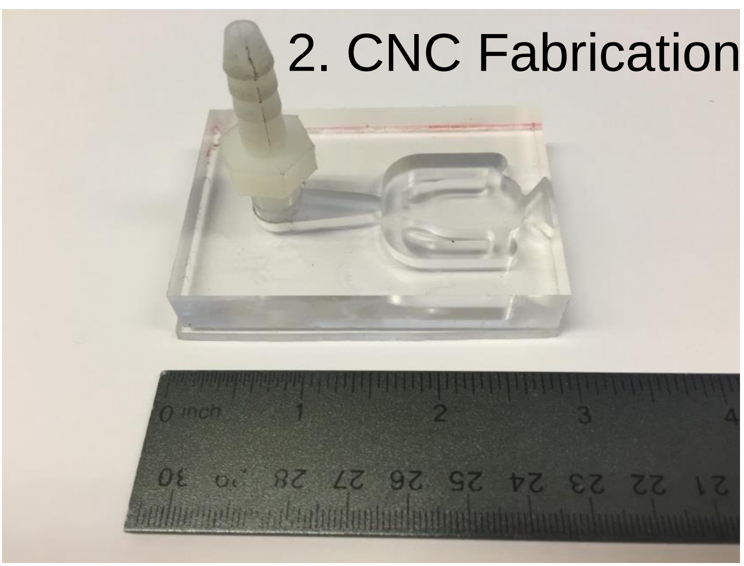
Conclusions

- 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.

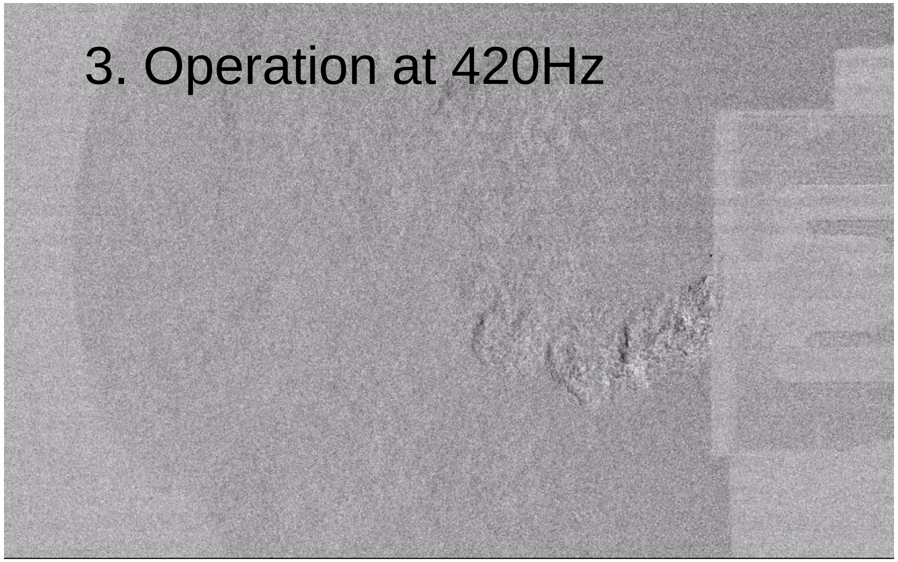
- We have the availability and have developed the expertise and gained the experience to perform such analyses using various steady and unsteady CFD methods to fulfil this task.

Preliminary Design/Test



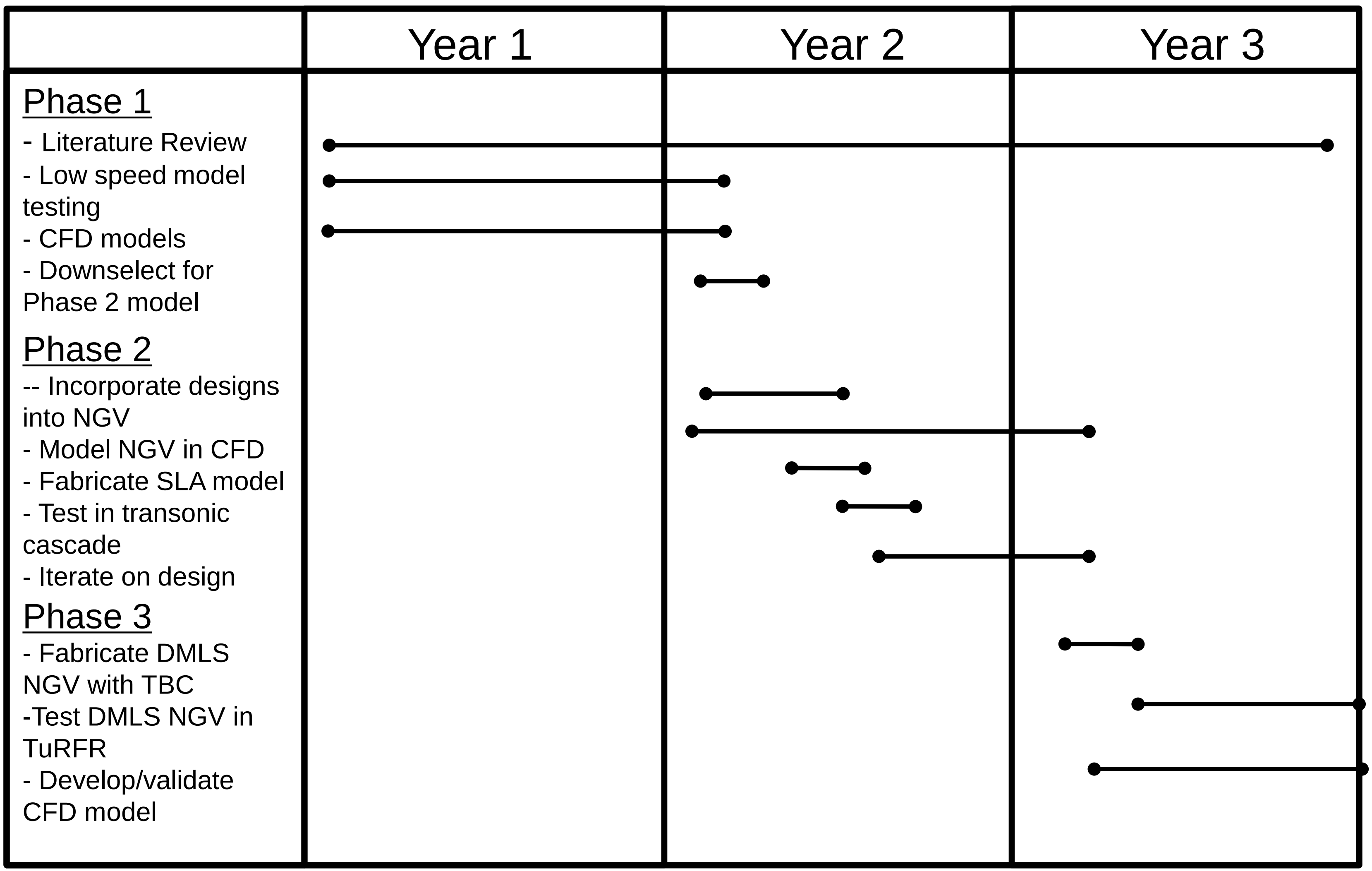


Sweeping Fluid Oscillator



4. Schlieren

Gantt Chart


Year 1
Year 2
Year 3
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


QUESTIONS?