LES and RANS/DERM Modeling for Design Optimization of Additively and Conventionally Manufactured Internal Turbine Cooling Passages

Annual Research Progress Report

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UTSR Program Review
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- Brief recall of background/objectives/technical approach/earlier progress
- Current activities and progress:
  - RIFT testing – heat transfer measurement focus
  - DERM model development/applications
  - DNS/LES/RANS tools, modeling, parameterizations
- Students and publications
- Summary and current/next steps

Background/Objectives/Technical Approach

- Metal AM enabling gas turbine design exploration of cooling schemes not currently manufacturable
- Potential *transformational* turbine operating temperature, durability gains
- *Need to mature thermal design tools*
  - Very complex "roughness field" that invariably characterizes flow passages
  - Conventional area parametrized roughness modeling for CFD inadequate
- Discrete Element Roughness Modeling (DERM)
  - *Necessary and sufficient* for mechanistic predictions of additively manufactured turbine cooling scheme configurations
  - Viable design approach for conventionally manufactured blade cooling features

Background/Objectives/Technical Approach

- Synthesis of state-of-the technology:
  - CFD modeling (DNS/LES/RANS) and optimization
  - Powdered metal additive manufacturing
  - Multiscale 3D scanning and attendant roughness field characterization
  - Flow/heat transfer measurements
- Deliver to turbine design community sufficiently physics rich, validated model set for design of cooling passages characterized by roughness morphology, tolerancing inherent to L-PBF manufacturing
  - Straightforwardly implemented within current OEM turbine design practice
  - 3D ∴ far more general in breadth of applicability than Q1D

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Background/Objectives/Technical Approach

Engine scale testing
- Δp and q”
- PSU legacy data
- PSU new data
- GE data

100x scale testing at Baylor
- Δp and q”
- Hotfilm and LDV
- As built and surrogate roughness morphologies

Design and build of surrogate L-PBF cooling passage geometries
- GE input
- Coverage of geometry parameter space
- Cover build parameter space

Multi-modal inspection
- CT, OP, SEM as necessary

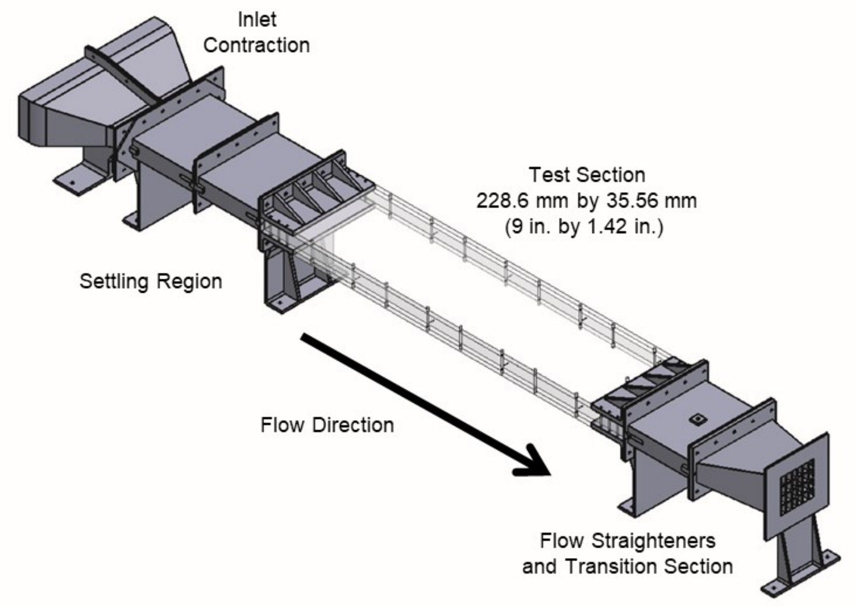
Develop CAD suitable for scale-up, CFD mesh generation, and statistical characterization

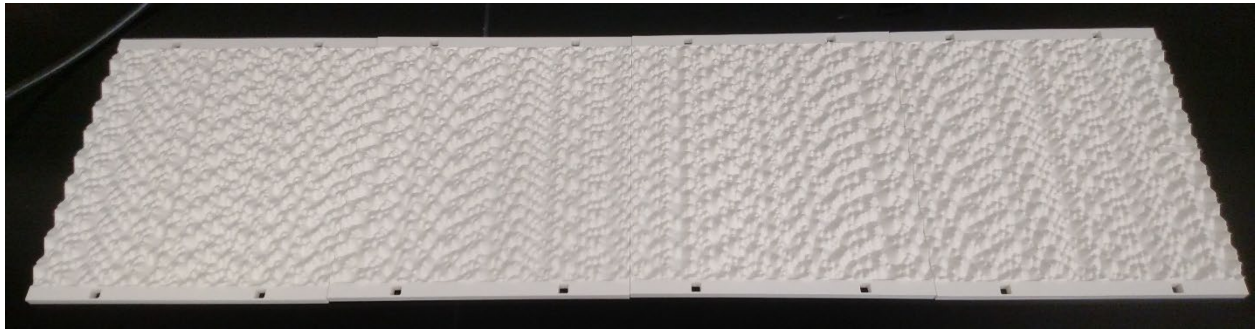
DERM model development
- Formulation
- Morphology parameterization
- DNS calibration
- At scale and up scale calibration

Application and Optimization

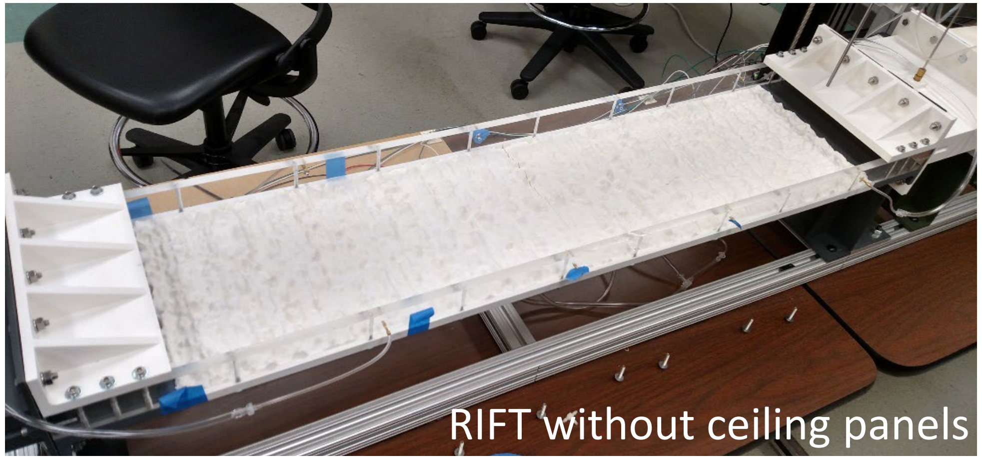
Roughness and Internal Flow Tunnel

- Adiabatic work to date:
  - 50x or 100x geometric scale
  - Panels printed using FDM
  - Channel flow with two rough walls (86% of perimeter)
  - Bulk pressure loss measurements
  - Single wire and X-array anemometry



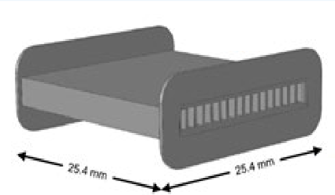


Ellipsoidal Cone Surface Panels

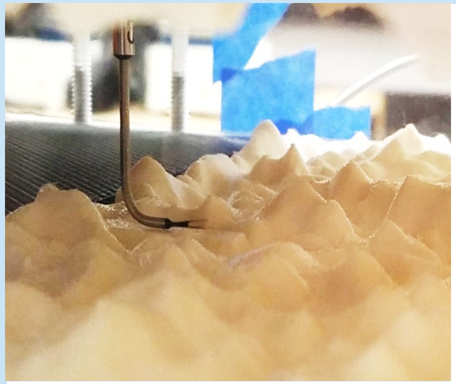


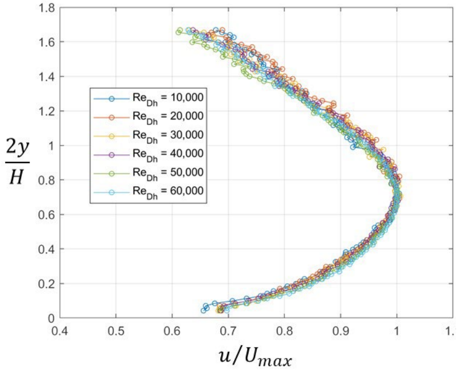
RIFT without ceiling panels

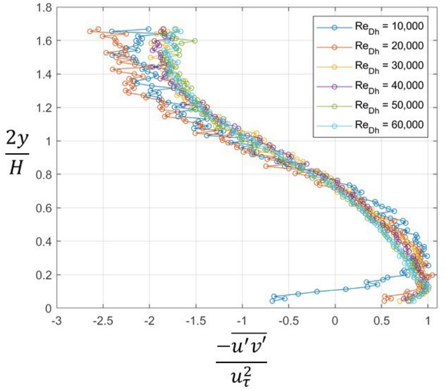
Roughness and Internal Flow Tunnel

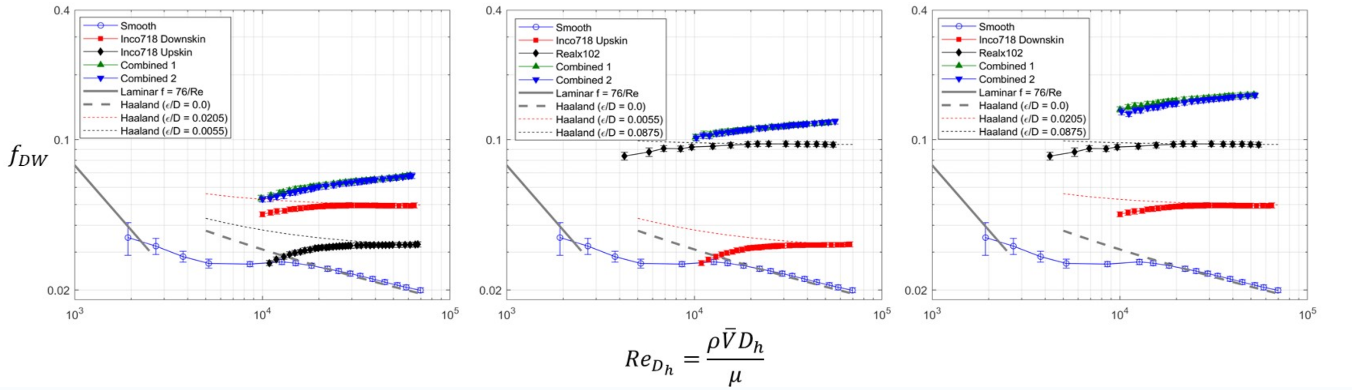


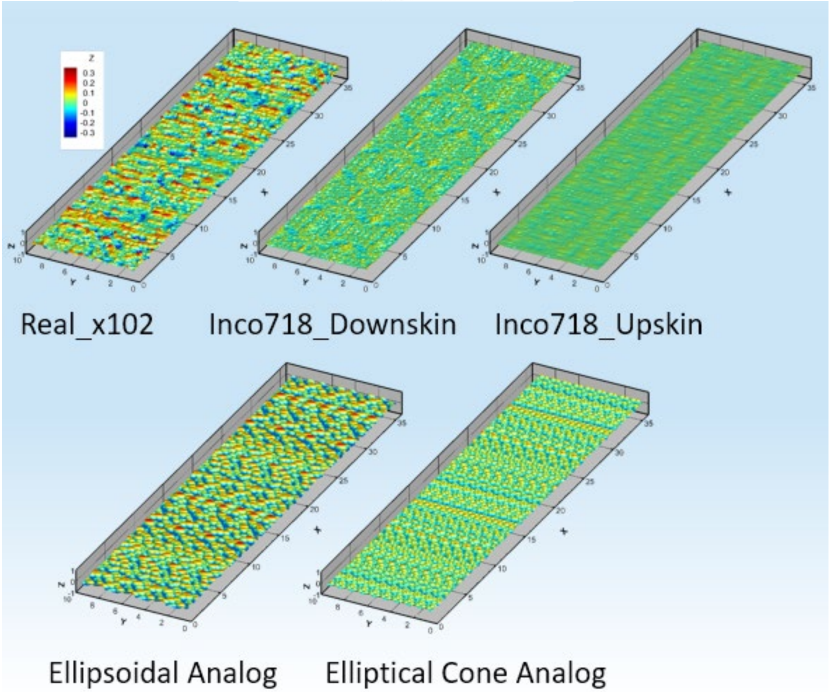
- Adiabatic work to date:
  - 8 upscaled engine scale START configurations
  - 2 surrogate analog configurations

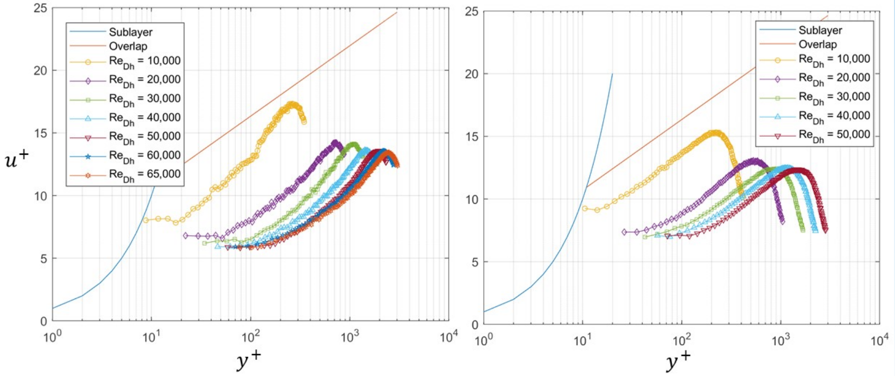






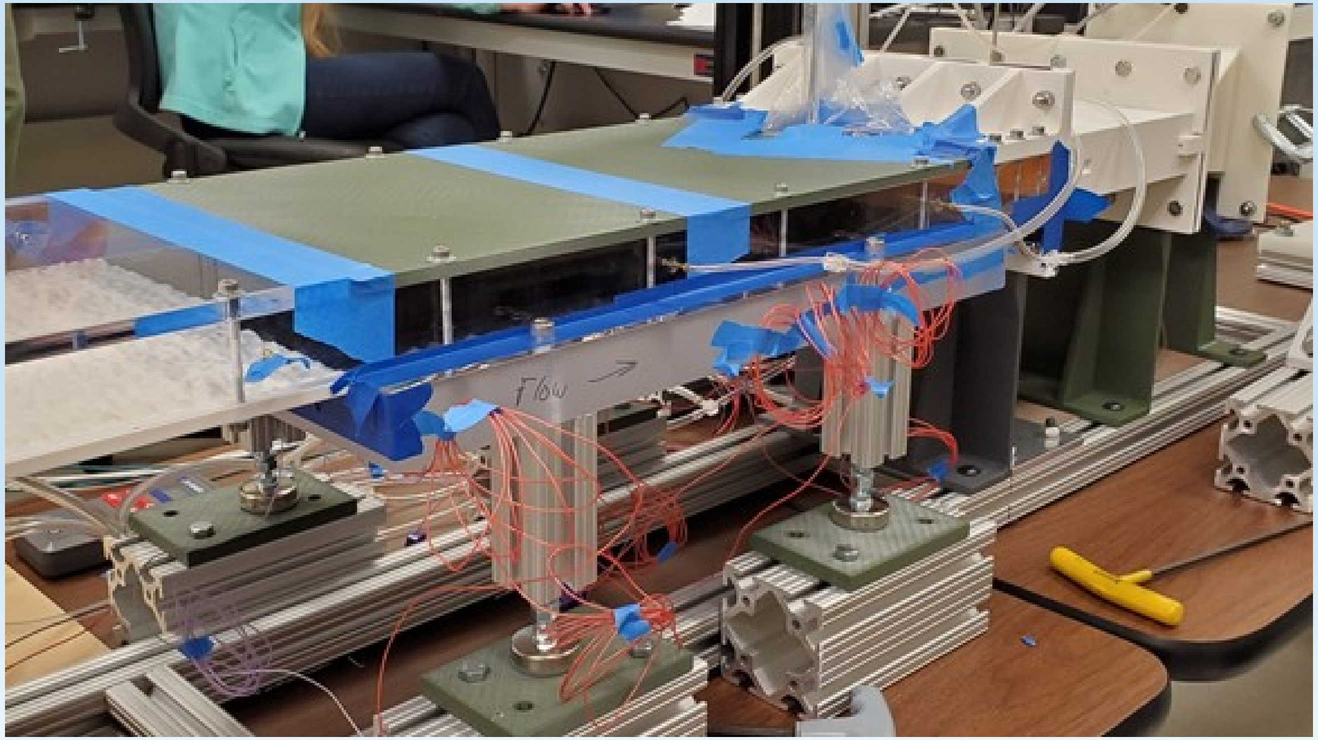


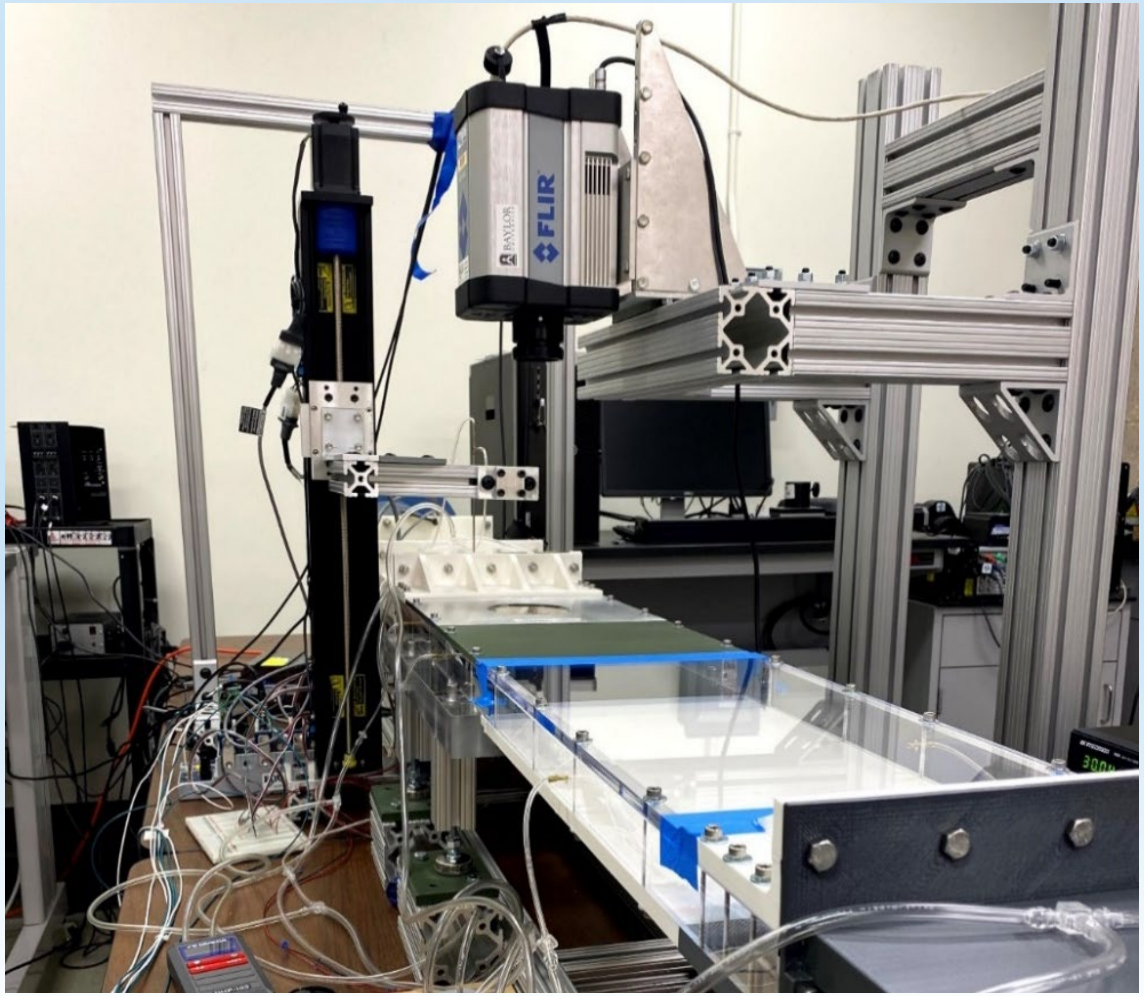




Heat Transfer Measurements

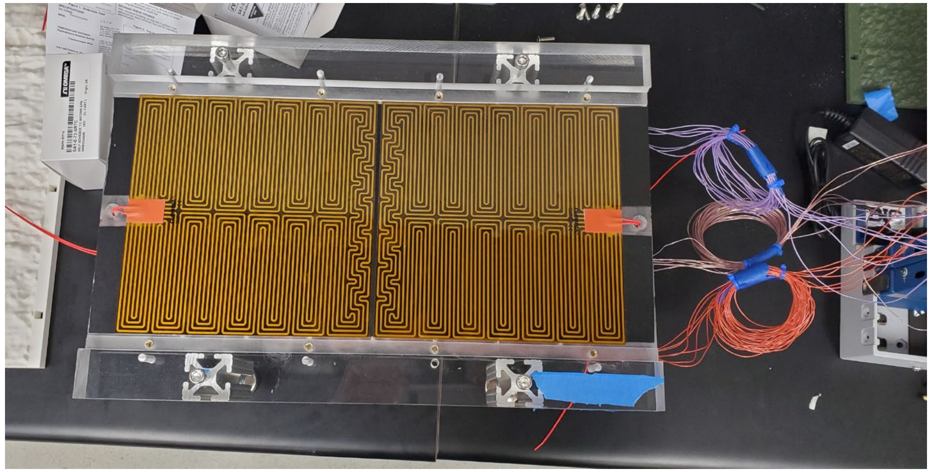
- Started late 2019 to date

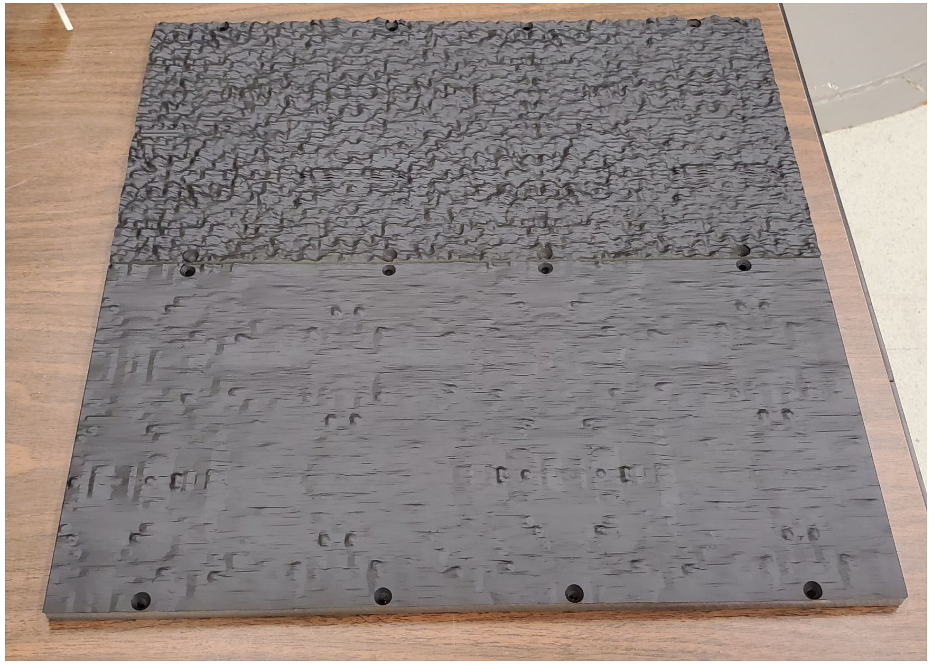




Heat Transfer Measurements

- IR window and plates constructed
- Heat transfer plates etched & painted
- Flat black for the infrared emissivity
- Three rough surfaces
    - Inconel 718 upskin
    - Inconel 718 downskin
    - Hastelloy “Real_x102”
- Smooth surface for benchmarking





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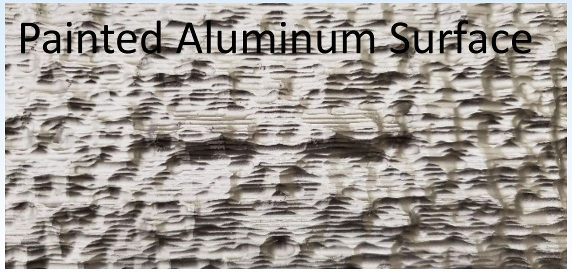
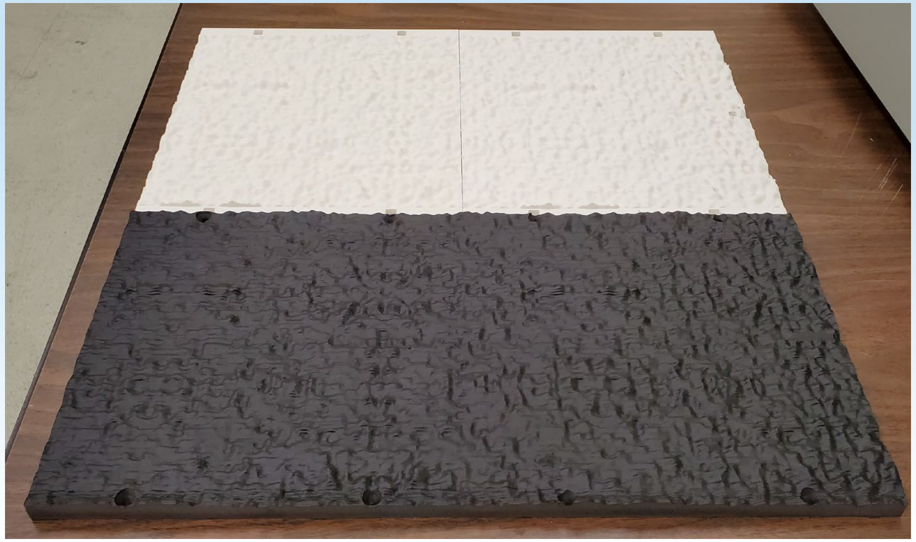
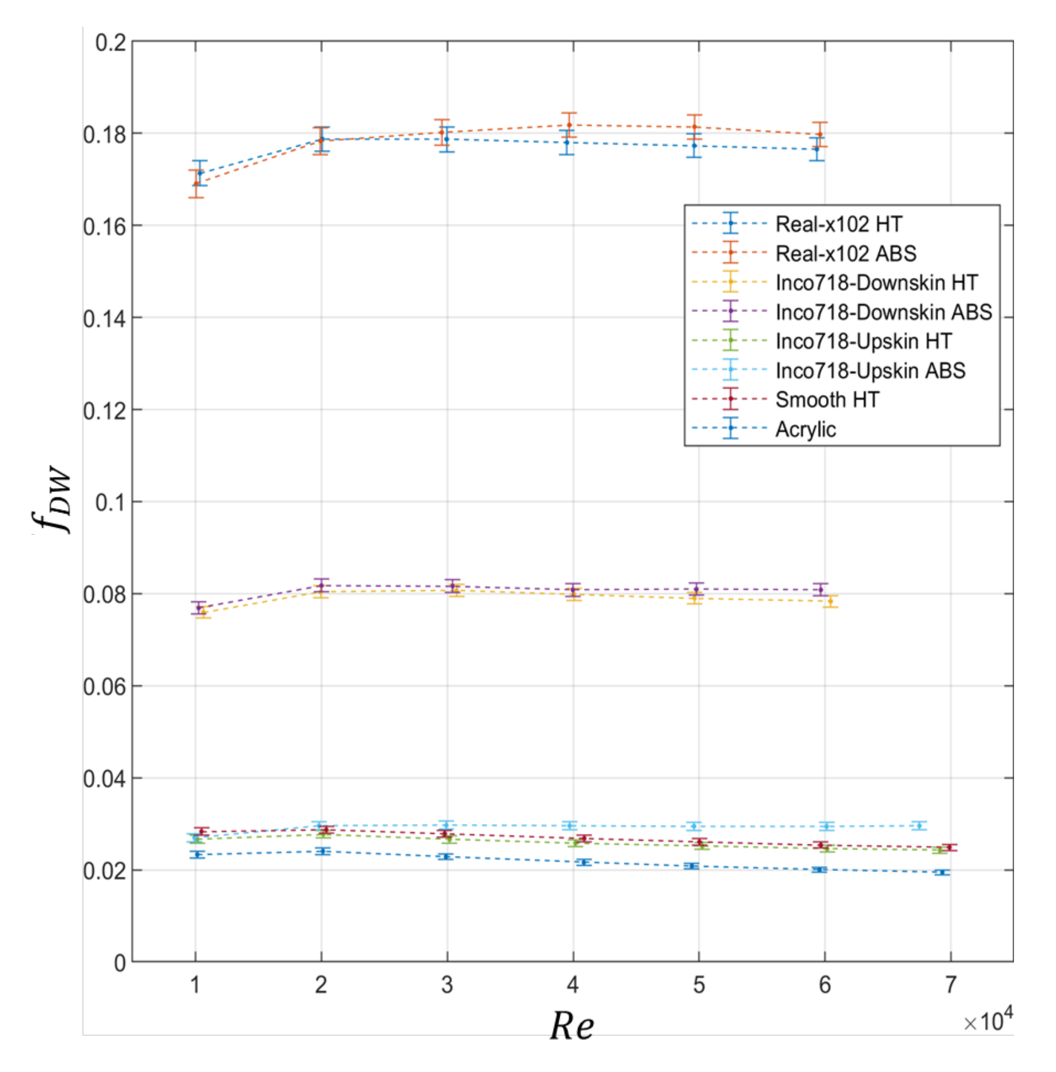
Results

- Prior measurements performed using additively manufactured (FDM) ABS plates
- HT plates machined from aluminum 6061 plates
- Do both methods produce the same roughness?
- Friction factor measurements
  - Good agreement
  - Aluminum to smooth acrylic has most significant difference (paint)







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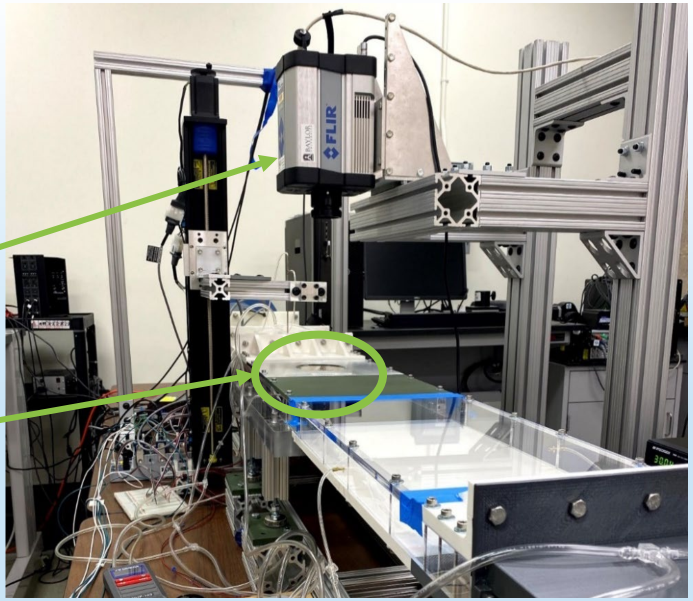
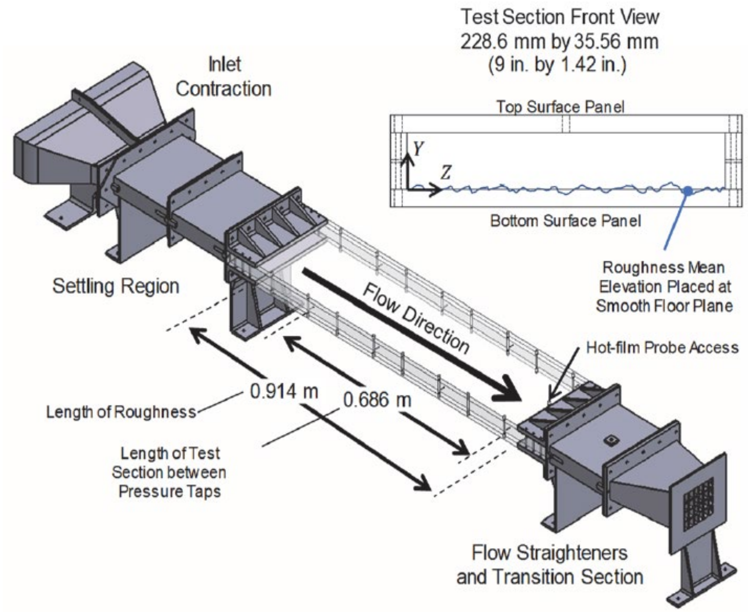
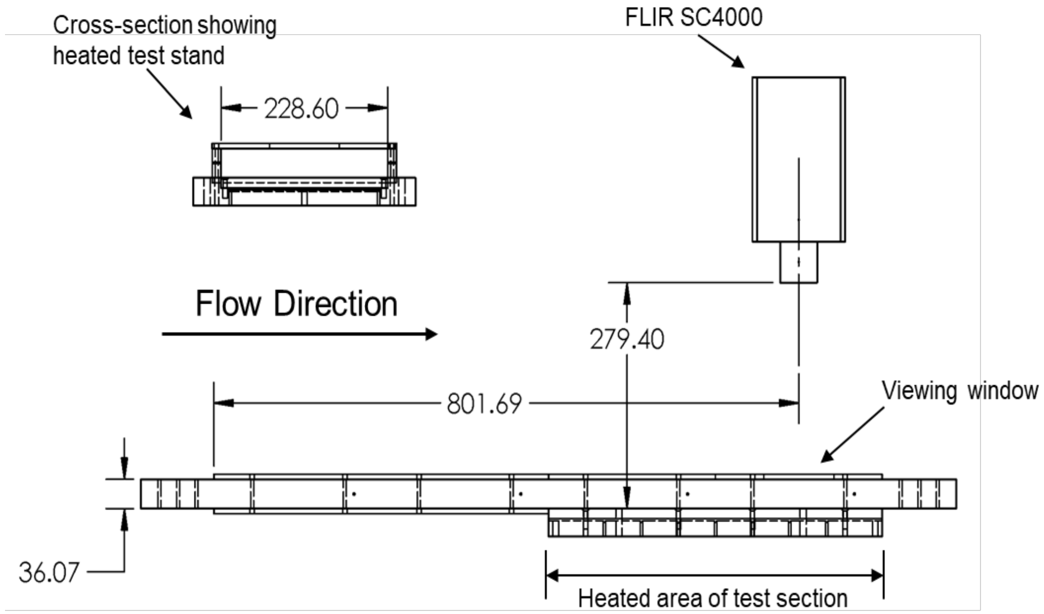
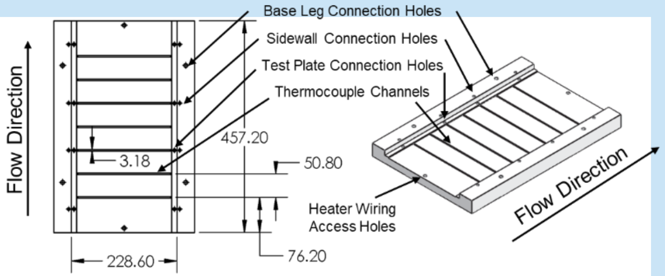
Surface Imaging



- RIFT Modified for HT Measurements
- IR Temperature Measurements
  - FLIR SC4000 on stand
  - IR viewing window

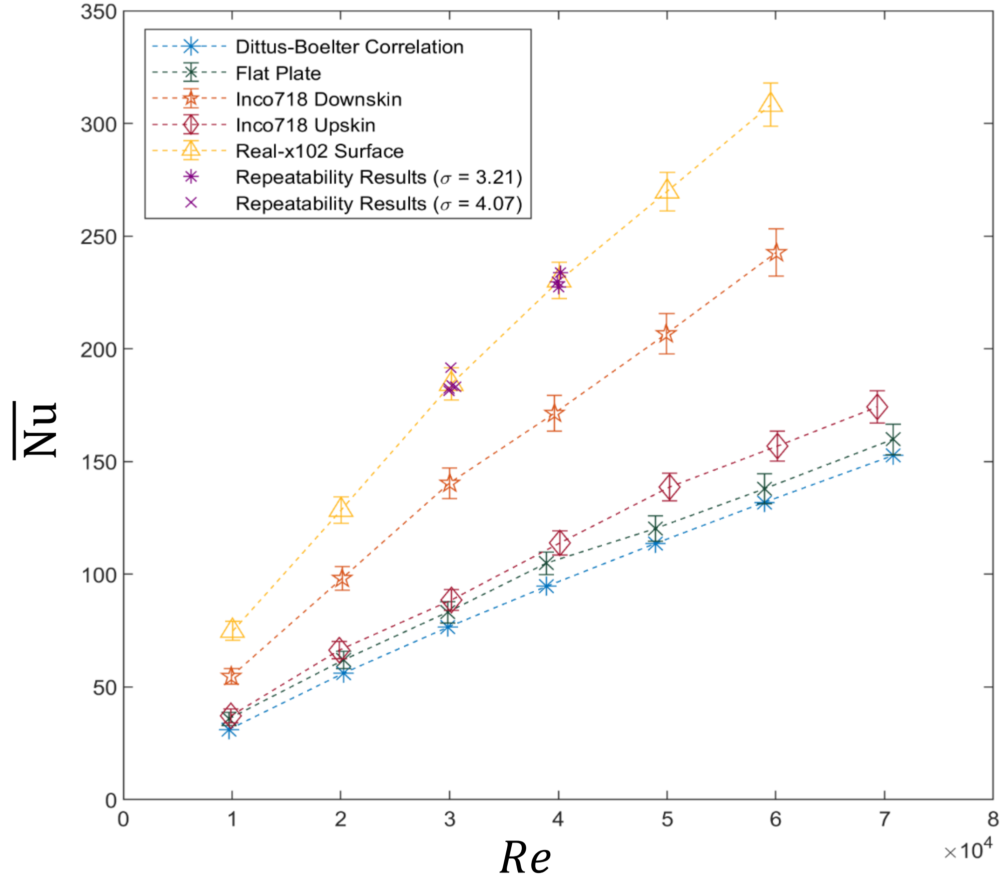


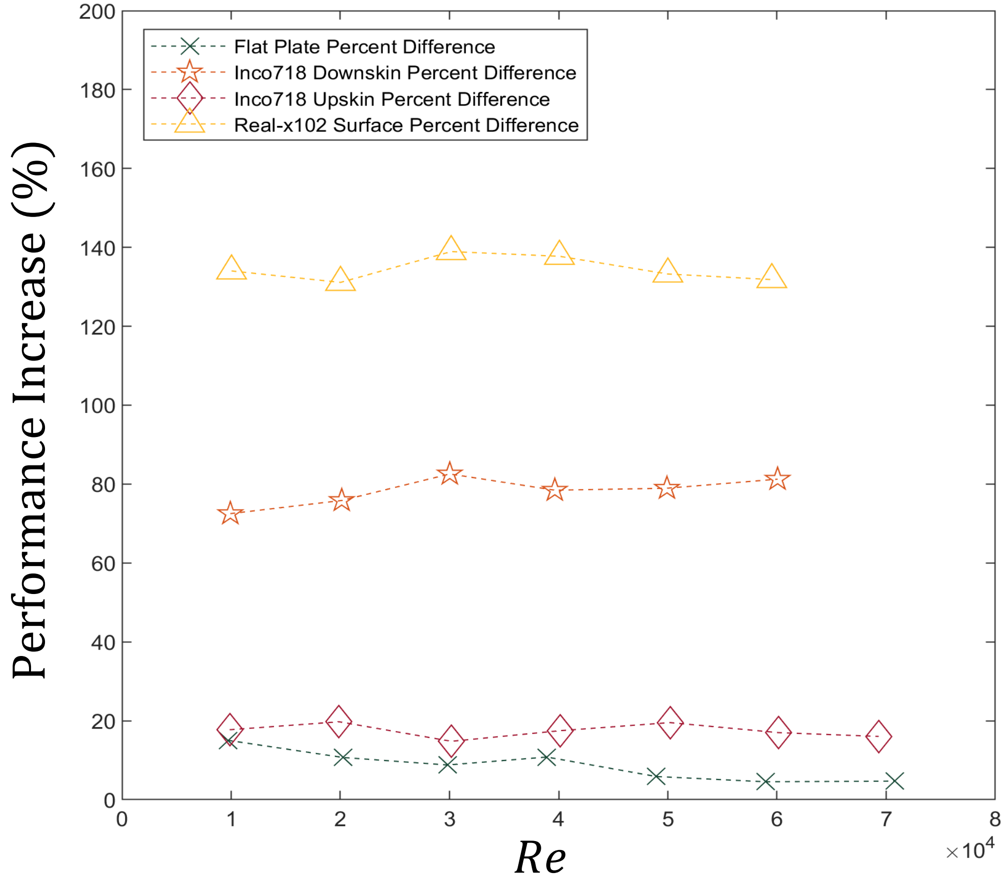




Results

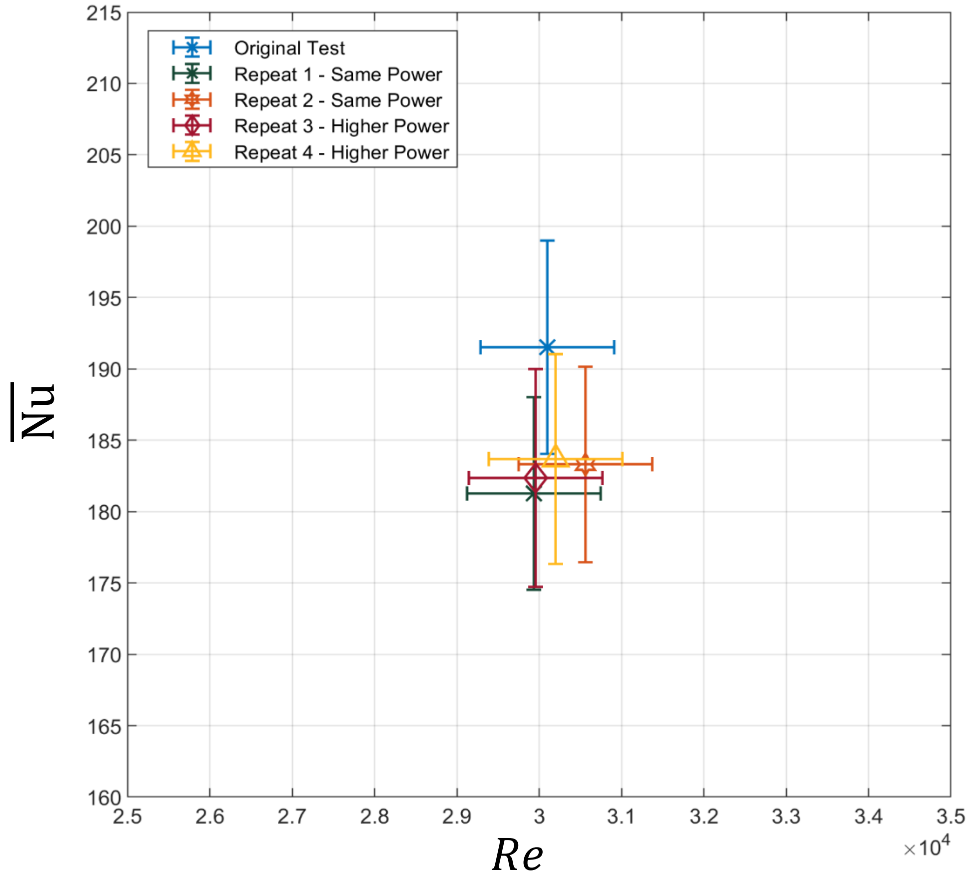
- Nusselt Number Results
- Percentage Enhancement Results

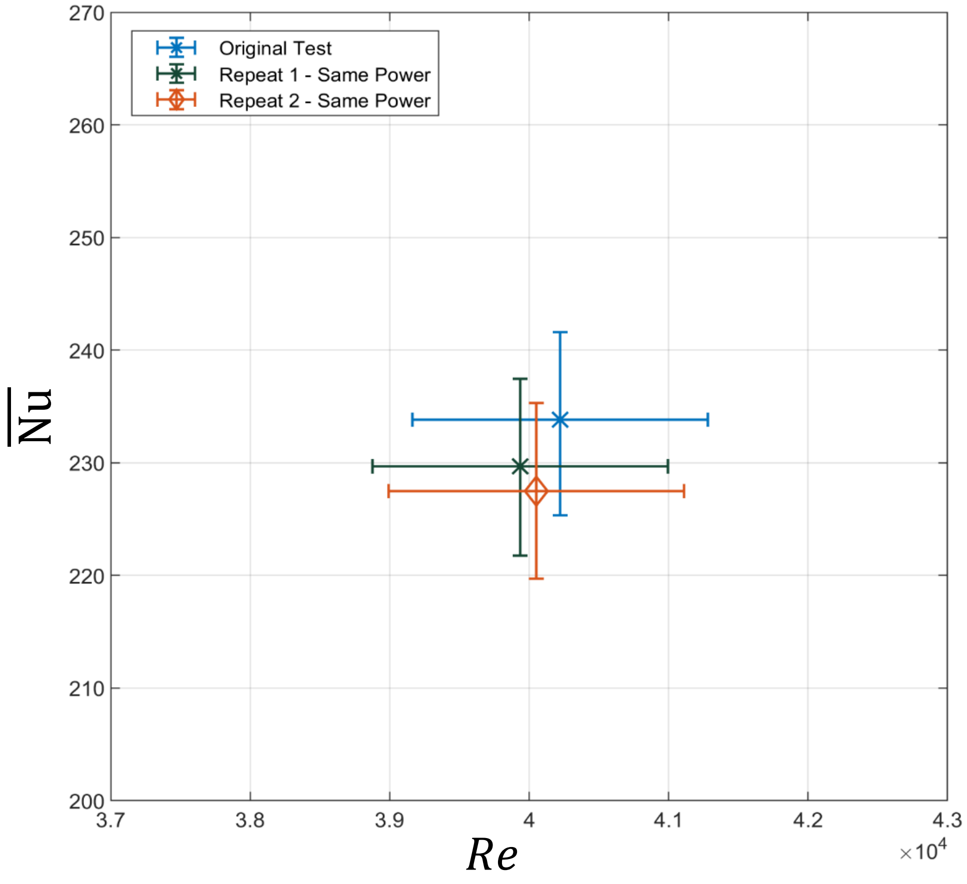




Repeatability

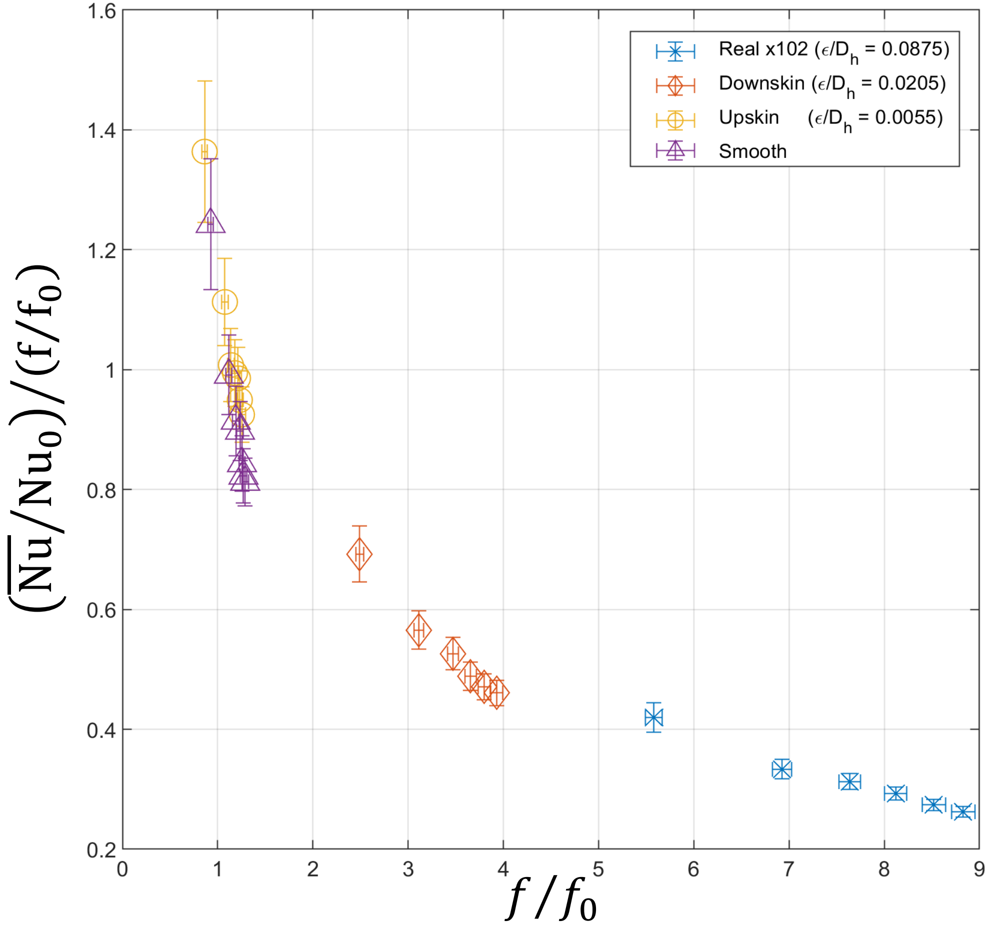
- Six repeatability tests on Real-x102 Surface (Re = 30K, 40K)
- Overlapping uncertainty bars

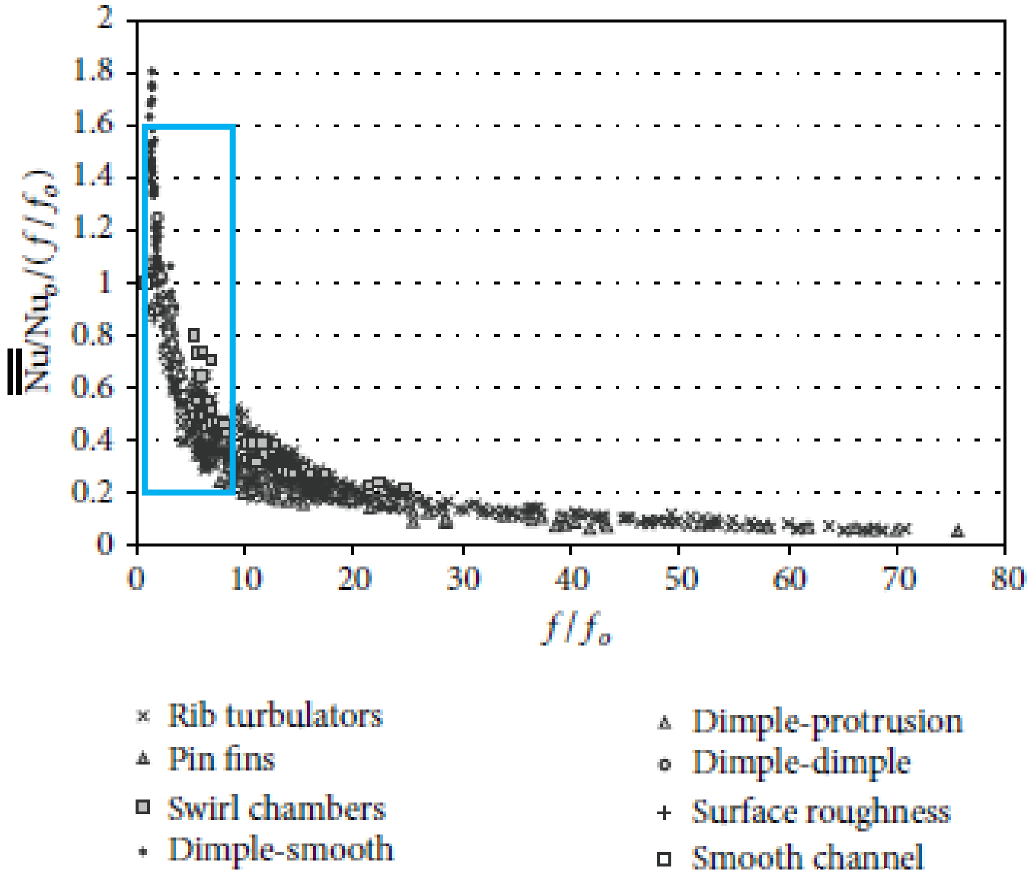




Results

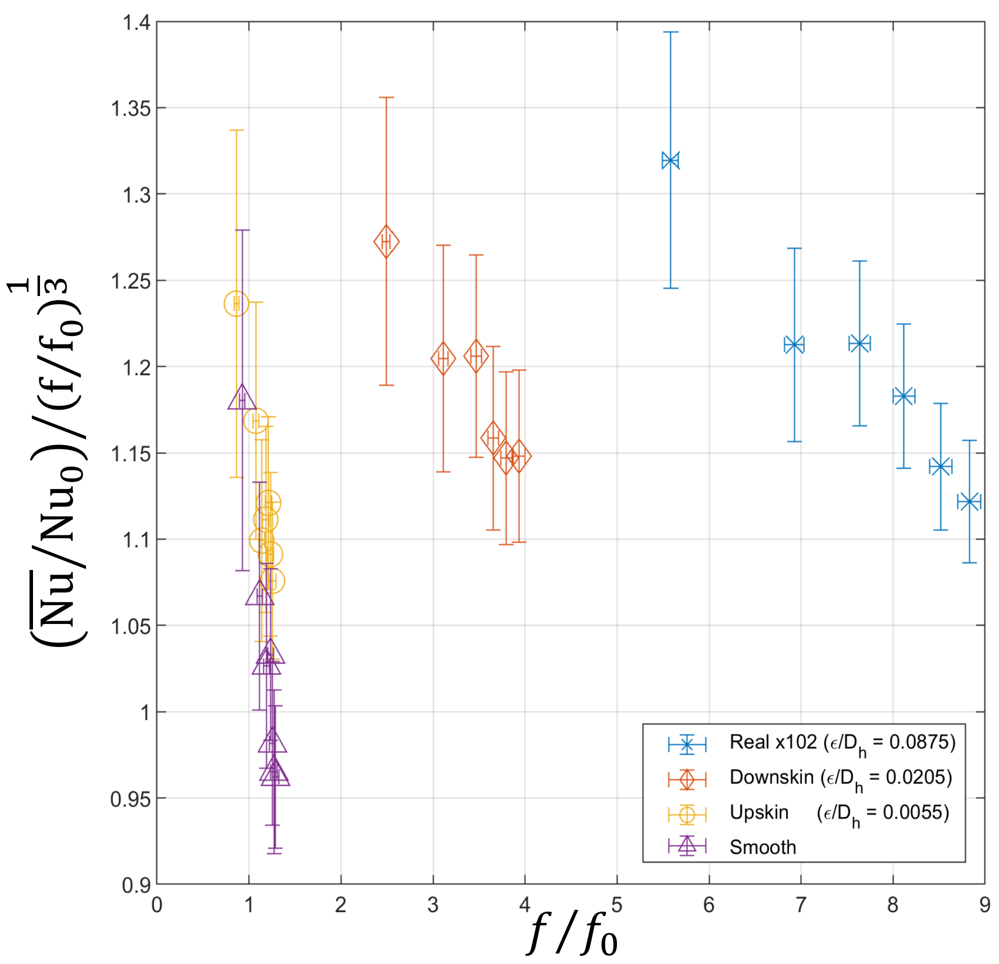
- Reynolds Analogy Performance Parameter

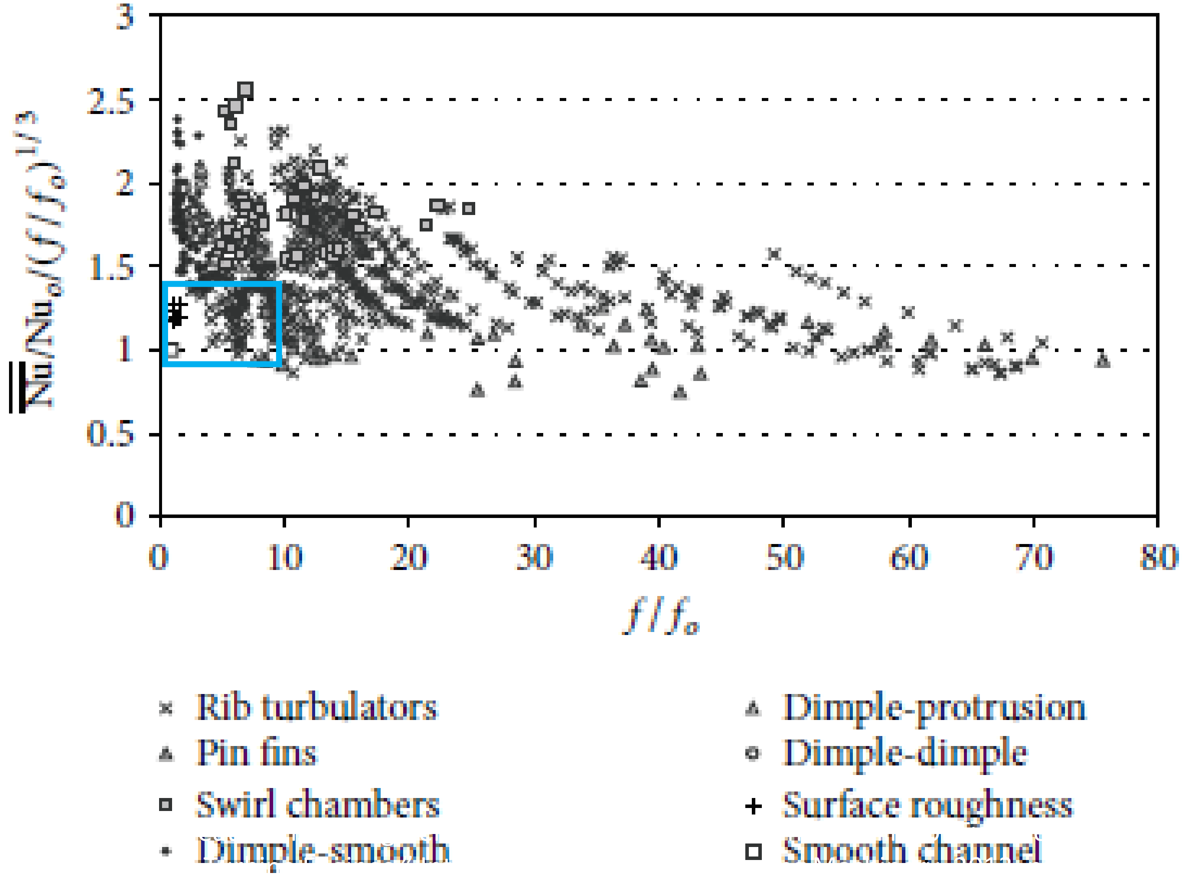




Results

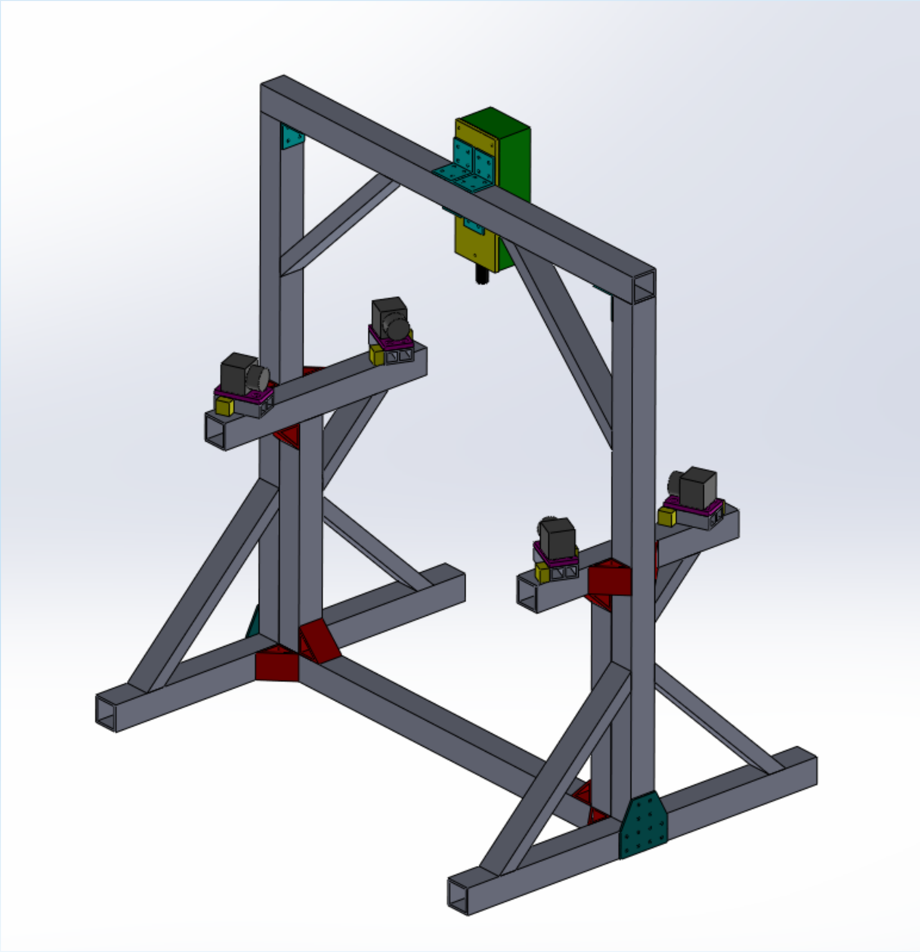
- Global Thermal Performance Parameter





Next Steps

- Use of V3V System (4-camera, tomographic PIV)
- Extruded aluminum frame for V3V system
  - Covid delayed
  - Import/trade issues with source country
  - Arrived Nov. 6
- Construction starts immediately!
- Start using soon with DEHS seeder
- TSI rep will visit early January to fully commission system and explore different seeding options



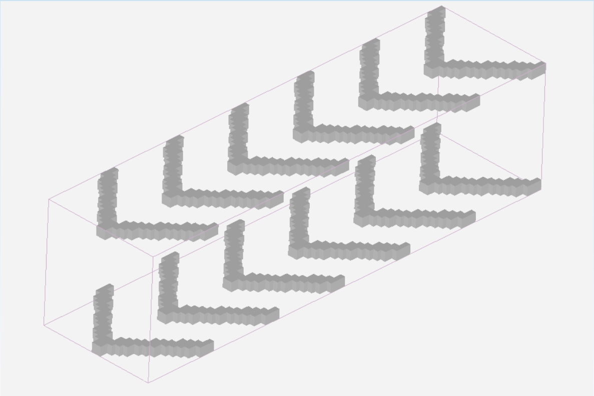
DERM model - review

- Volumetric vs. surface roughness parameterization
  - Draws on thinking from many researchers (Schlichting, Bons, Aupoix, McClain, Meteorology, Icing, Turbine heat transfer)
  - Approach here evolves from non-equilibrium 2-fluid modeling. Closure involves:
    - Statistical volume fraction representation of roughness morphology
    - Interfacial force modeling of (minimally) drag, spatial dispersion
    - Interfacial heat transfer and turbulence transport modeling
    - E.g.,

$$\frac{\partial \alpha \rho u_i u_j}{\partial x_j} = \alpha \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\alpha(\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - D u_i + M_i$$

$$\frac{\partial \alpha \rho h_0 u_j}{\partial x_j} = \text{viscous/turbulent diffusion} + \text{viscous work} + \text{interfacial heat transfer}$$

$$\frac{\partial \alpha \rho k u_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\alpha\left(\mu + \frac{\mu_t}{Pr_k}\right)\left(\frac{\partial k}{\partial x_j}\right)\right] + P - \alpha\varepsilon + \text{Other terms}$$



DERM model motivation

- Orders of magnitude reduction in CPU compared to DNS, LES, Resolved RANS, IBM

Approximate Grid Size and Relative CPU Time Per Element @ Re_τ=540

Method	Grid Requirements	Relative CPU Time	Meshing Complexity
DNS[1]	$O(10^7)$	1.0	High
Sublayer resolved RANS[2]	$O(10^6)$	10^{-3}	High
Immersed Boundary Method[3]	$O(10^{4,5})$	$10^{-4,-5}$	Medium[4]
DERM[2]	$O(10^3)$	10^{-6}	Low[5]
k^+ based parametrization	$O(10^3)$	10^{-6}	Low

[4]Spatially precise element geometry is required for cut cell

[5]Spatial distribution of volume fraction, C_D, C_S required

[1]Chan JFM 2015 [2]Present [3]Estimate

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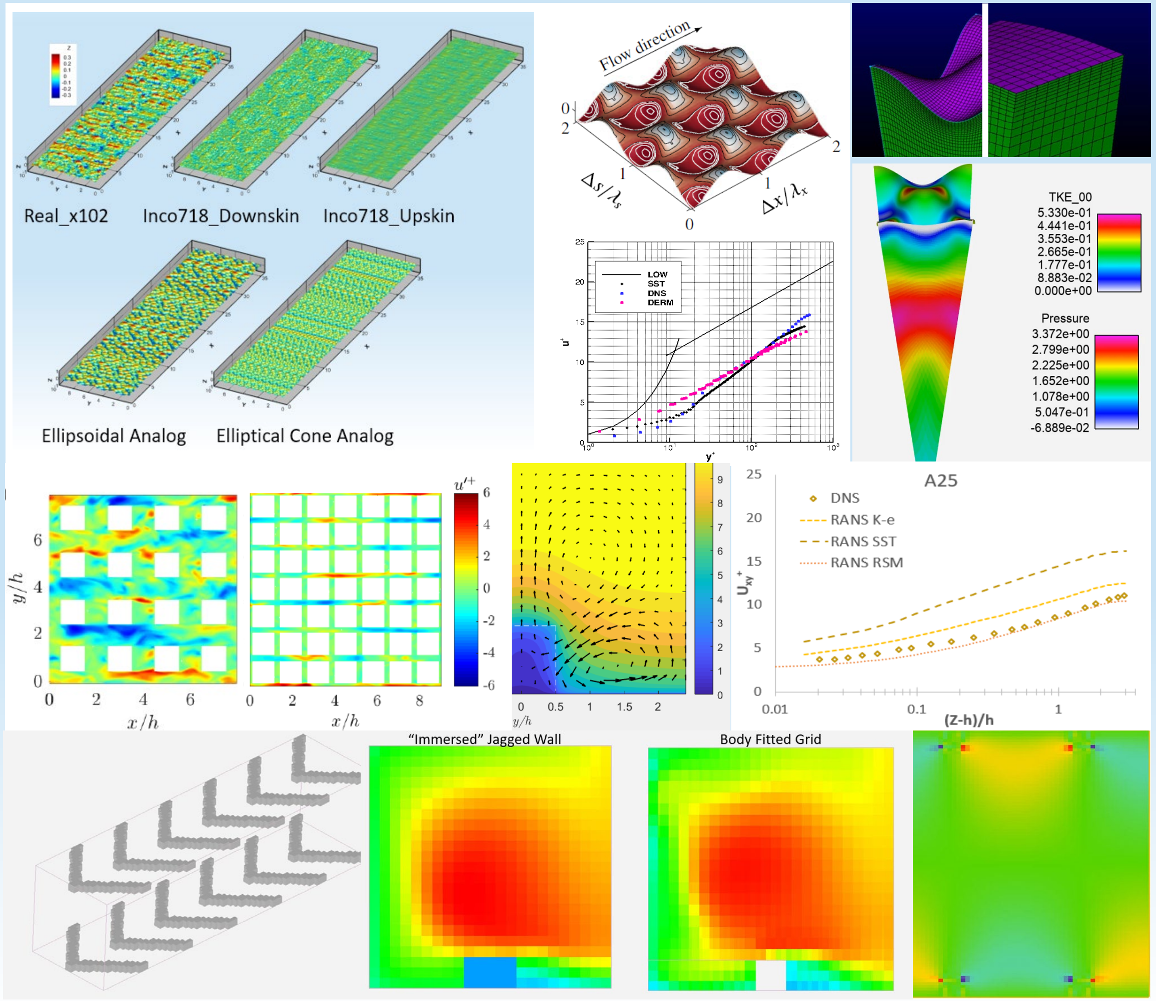
DERM model development/application

- Surfaces studied/parametrized to date using combinations of DNS/LES/RANS/DERM:
  - 8 engine scale START configurations
  - Surrogate ellipsoid, elliptical cone surfaces
  - Sinusoidal
  - Cube arrays
    - Aligned and staggered
    - Range of coverage densities: <1% ➔ 100%
  - Wedges (Han)



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DNS/LES/RANS tools, modeling, parameterizations

- DERM implementation in research code NPHASE-PSU
  - Straightforward to implement within any code that has Eulerian 2-phase capability
  - Coarse mesh per k^+ RANS run with wall functions – roughness not resolved
  - Volume fraction and permeability tensor pre-processing per roughness morphology model - **deterministic**
  - Drag model
  - Spatial dispersion model*
  - Turbulence amplification

Non-deterministic Need to be modelled per exact form (e.g., Aupoix [2016]), conventional drag modeling (e.g., per A''' and porous flow literature), "new" modeling for spatial dispersion

Modeling ← → Calibration

*Xu, Altland, Yang, Kunz JFM 2020

DNS/LES/RANS tools, modeling, parameterizations

- Inherently challenging details include:
  - **Mesh size/roughness scale being part of model** (per Eulerian multiphase flow)
  - Designation of virtual origin
  - Variation of C_D, C_S with distance from wall to match per-element C_{Dtot}, C_{Stot}
  - Limiting behavior as sparsity ➔ 0 or 100%
  - Underlying RANS models can perform poorly for explicitly resolved roughness*
    ➔ so how to use for calibration?
  - Model coefficients:
    - Minimal number of coefficients
    - Minimal parameterization/empiricism, e.g., C_D, C_S = f(Re, geometric descriptors for particular element type)

*Altland, Xu, Kunz, Yang JFE 2020

Current DERM Model Set

- Drag:
  - $D = \frac{C_D}{l}\alpha\rho|U|, C_D = f(Re, l, \text{roughness unit coverage density} = \lambda_p)$
  - E.g. $C_D \cong .45$ for cube arrays*

- Dispersion:
  - Exact term (cartesian streamwise momentum) $\frac{d\langle(U-U_{xy})(W-W_{xy})\rangle_{xy}}{dx}$
  - $M_{i,disp} = C_S \nabla\alpha|U|$
  - E.g., $C_S = .1\lambda_p \frac{\text{filter width}}{l}$, $\text{filter width} = \forall/\Delta x\Delta z$

*Yang, Xu, Huang, Ge JFM 2019

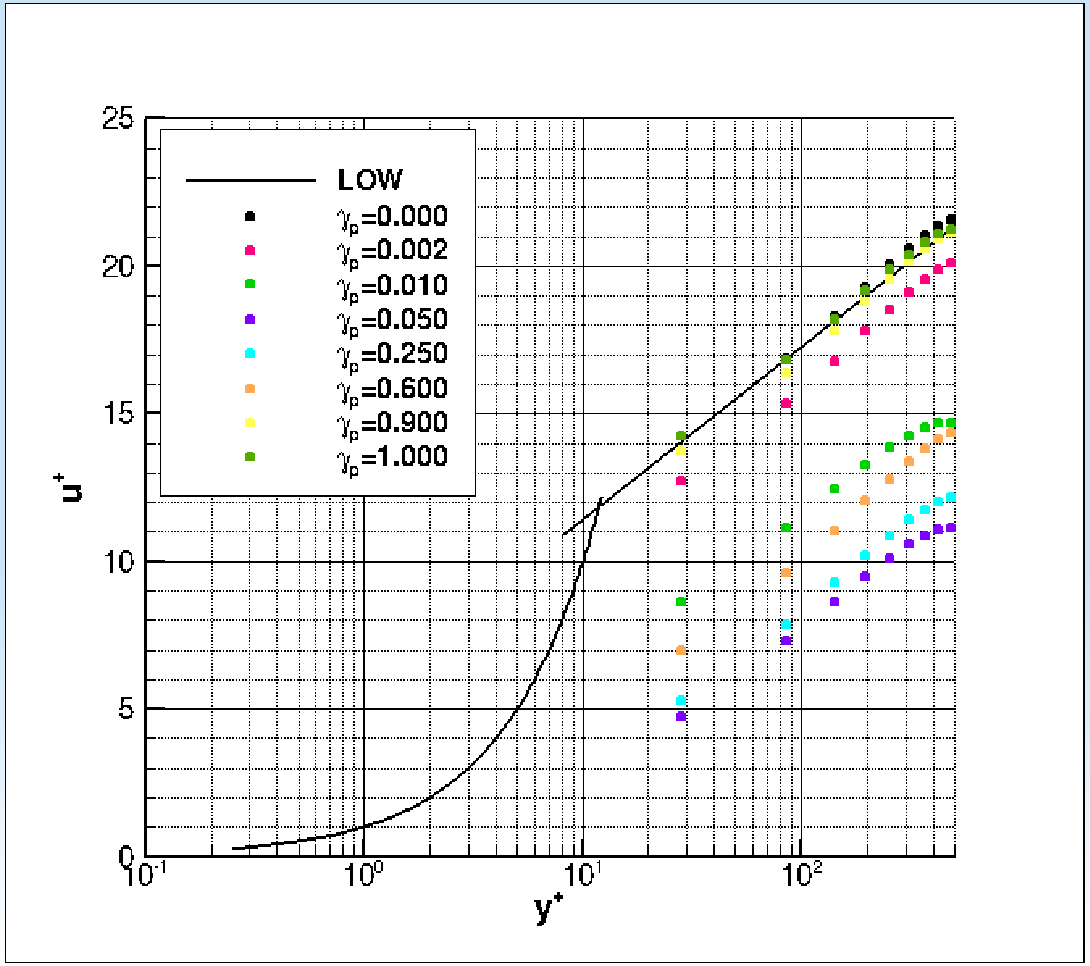
Current DERM Model Set

- Turbulence Amplification*
  - $$\frac{\partial \alpha \rho k u_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\alpha\left(\mu + \frac{\mu_t}{Pr_k}\right)\left(\frac{\partial k}{\partial x_j}\right)\right] + P - \alpha\varepsilon + \underbrace{D|U|^2}_{\text{Drag Production}}$$
- Fully instrumented for "large" cell size: $\forall_{cell} \gg k^3, y \gg k$, and homogeneous roughness distributions

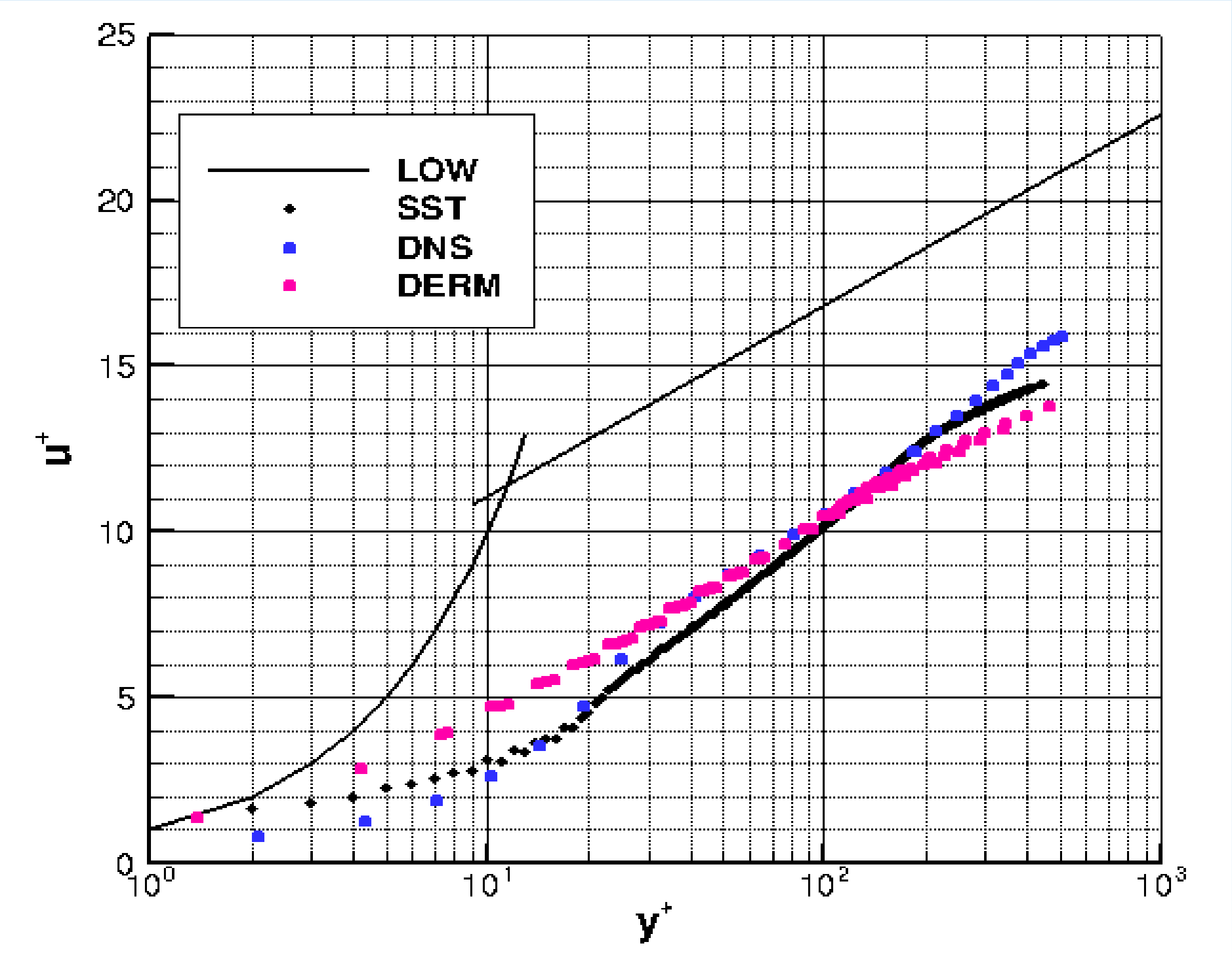
*Gillandt, Crowe ICMF'98

DERM Model

- Cube array roughness (aligned)



- Sinusoidal roughness (sublayer resolved)

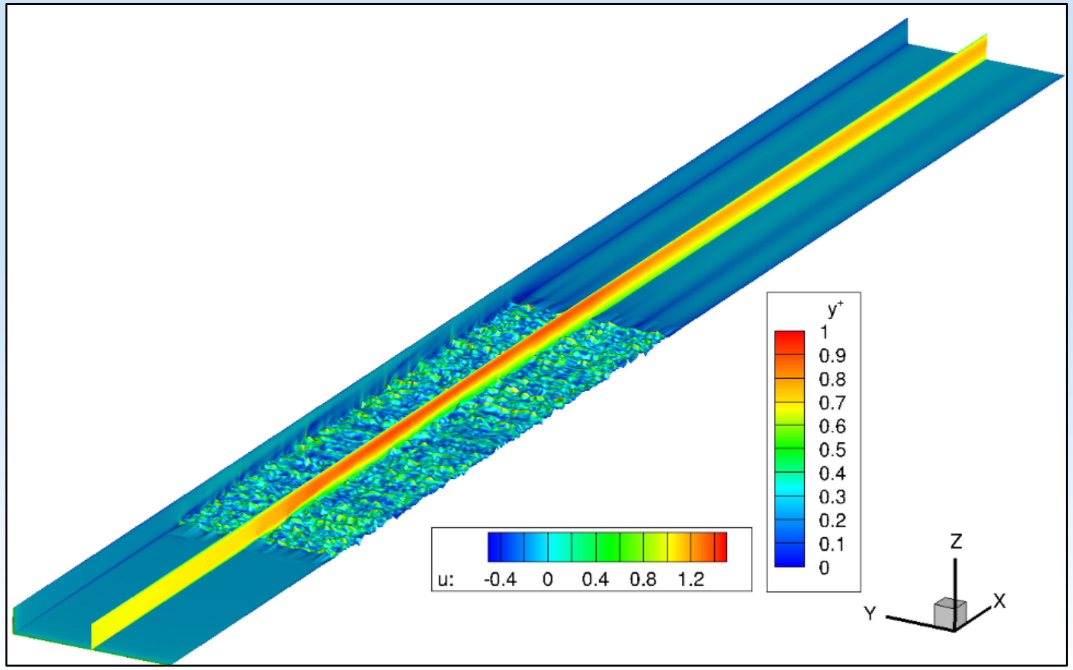


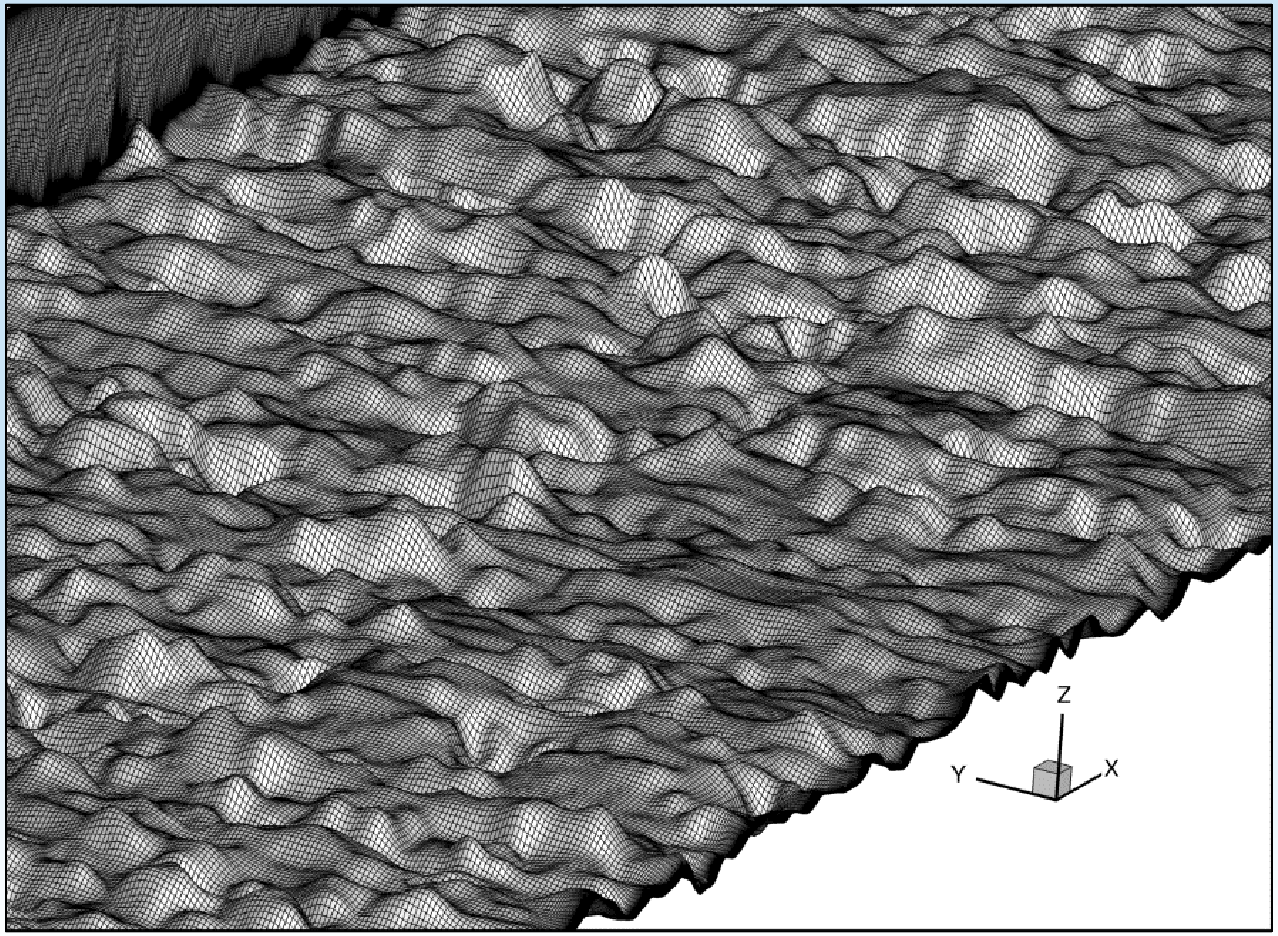
DNS/LES/RANS tools, modeling, parameterizations

- In addition to DERM framework, we require DERM calibration
- Surfaces studied/parametrized to date using DNS, LES, RANS:
  - 8 engine scale START configurations
  - Surrogate ellipsoid, elliptical cone surfaces
  - Sinusoidal
  - Cube arrays
    - Aligned and staggered
    - Range of coverage densities: <1% → 100%
  - Wedges (Han)
- Building a matrix of EFD+DNS/LES/RANS aimed at DERM calibration
- Using in house and some open-lit DNS/LES/RANS

RANS modeling/parameterizations

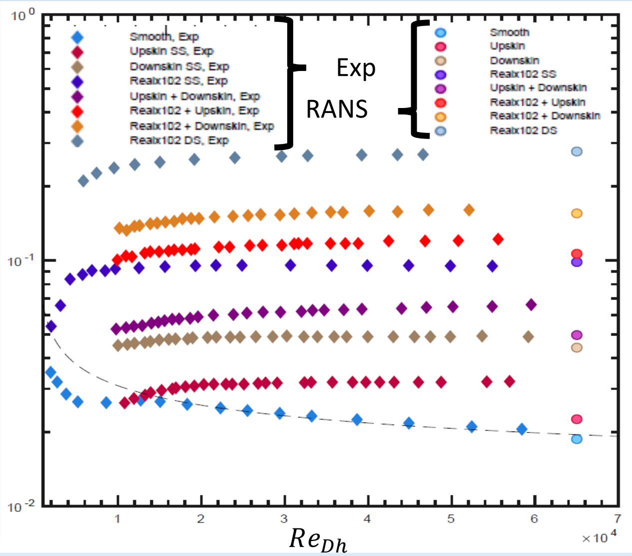
- In-house RANS models of each of 8 RIFT configurations
  - Geometrically-resolved roughness
  - 60 million cells
  - Steady flow, third-order accurate in space
  - Spalart-Allmaras turbulence model

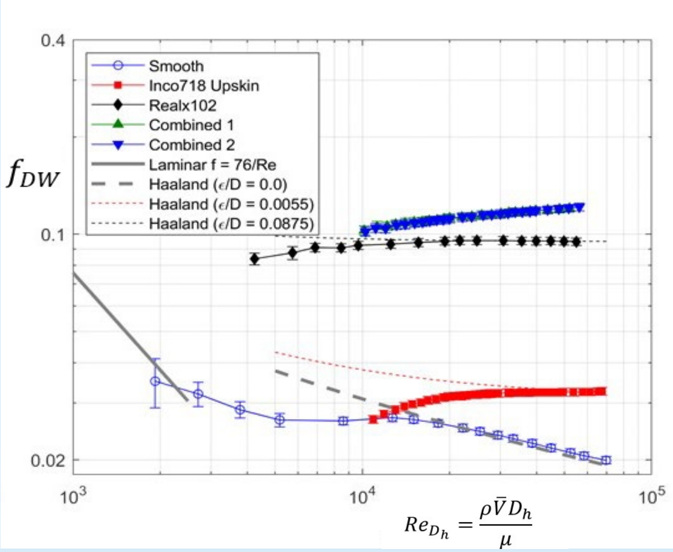


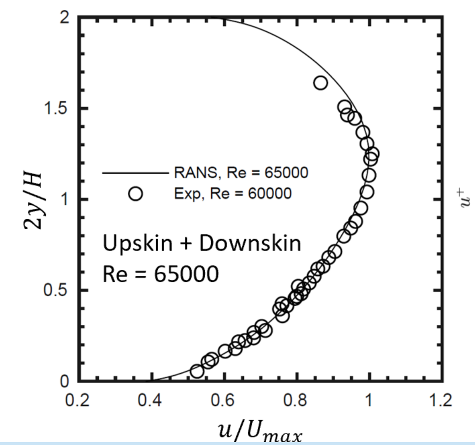


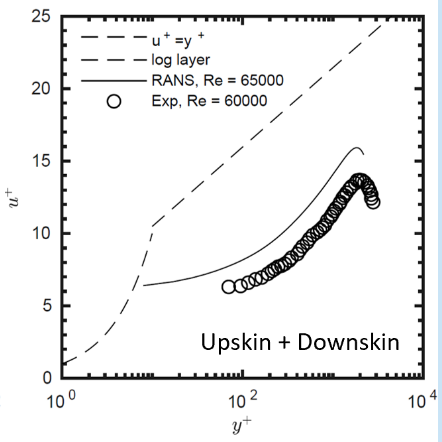
RANS modeling/parameterizations

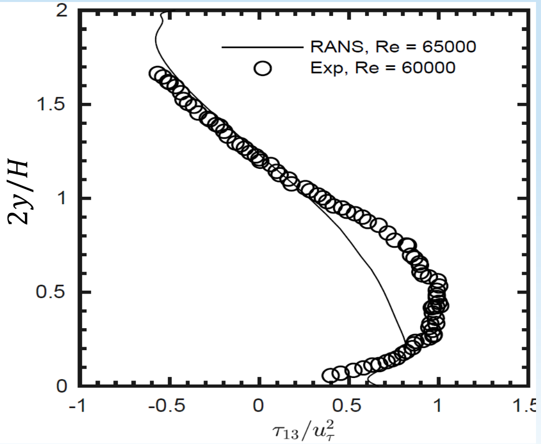
- Cross-section of RIFT results from previous UTSR reviews and publications to date*

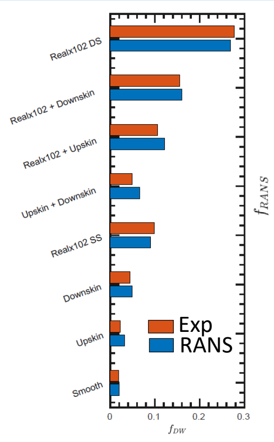


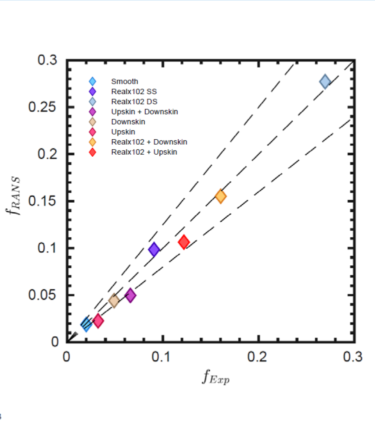












*GT2019-90931, GT2020-14809, APS-DFD 2018: M32.00002

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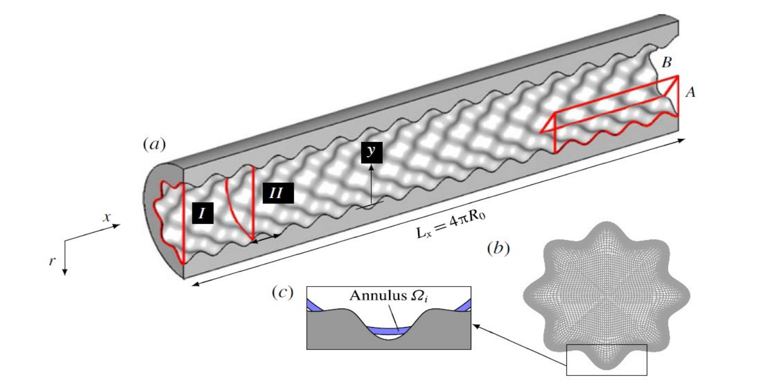
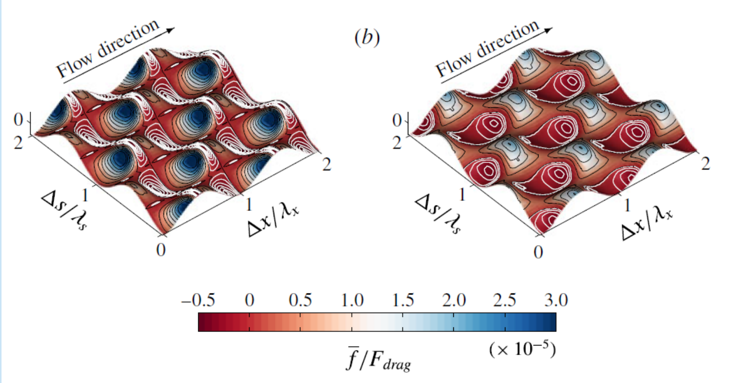
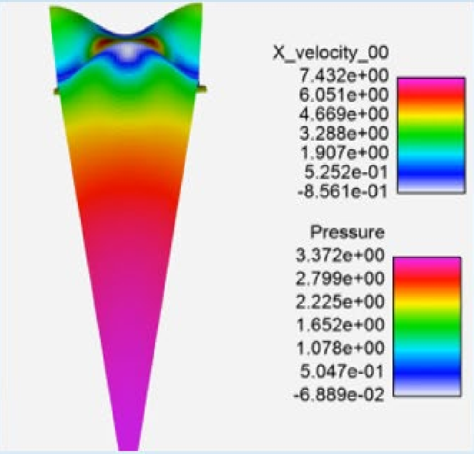
RANS modeling/parameterizations

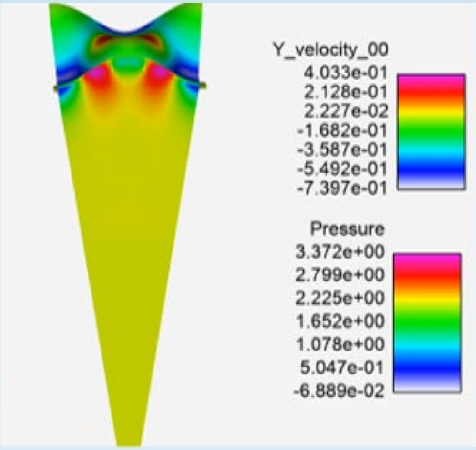
- In-house RANS and open-lit DNS models of sinusoidal pipe



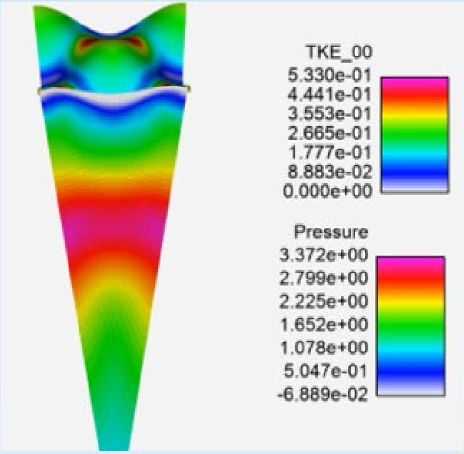




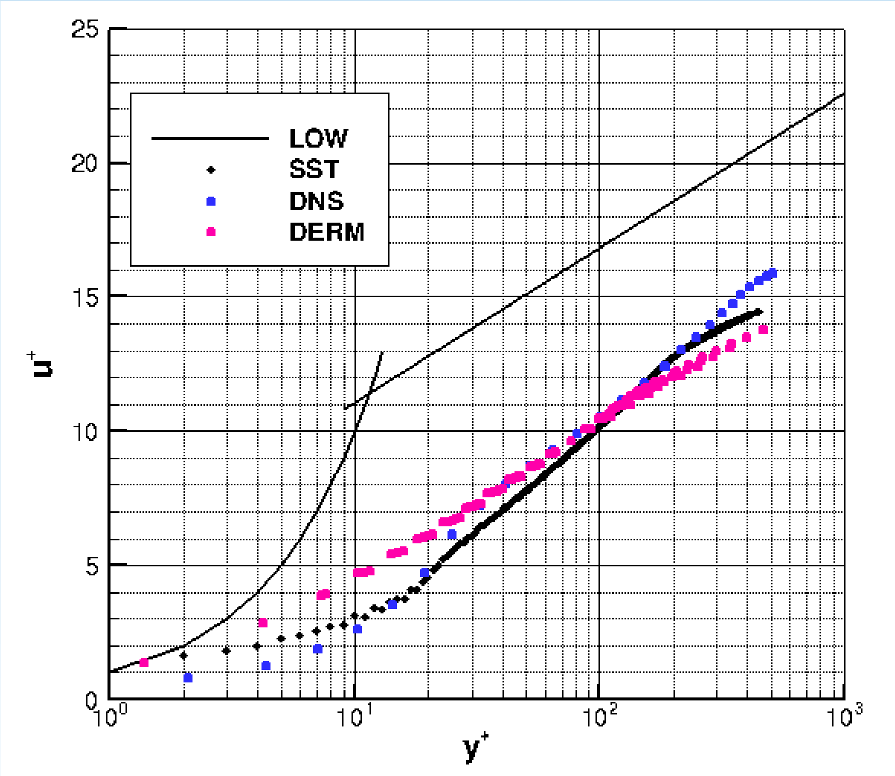
Wall pressure, axial velocity contours along streamwise stations



Wall pressure, vertical velocity contours along streamwise stations

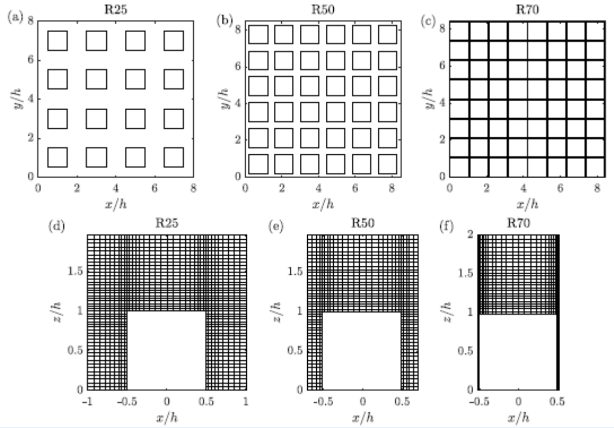


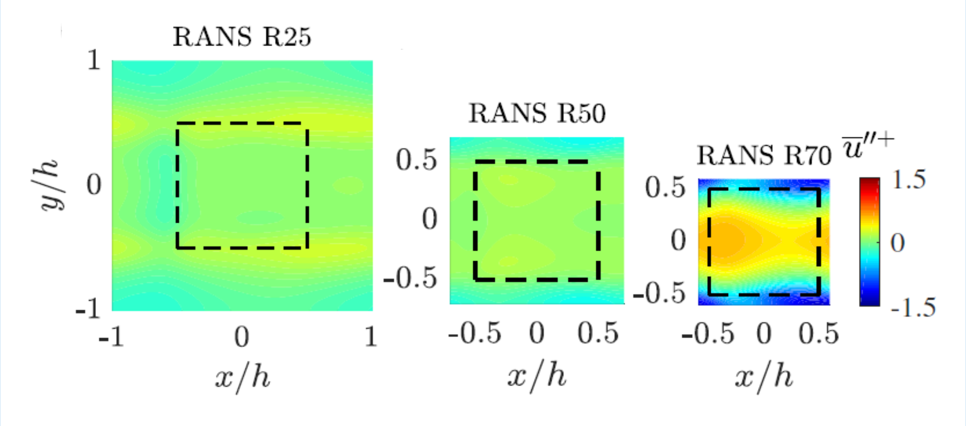
Wall pressure, turbulent kinetics energy contours along streamwise stations

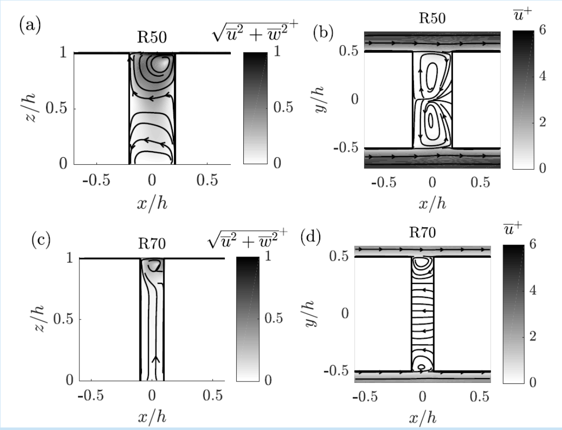


RANS modeling/parameterizations

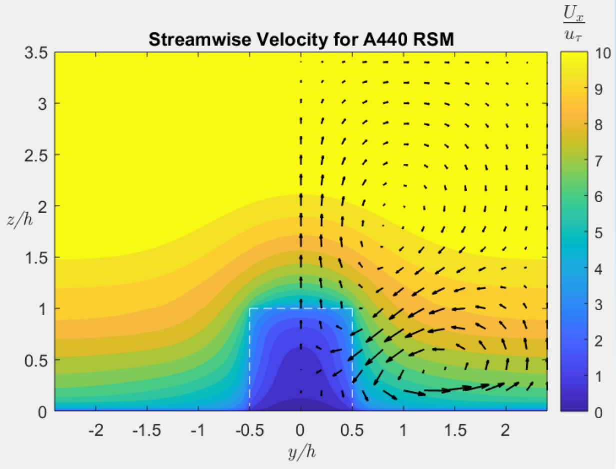
- In-house RANS and in-house DNS models of cube arrays*

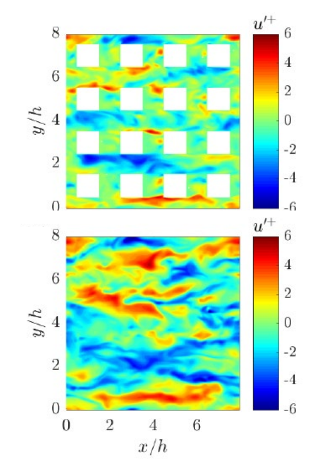


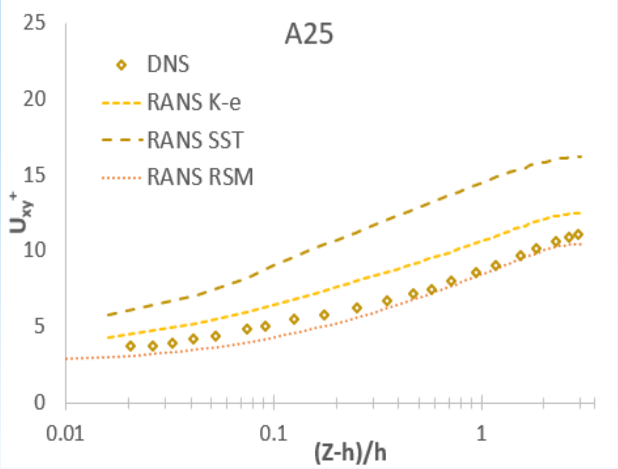


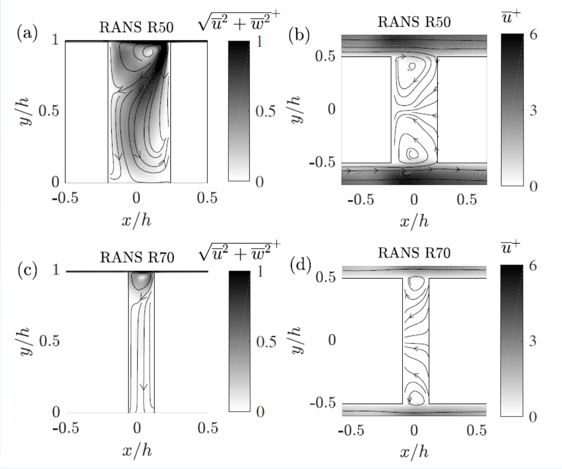


DNS







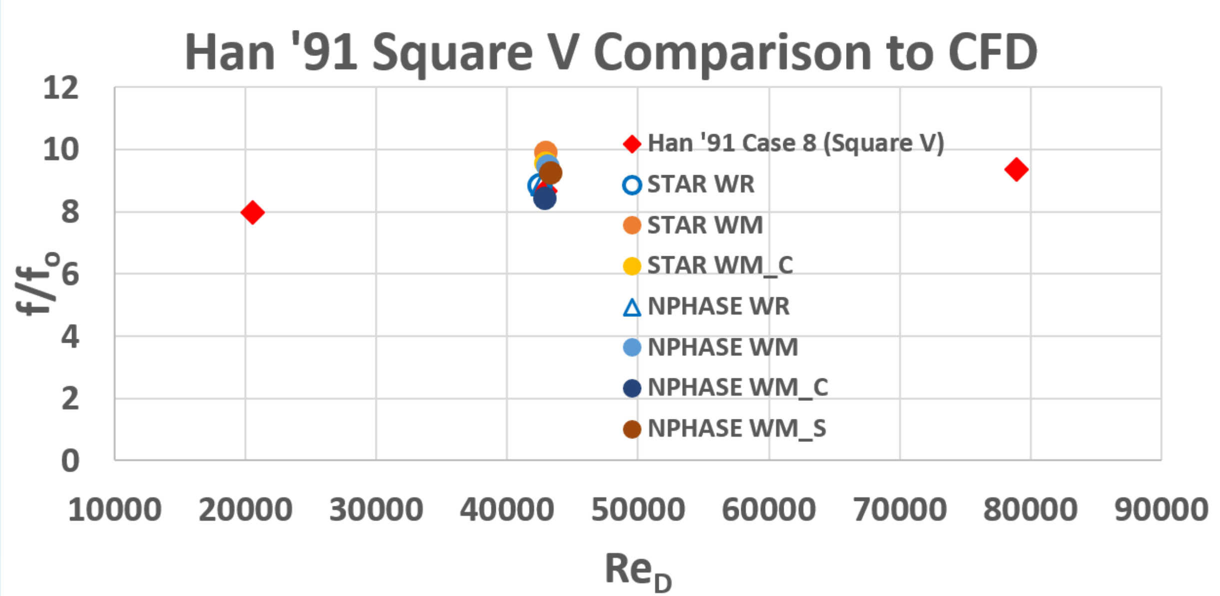


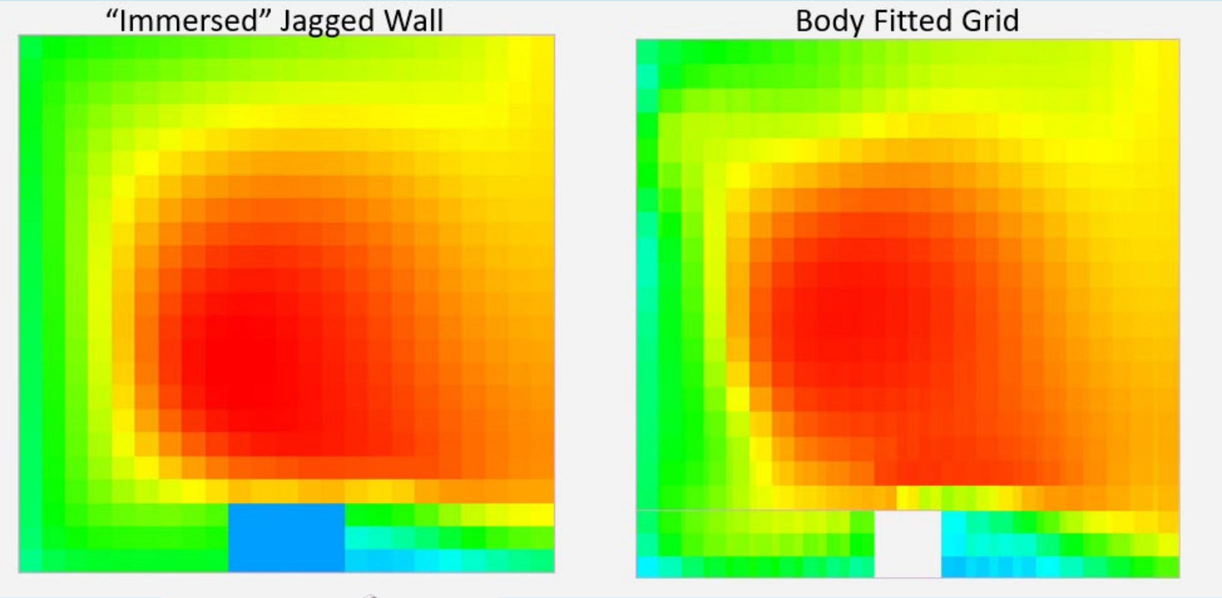
RANS

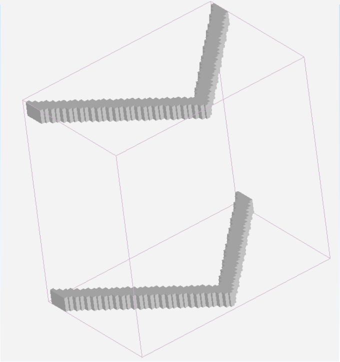
*Xu, Altland, Yang, Kunz JFM 2020 Altland, Xu, Kunz, Yang JFE 2021

RANS modeling/parameterizations

- In-house RANS models of Han* wedges







*Han JHT 1991

Students on Project

- Sam Altland
  - Penn State, Mechanical Engineering, PhD, Expected Graduation December 2021
  - Passed PhD Candidacy Exam September 2019, course work complete, Comps in December 2020
  - Spent Summer 2018 and Summer 2019 at GE Global Research as an intern developing experimental protocols for additively manufactured passages.
- Emily Cinnamon
  - Baylor University, Mechanical Engineering, MS, Graduated May 2020
  - Thesis: "X-Wire Examination of Turbulent Internal Flow in Simulated Additively Manufactured Turbine Blade Cooling Channels"
- Gabriel Stafford
  - Baylor University, Mechanical Engineering, MS, Defended 10/29/20, Graduating December 2020
  - Thesis: "Convection Measurements in Scale Models of Additively Manufactured Turbine Blade Cooling Passages"
- Ryan Boldt
  - Baylor University, Mechanical Engineering, MS, Started July2020
  - Topic: "Tomographic PIV Investigations of Flow in Scaled AM Turbine Blade Cooling Passages"

PennState Mechanical Engineering

Baylor University

Publications to Date

APS-DFD 2018: M32.00002
Title: Direct Numerical Simulation of Additively and Conventionally Manufactured Internal Turbine Cooling Passages

ASME Paper Number: GT2019-90931
Title: Flow in a Scaled Turbine Blade Cooling Channel With Roughness due to Additive Manufacturing

ASME Paper Number: GT2020-14809
Title: Flow in a Simulated Turbine Blade Cooling Channel With Spatially Varying Roughness Caused by Additive Manufacturing Orientation. **Accepted ASME Journal of Turbomachinery**

Title: Flow over Closely Packed Cubical Roughness
Revisions submitted Journal of Fluid Mechanics

APS-DFD 2020: 2020-000876
Title: Closure of Distributed Element Roughness Modeling for Deterministic Roughness Morphologies Using DNS

ASME Paper: GT2021
Title: Convection in Scaled Turbine Internal Cooling Passages with Additive Manufacturing Roughness
Abstract Accepted, In preparation

Title: Modeling of Cube Array Roughness; RANS, LES and DNS **In preparation Journal of Fluids Engineering**

PennState
Mechanical Engineering

Baylor University

Recent Publications

Proceedings of ASME Turbo Expo 2020
Turbomachinery Technical Conference and Exposition
GT2020
June 22-26, 2020, London, England

GT2020-14809

FLOW IN A SIMULATED TURBINE BLADE COOLING CHANNEL WITH SPATIALLY VARYING ROUGHNESS CAUSED BY ADDITIVE MANUFACTURING ORIENTATION

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David R. Hanson
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ABSTRACT
Because of the effects of gravity acting on the melt region created during the laser sintering process, additively manufactured surfaces that are pointed upward have been shown to exhibit roughness characteristics different from those seen on surfaces that point downward. For this investigation, the Roughness Internal Flow Tunnel (RIFT) and computational fluid dynamics models were used to investigate flow in channels with different roughness on opposing walls of the channel. Three rough surfaces were employed for the investigation. Two of the ... roughness condition of the opposing wall providing evidence that Townsend's Hypothesis holds even for the large relative roughness values expected for additively manufactured turbine-blade cooling passages.

NOMENCLATURE
A_{ts} = test section cross-sectional area = 8,200 mm^2
A_{PF} = the planform area (top-view projected area)
B = the Law of the Wall intercept
C_0 = nozzle or Venturi discharge coefficient

Under consideration for publication in J. Fluid Mech. 1

Flow over closely packed cubical roughness

Haosen HA Xu[1], Samuel J Altland[1], Xiang IA Yang[1]†, and Robert F Kunz[1]

[1]Mechanical Engineering, Penn State University, State College, PA 16802, USA

(Received xx; revised xx; accepted xx)

Cube arrays are one of the most extensively studied types of surface roughness, and there has been much research on cubical roughness with low to moderate surface coverage densities. In order to help populate the literature of flow over cube arrays with high surface coverage densities, we conduct direct numerical simulations (DNSs) of flow over ...

Modeling of Cube Array Roughness; RANS, LES and DNS

Sam Altland, Haosen Xu, Robert Kunz*, Xiang Yang
Department of Mechanical Engineering,
Pennsylvania State University,
University Park, PA 16802

Flow over arrays of cubes is a classic method for CFD modeling of rough wall turbulent boundary layers. While considerable effort has been made in investigating these flows using DNS and LES, the ability of sublayer-resolved RANS to predict the bulk flow phenomena of these systems is relatively unexplored. Here, RANS simulations are conducted on six different packing densities of cubes in aligned and staggered configurations using multiple turbulence closure models, including a Reynolds stress models The packing densities in-...

that attempt to predict the effects of even irregular roughness on the mean flow as a function of the surface statistics [6,7]. In addition, with the growth of additive manufacturing as a viable alternative to conventional metallurgy, there is active research in the characterization of how the roughness of an AM surface affects friction and heat transfer [8,9].

However, due to the high overhead costs and limited bandwidth of experimental investigation, using CFD as a predictive method for rough wall turbulent boundary layer ...

Proceedings of ASME Turbo Expo 2021
Turbomachinery Technical Conference and Exposition
GT2021
June 7-11, 2021, Virtual Conference

GT2021-59684

CONVECTION IN SCALED TURBINE INTERNAL COOLING PASSAGES WITH ADDITIVE MANUFACTURING ROUGHNESS

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ABSTRACT
Additive manufacturing processes, such as direct metal laser sintering (DMLS), enable creation of novel turbine cooling internal passages and systems. However, the DMLS method produces a significant and unique surface roughness. Previous work in scaled passages analyzed pressure losses and friction factors associated with the rough surfaces, as well as investigated the velocity profiles and turbulent flow characteristics within the passage. In this study, the heat transfer characteristics of scaled additively manufactured surfaces were measured using infrared thermography. ... passages investigated in this study do not include long-wavelength artifacts and channel geometric deviations observed by Wildgoose et al. (2020). However, the results of this study indicate that, based on the roughness augmentation alone, artificial convective cooling enhancers such as turbulators or dimples may still be required for additively manufactured turbine component cooling.

NOMENCLATURE
A_{ts} = test section cross-sectional area = 8,200 mm^2

Summary and Current/next steps

- 13 months out from end of project (12/31/2021)
- Progress to date:
  - RIFT adiabatic
  - RIFT convection
  - DERM formulation development
  - DNS, LES, RANS for DERM calibration of numerous roughness morphologies
  - DERM calibration

Summary and Current/next steps

- DERM development is now focus
  - Adiabatic calibration
  - Heat transfer
- “Winding down” and publishing the EFD, DNS/LES/RANS elements
- Optimization (Task 4) will “compete” with DERM effort through end of current project