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

Year 2 Research Progress

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UTSR Program Review
5 November 2018

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- Review of Background/Objectives/Technical Approach
- Year 2 activities and progress:
  - Numerous new configurations studied (build angle, powder)
  - RIFT testing
  - RANS modeling/parameterizations
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- Publications
- Summary and current/next steps

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Review of Background/Objectives/Technical Approach

- Metal AM enabling gas turbine design exploration of cooling schemes not currently manufacturable
- Potential *transformational* gains in turbine operating temperature and durability
- *To harness opportunity need to mature thermal design tools*
  - Accommodate the very complex “roughness field” that invariably characterizes these engineered flow passages
  - Conventional roughness modeling for CFD predictions of flow field/convective heat transfer are inadequate

Review of Background/Objectives/Technical Approach

- Accordingly, this project develops Discrete Element Roughness Modeling (DERM), in the context of Large Eddy Simulation (LES) and Reynolds Averaged Navier-Stokes (RANS) methods
  - *Necessary and sufficient* for mechanistic predictions of additively manufactured turbine cooling scheme configurations
  - DERM also represents a viable design approach for conventionally manufactured internal blade cooling features

Review of Background/Objectives/Technical Approach

- Advance CFD methods for accuracy and run time requirements for design and optimization relevant to additively and conventionally manufactured turbine cooling scheme configurations
  - Discrete Element Roughness Modeling (DERM) mechanistic-based model for roughness predictions
  - Context of Large Eddy Simulation (LES) and Reynolds Averaged Navier-Stokes (RANS) methods
- 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

Review of Background/Objectives/Technical Approach

- Deliver to turbine blade design community a sufficiently physics rich and validated model set for design of blade cooling passages characterized by roughness morphology and tolerancing inherent to L-PBF manufacturing of these blades.
  - Straightforwardly implemented within current OEM CFD-based turbine design practice.
  - 3D $\therefore$ far more general in breadth of applicability than Q1D

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Review of 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

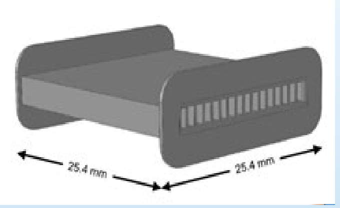
Multi-modal inspection
- CT, OP, SEM as necessary

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

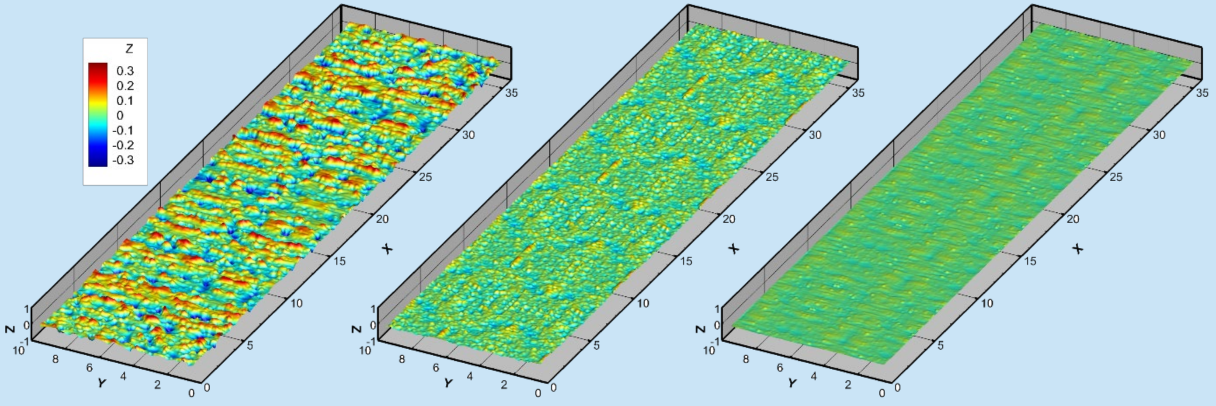
DERM model development
- Formulation
- Morphology parameterization
- DNS calibration
- At scale and up scale calibration

Application and Optimization

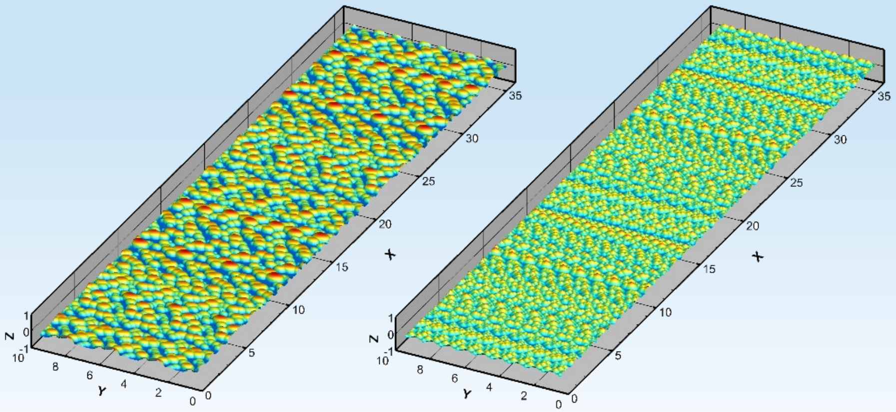
Numerous new configurations tested in RIFT



- Real DMLS surfaces from CT scans/optical profilometry
  - Real_x102_Upskin: Hastelloy-X (a nickel-chromium-iron-molybdenum alloy)
  - Inco718_Upskin: Inconel 718 printed with surface pointed “up” at 45°, x50
  - Inco718_Downskin: Inconel 718 printed with surface pointed “down” at 45°, x50
- DERM Analog surfaces replicating features of real surfaces with real AM roughness
  - Elliptical Analog: Created to match k_s of Real_x102 from Flack and Shultz correlation
  - Elliptical Cone Analog: Created to match k_s of Real_x102 from Flack and Shultz correlation
- Single sided and double sided
- Combinations of the surfaces (top versus bottom)



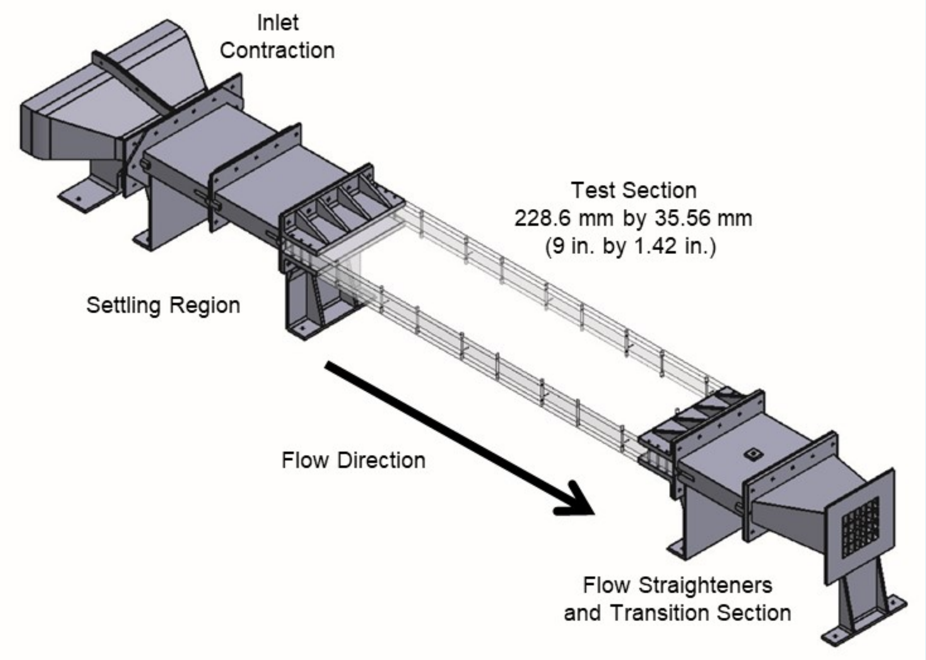
Real_x102 Inco718_Downskin Inco718_Upskin

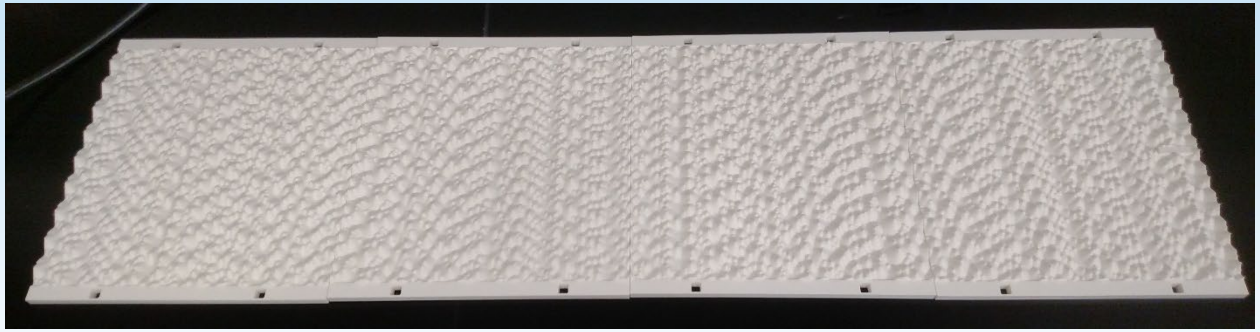


Ellipsoidal Analog Elliptical Cone Analog

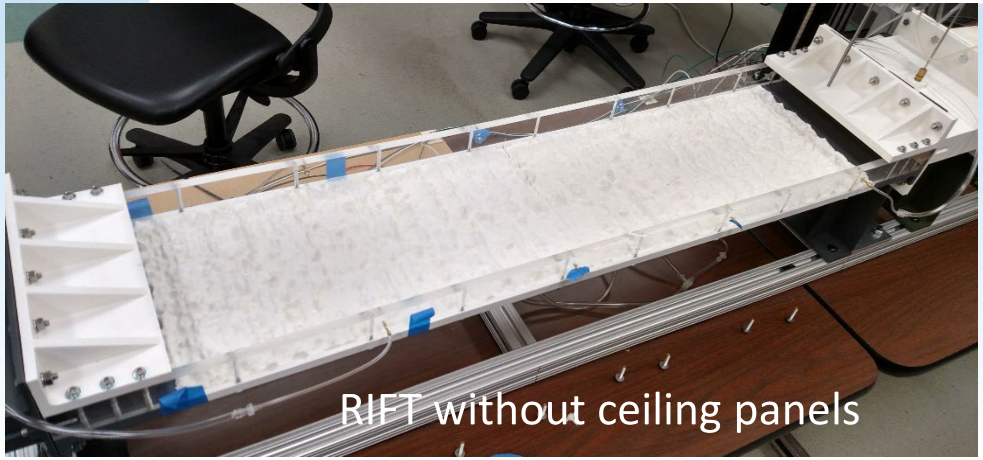
Experimental Approach and Roughness Panel Construction

- Roughness and Internal Flow Tunnel (RIFT)
- Panels printed using FDM or cut using CNC machine (heat transfer surfaces)
- Channel flow with two rough walls (86% of perimeter)
- Bulk pressure loss measurements
- Single wire and X-array anemometry





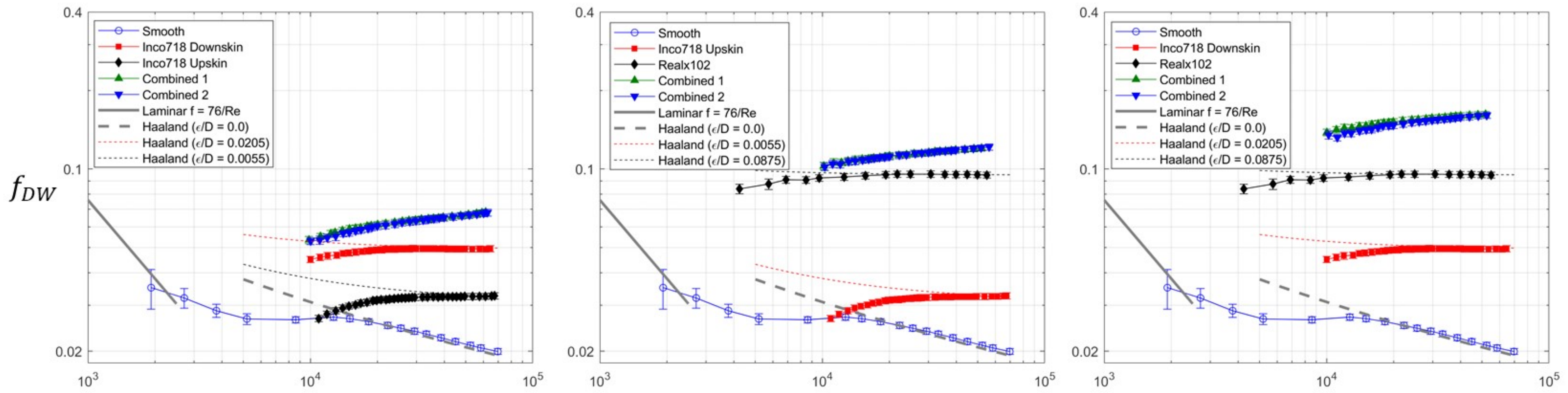
Ellipsoidal Cone Surface Panels



RIFT without ceiling panels

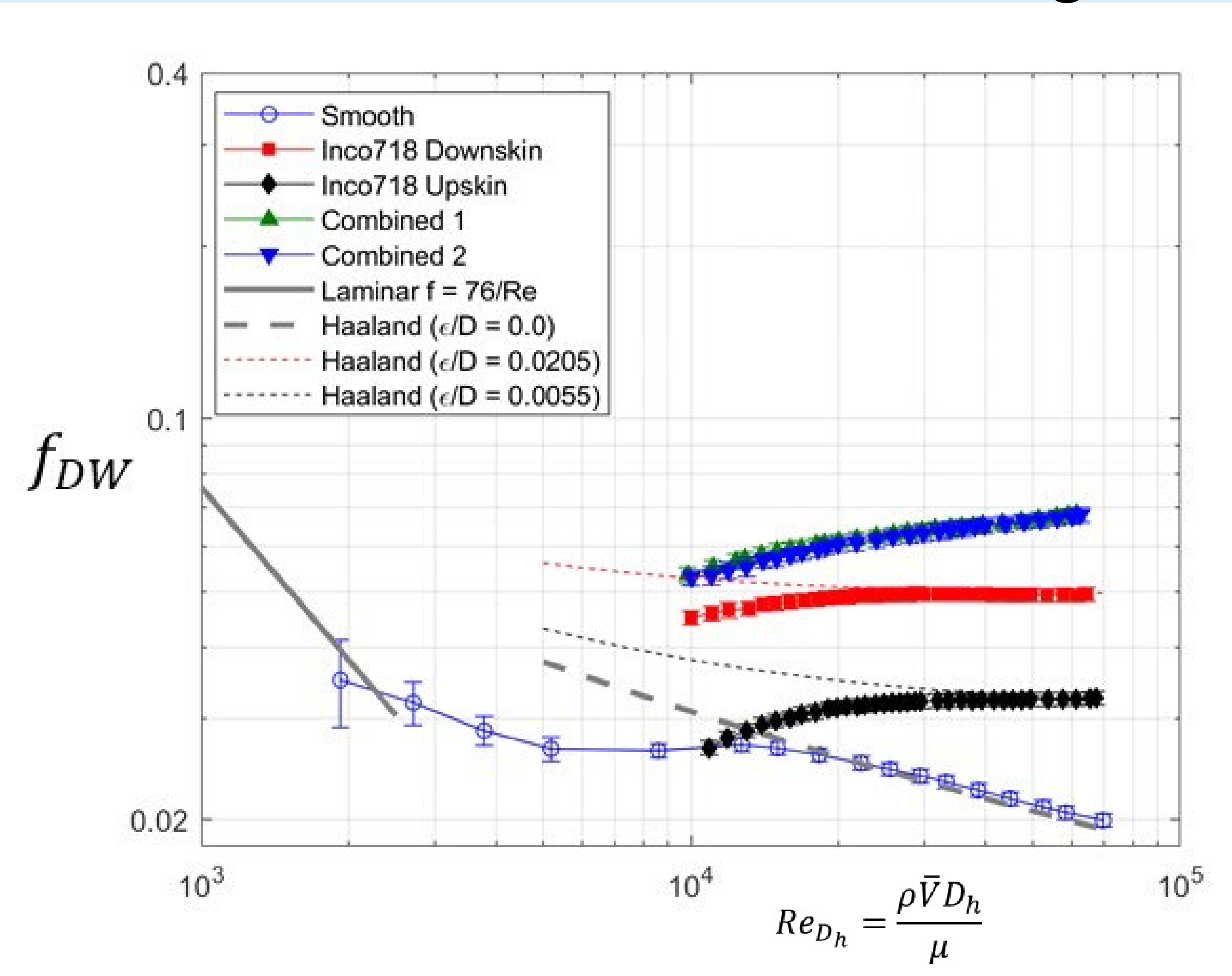
Bulk Flow Friction Factor Investigations

- Year 1: Real_x102 and the analog surfaces
- Year 2: AM printing orientation and combination effects (variations in roughness parameters along perimeter caused by AM printing orientation)
  - Focused on Inco718_Upskin and Inco718_Downskin combinations
  - Added Real_x102 surface to create wider range of R_{RMS}/Dh

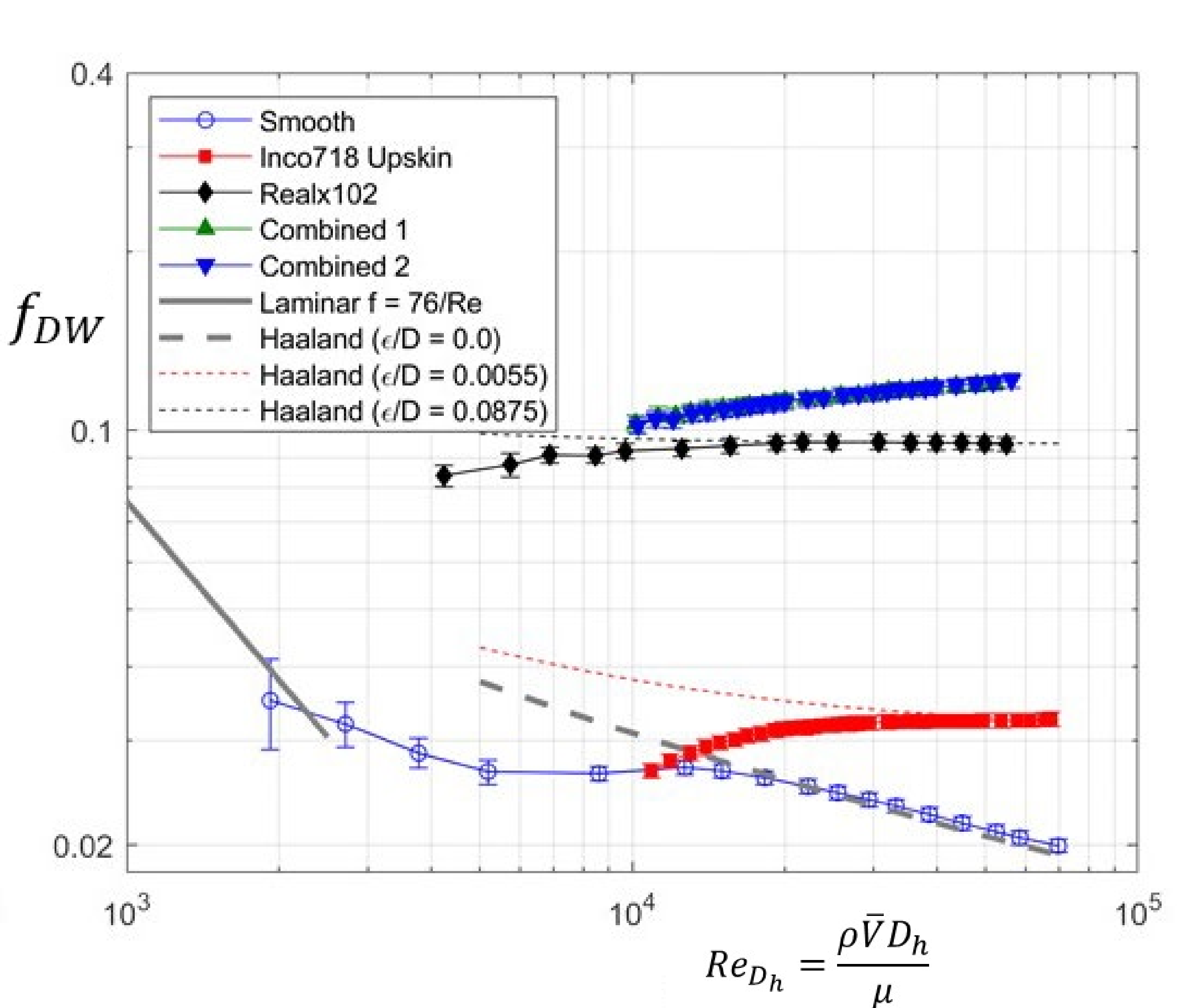


$$Re_{D_h} = \frac{\rho \bar{V} D_h}{\mu}$$

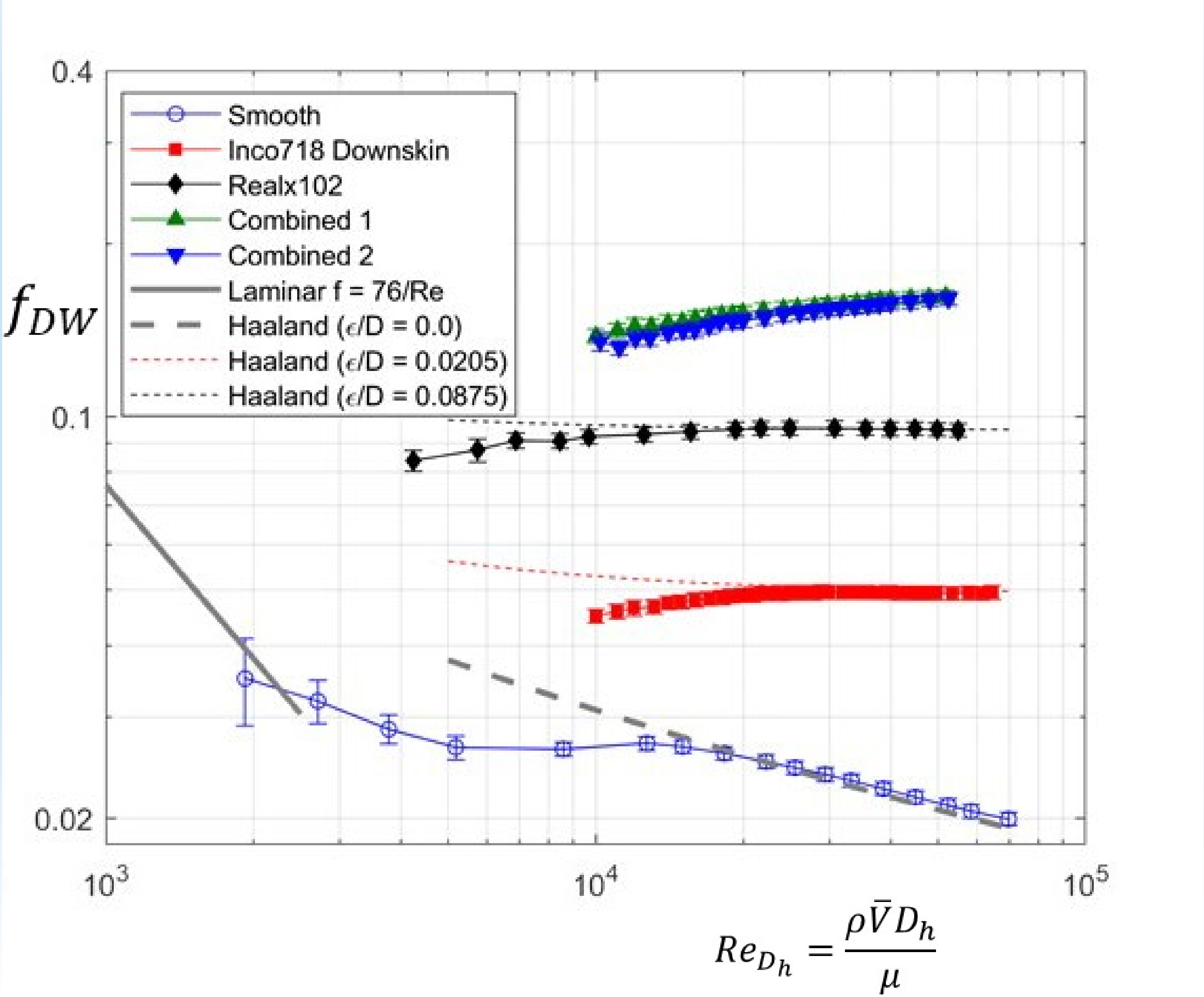
Bulk Flow Friction Factor Investigations



Bulk Flow Friction Factor Investigations

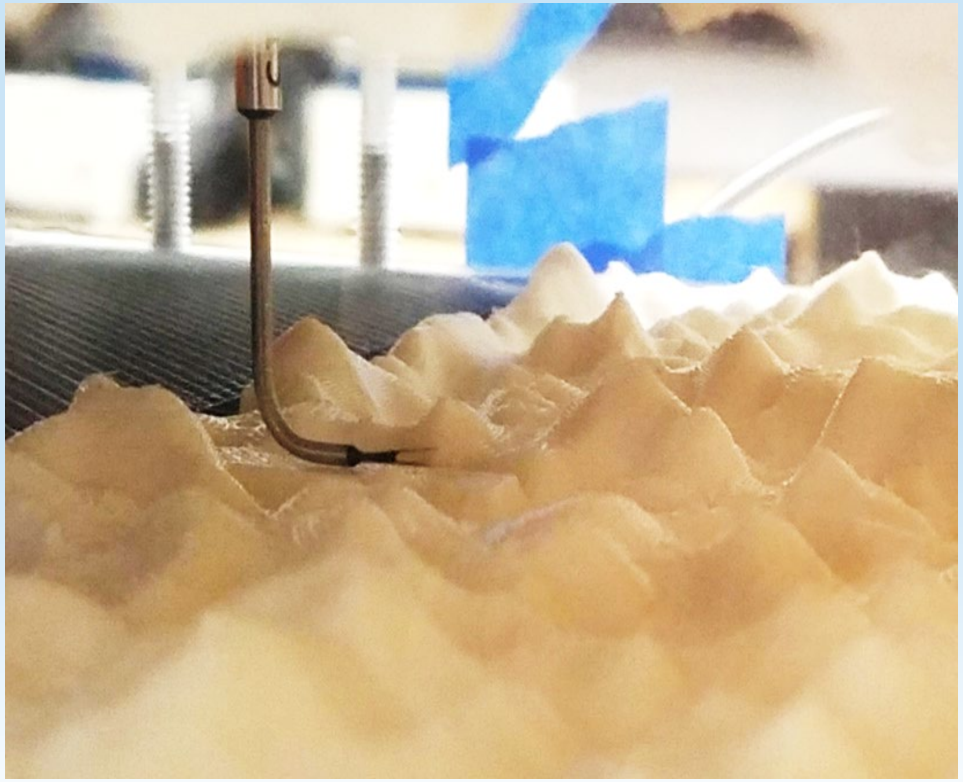


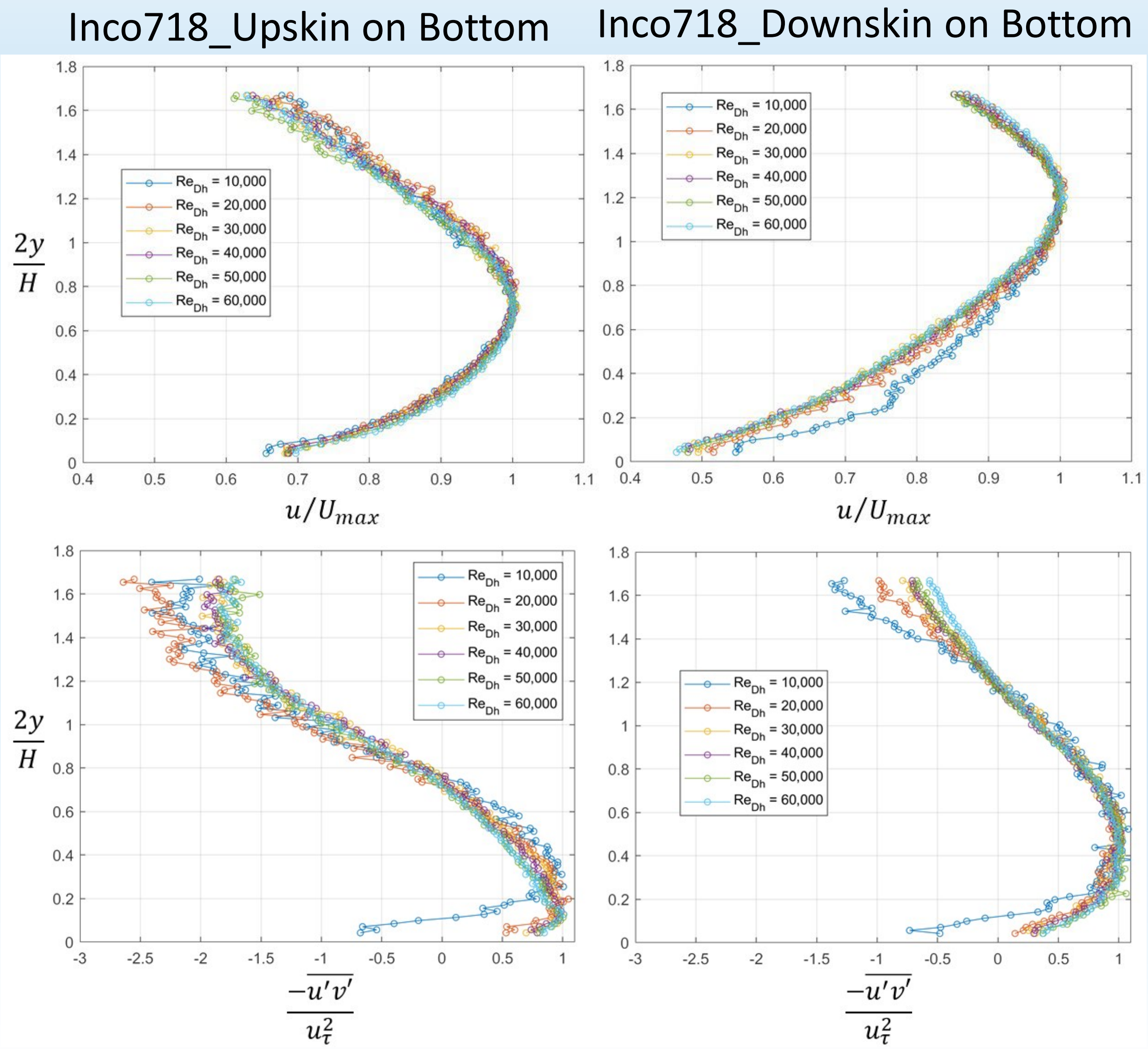
Bulk Flow Friction Factor Investigations



Hot film measurements

- $U, V, \overline{uv}, \overline{uu}, \overline{vv}$
- Different combinations of the rough panels





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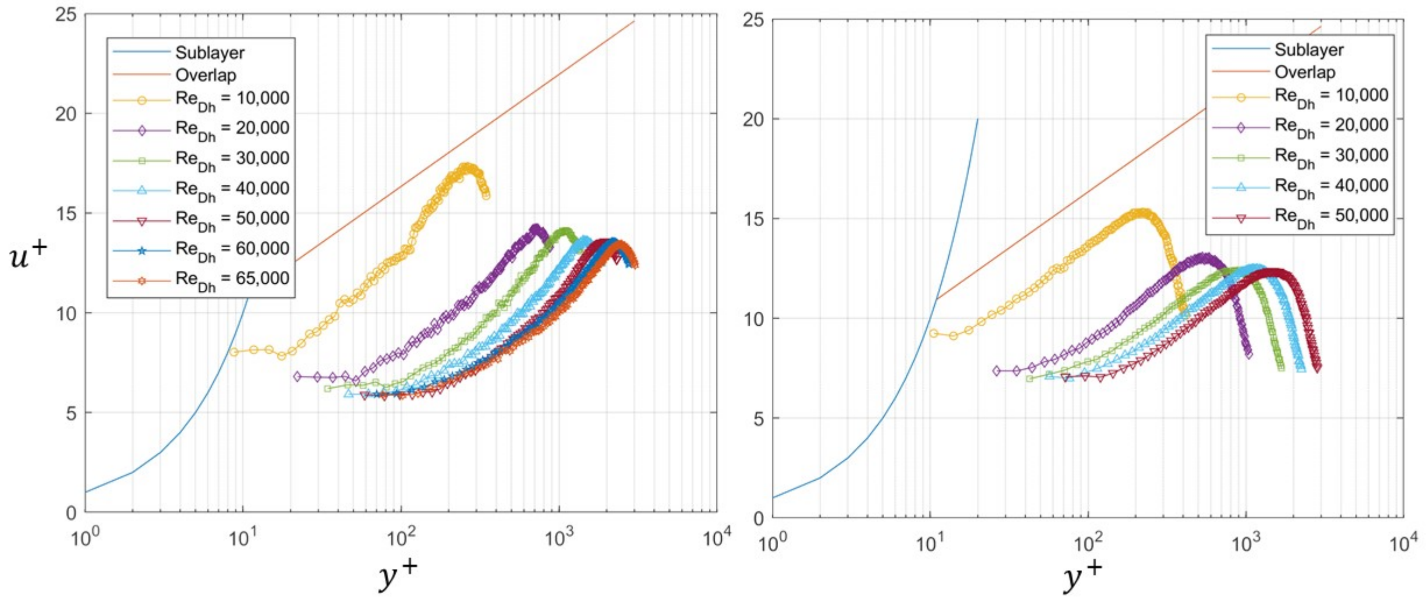
Hot film measurements: Law of the Wall

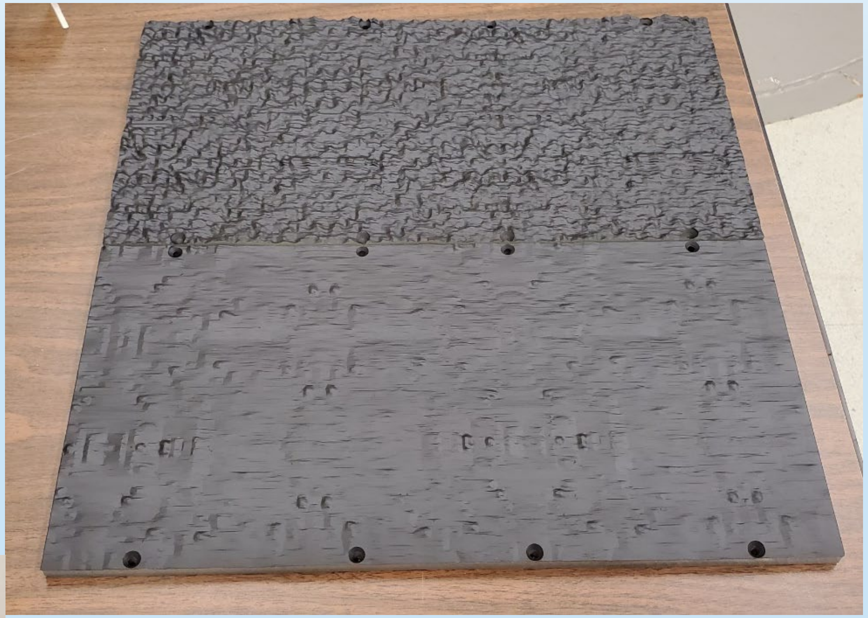
- Quantify ΔU^+
- Different panel combinations affect relative profile thickness
- CFD Validation quality local conditions for a range of roughness morphologies and Reynolds numbers of relevance to turbine cooling passages



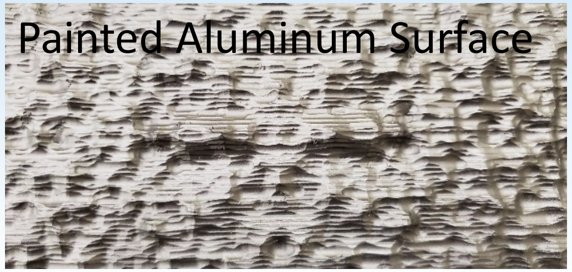
Inco718_Downskin with smooth ceiling

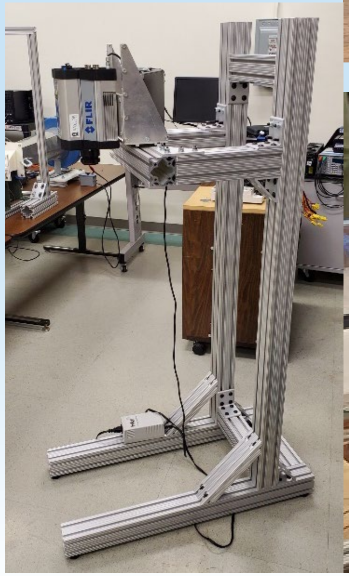
Inco718_Downskin with Real_x102 ceiling

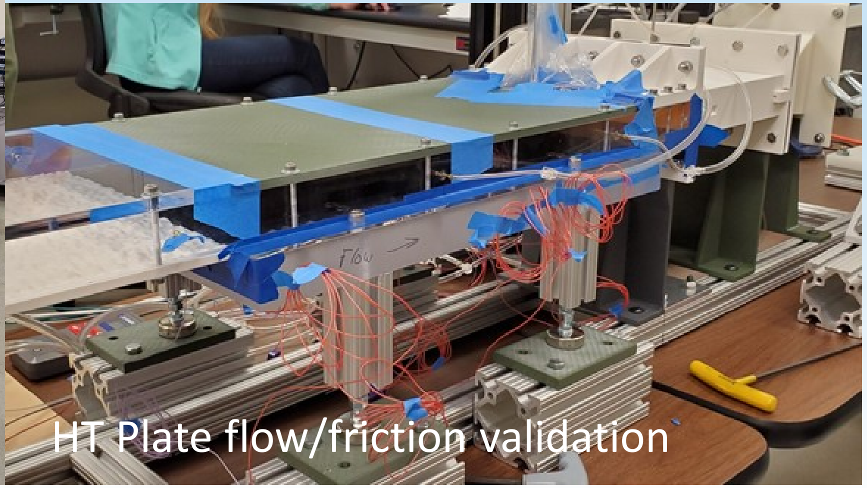
RIFT Modification for Convection Measurements



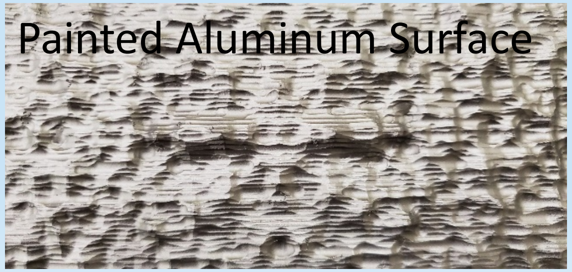
- Heat transfer plates have been etched (primer) and painted
- Flat black for the infrared emissivity
- IR window and thick acrylic HT base-plate have been constructed
- Aluminum plate with 0.020” lip and epoxy
- Convection shakedown tests imminent

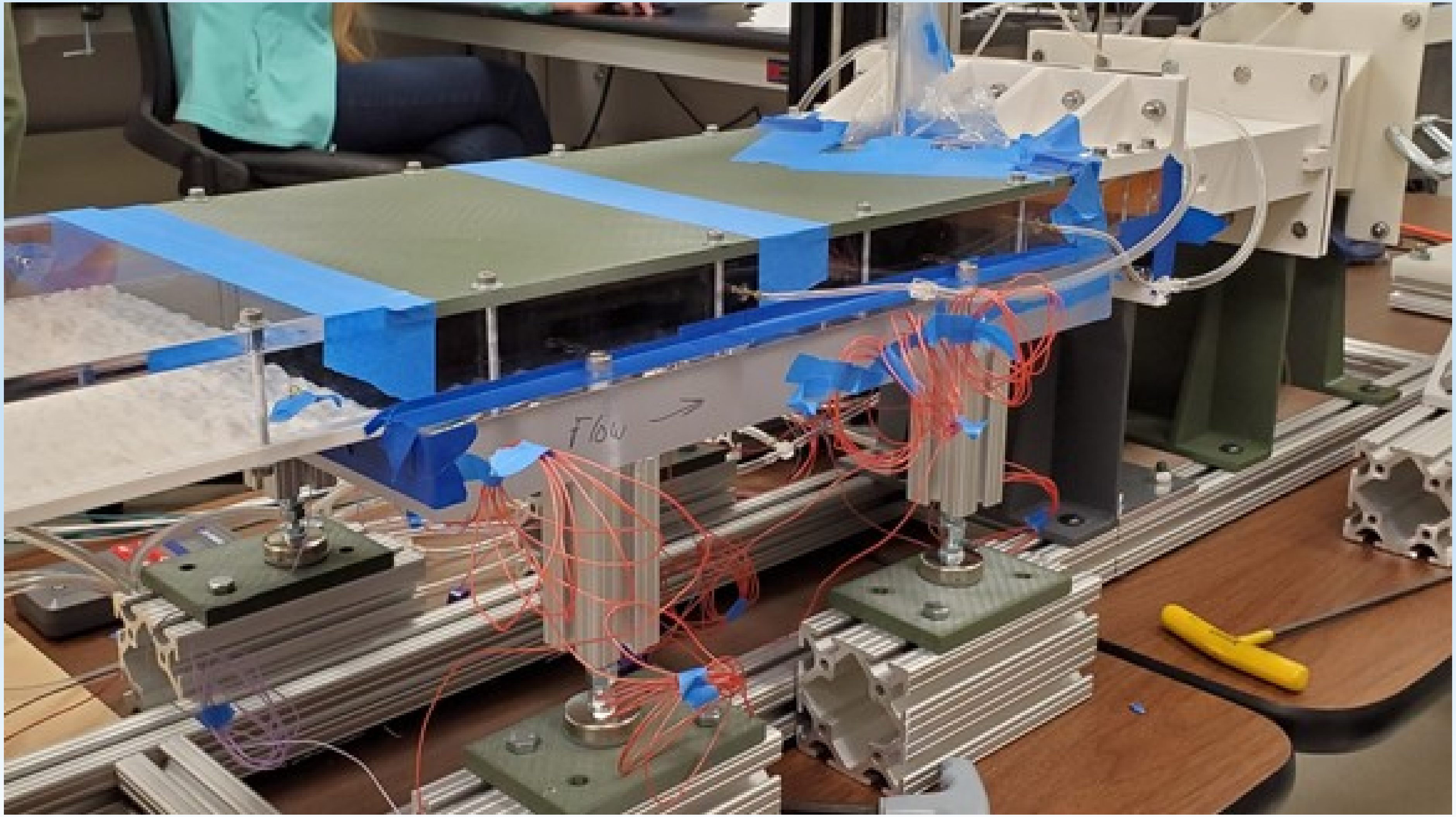






RIFT Modification for Convection Measurements

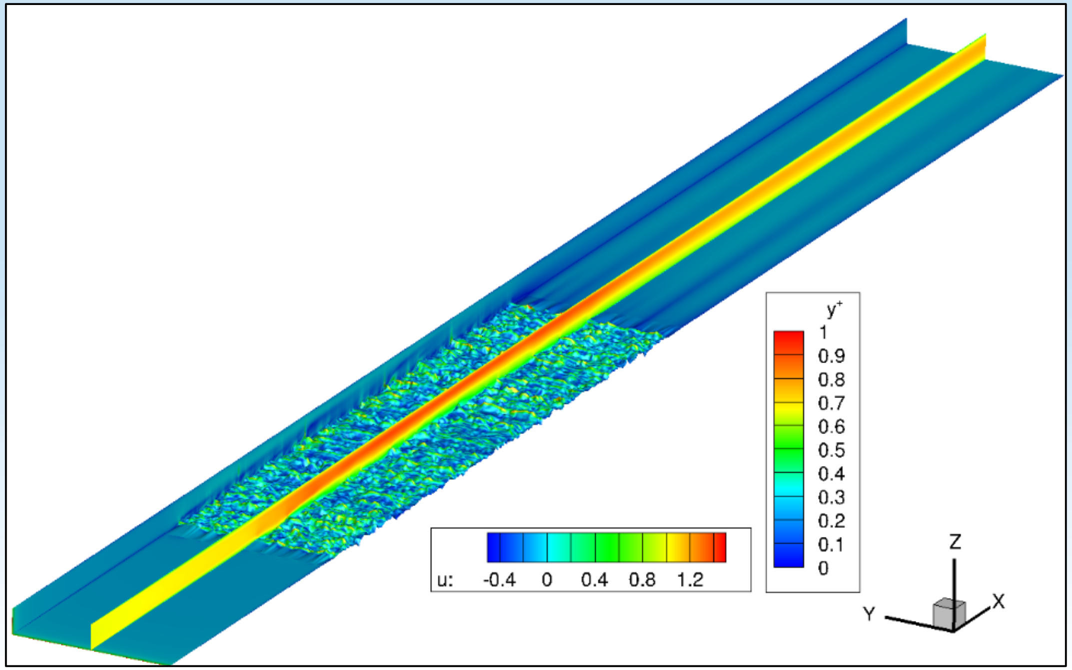


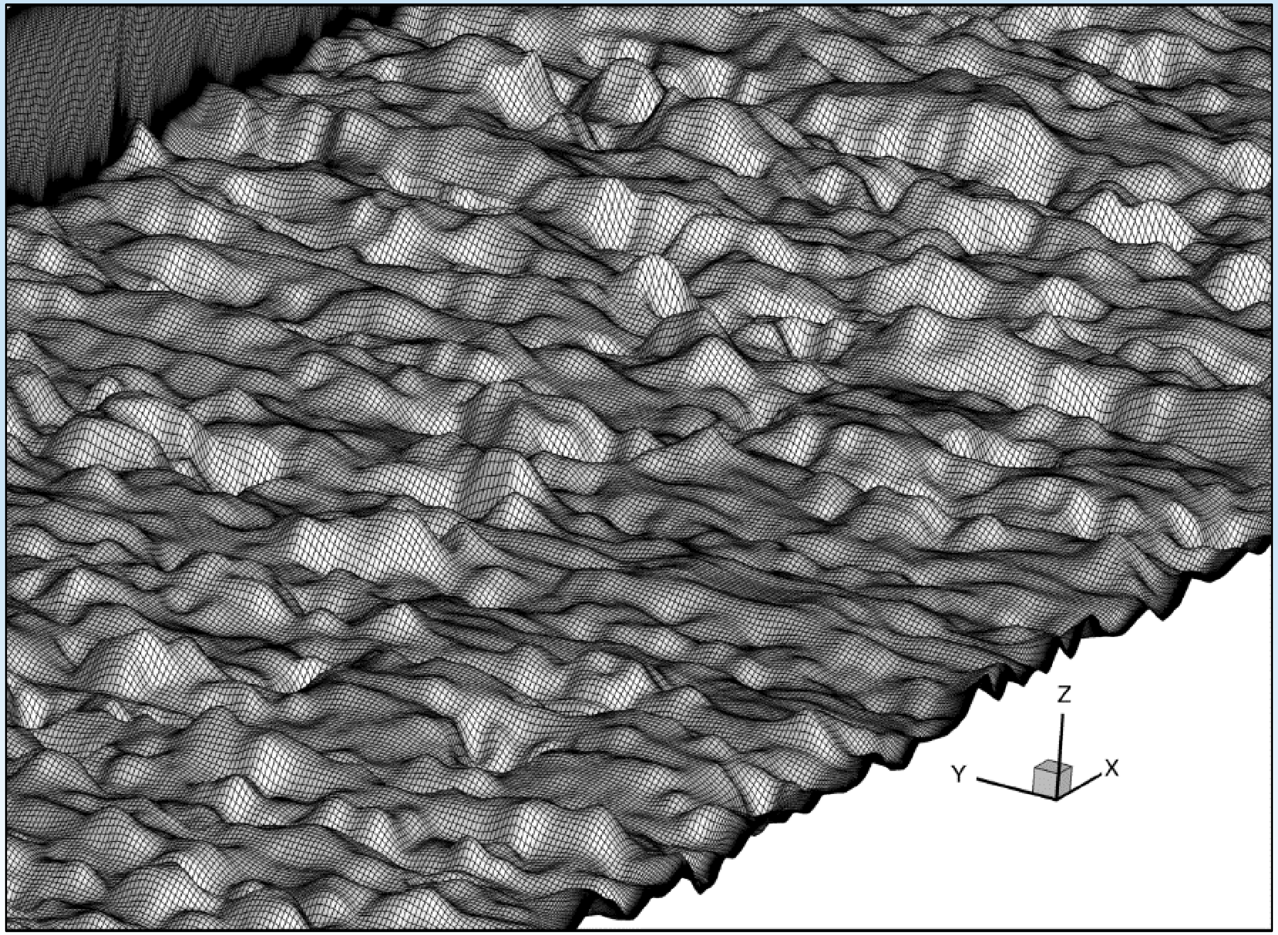


RANS modeling/parameterizations

RANS model of each RIFT configuration using in-house structured, finite-volume code

- Geometrically-resolved roughness
- 60 million cells
- Steady flow, third-order accurate in space
- Spalart-Allmaras turbulence model





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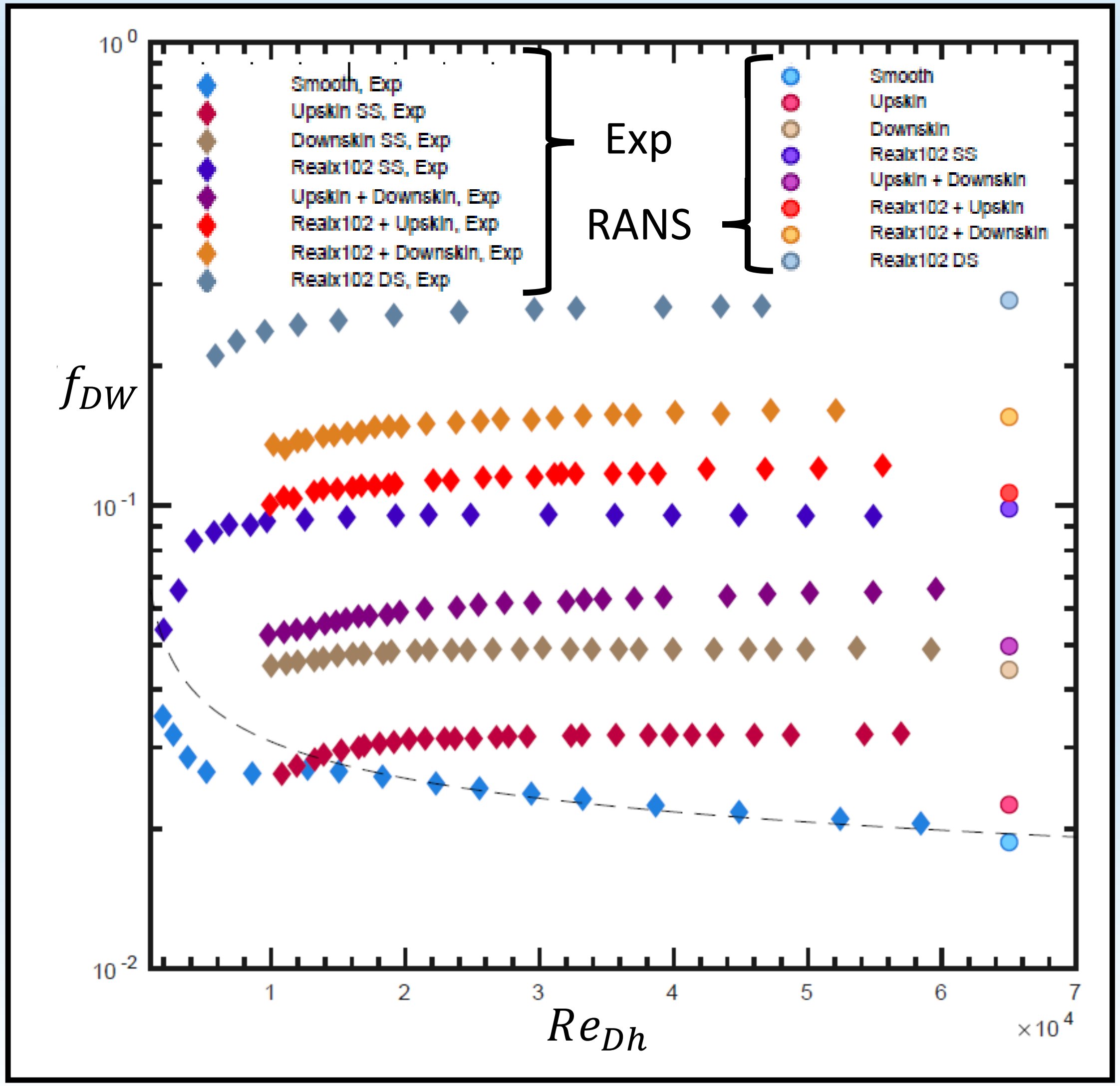
RANS modeling/parameterizations

Comparison with measured channel friction factor, f_{DW}

- One RANS simulation at Re=65,000 for each channel configuration
- Geometries are:
  - Flat surface
  - Upskin
  - Downskin
  - Real_x102
  - … and four combinations of the above



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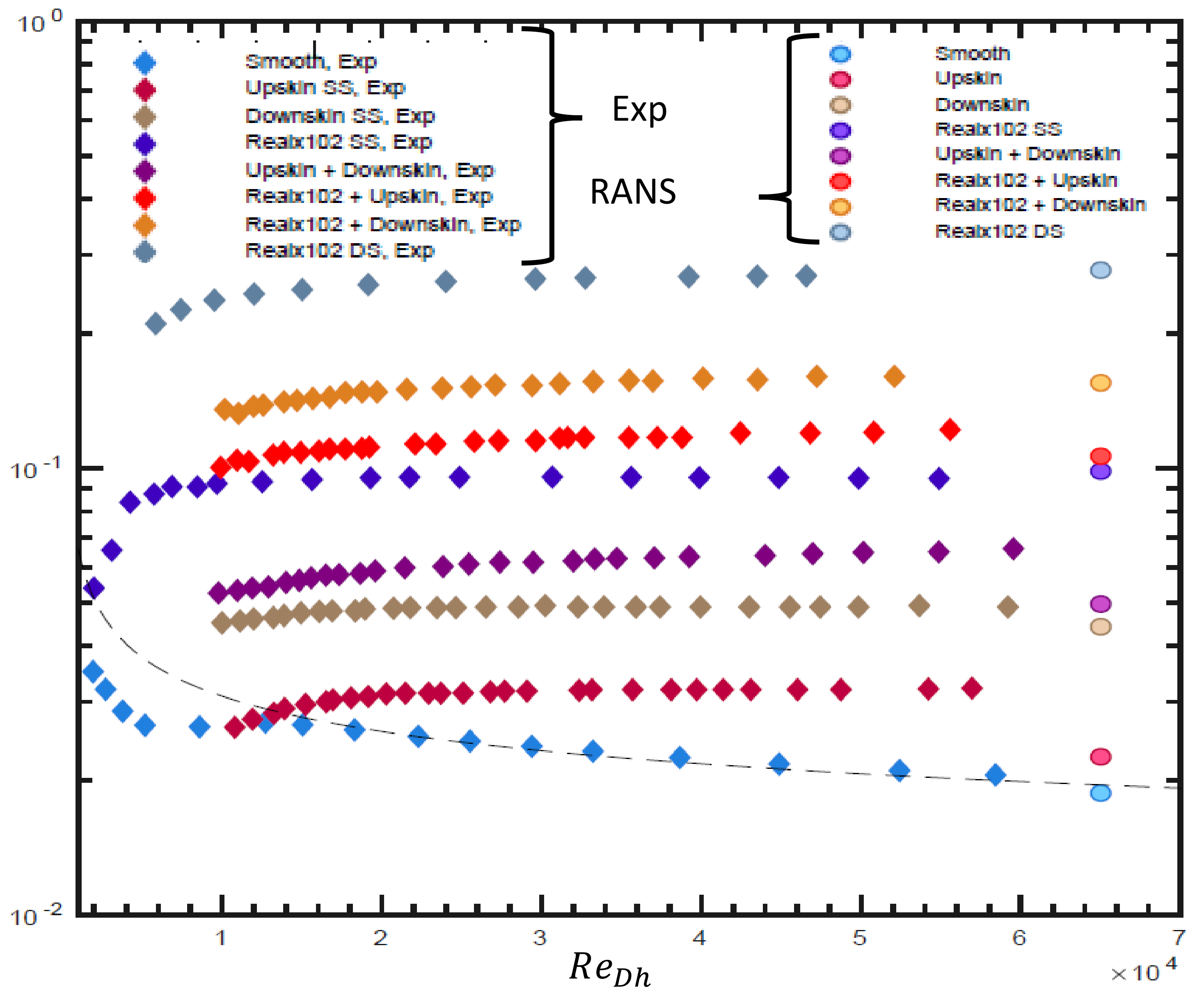
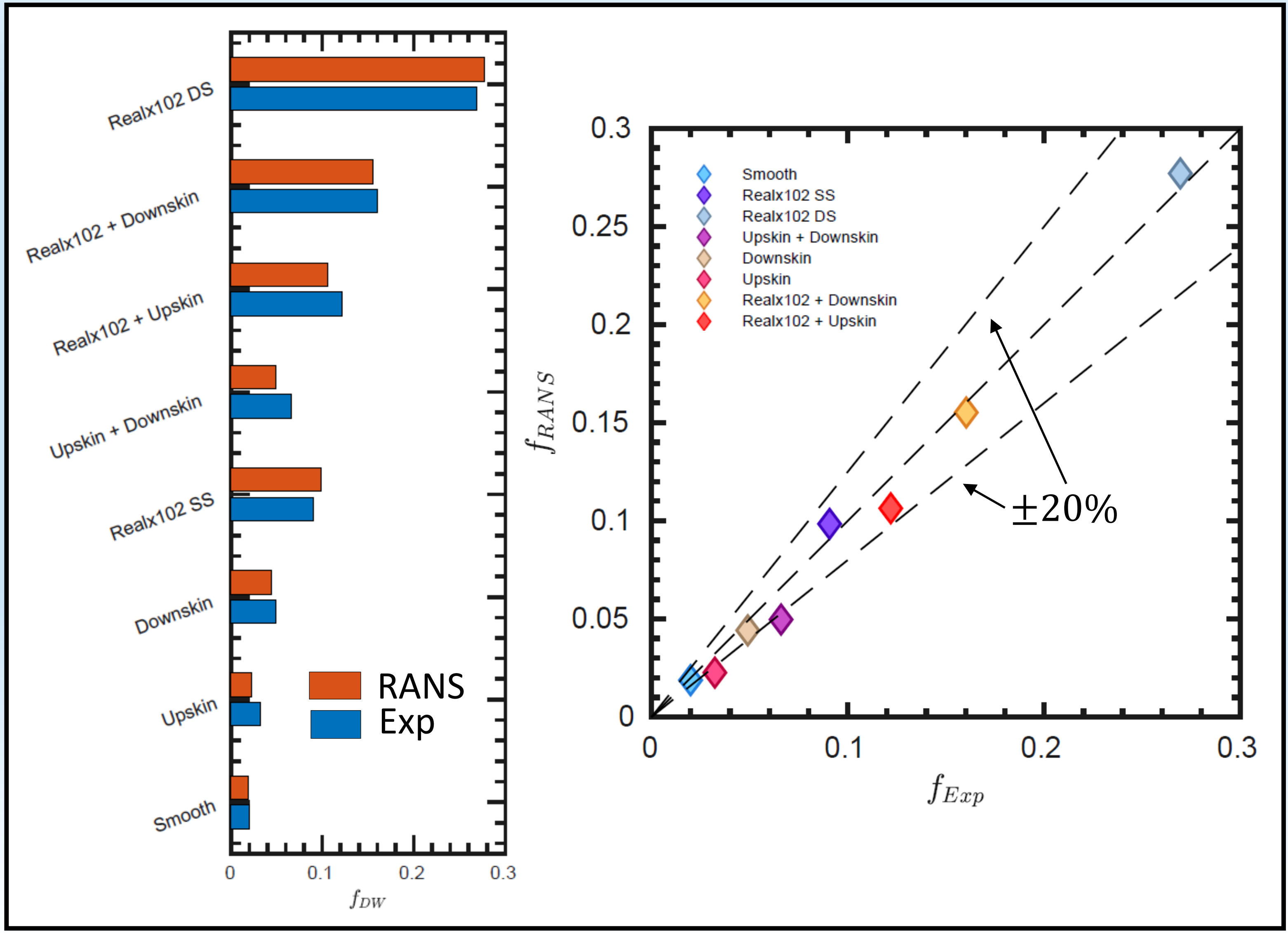


RANS modeling/parameterizations

Channel friction factor

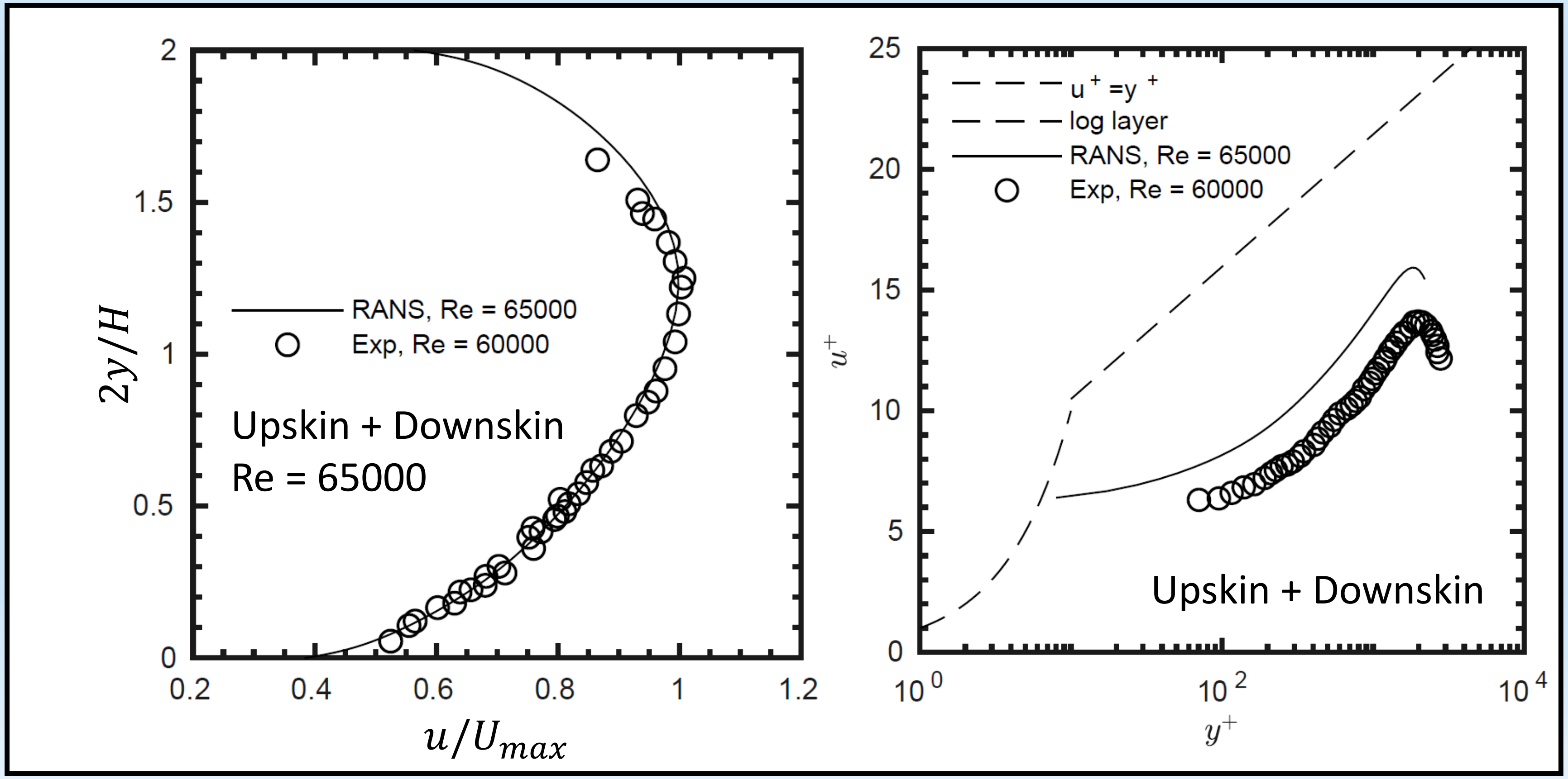
- One RANS simulation at Re=65,000 for each channel configuration
- Comparison with the highest available experimental Reynolds number
- Match within ±20% for six of eight configurations



RANS modeling/parameterizations

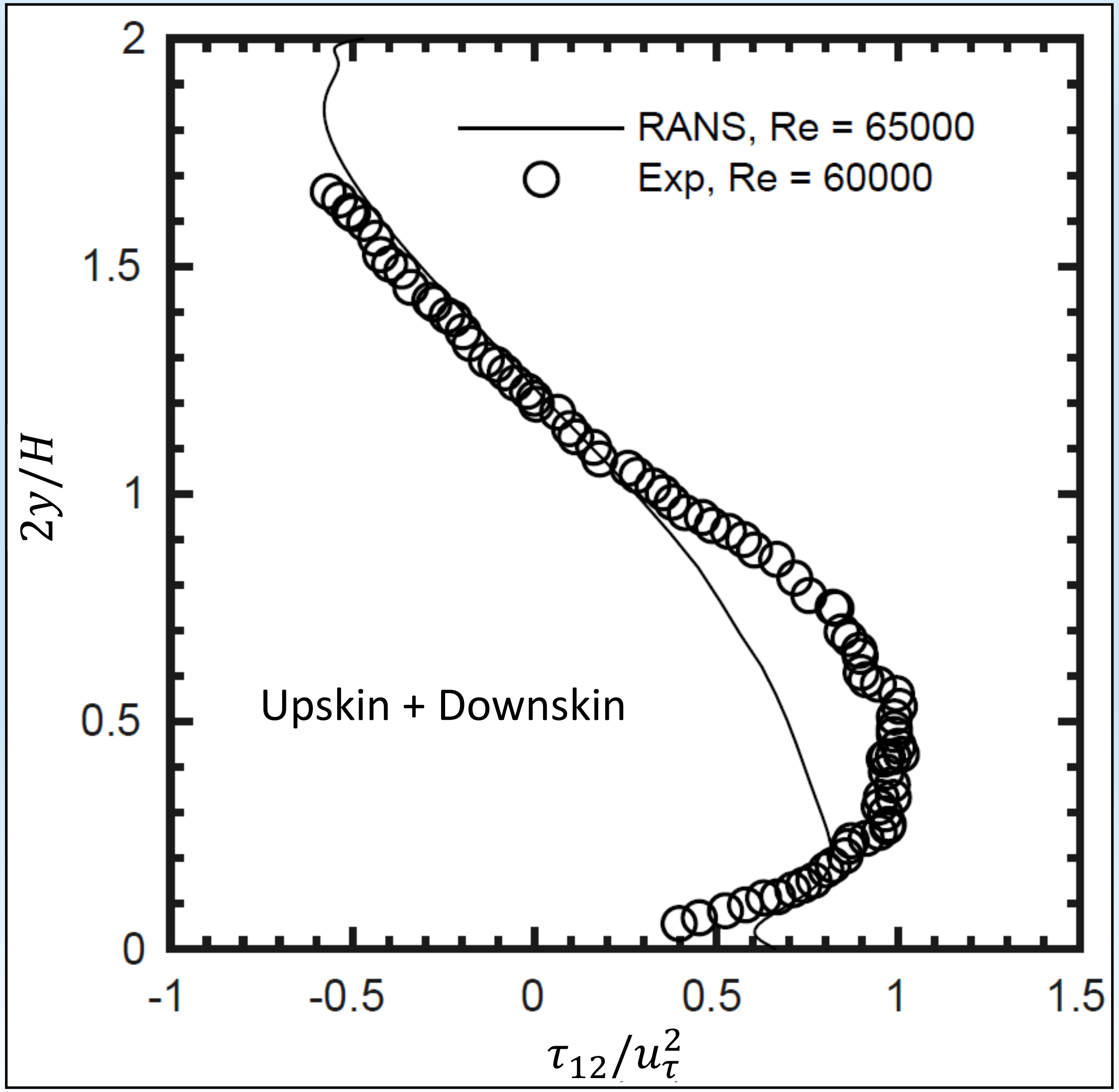
Comparison with measured velocity profiles at highest Reynolds number

- Velocity rake located 35.5” downstream of plate upstream edge
- Friction velocity u_τ approximated from total channel friction-factor, f_{DW}



RANS modeling/parameterizations

The present experiments allow comparison with the measured $-\overline{u'v'}$ Reynolds stress component at the location of the velocity rake



DERM model development/application

Minimal Model Form – Eulerian 2-"fluid" model

$$\frac{\partial \alpha \rho u_j}{\partial x_j} = 0$$

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

$\alpha \equiv$ volume distribution fraction of gas

$Du_i =$ drag model

$M_i =$ dispersion model

DERM model development/application

Attendant terms for turbulence closure and energy equations

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

$$\frac{\partial \alpha \rho \varepsilon u_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\alpha\left(\mu + \frac{\mu_t}{Pr_\varepsilon}\right)\left(\frac{\partial \varepsilon}{\partial x_j}\right)\right] + \frac{C_1\varepsilon}{k}P - \frac{C_2\alpha\varepsilon^2}{k} + \text{Other terms}$$

$$P = \frac{\partial}{\partial x_j}\left[\alpha\mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right]\frac{\partial u_i}{\partial x_j}$$

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

DERM model development/application

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

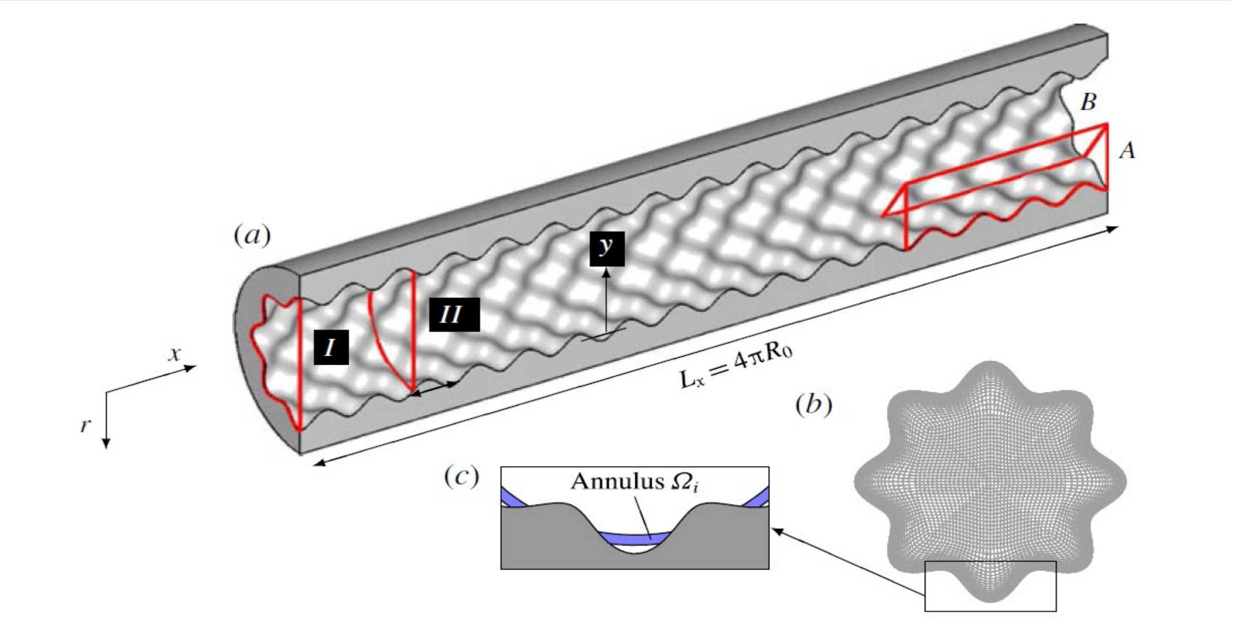
[4]Spatially precise element geometry is required for cut cell

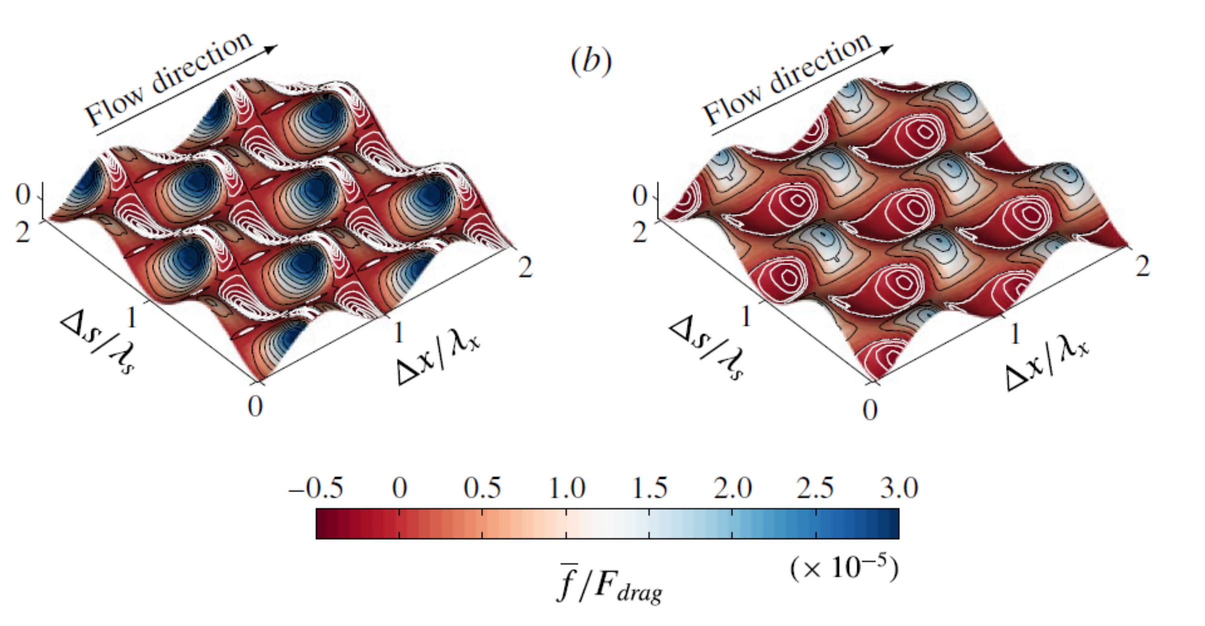
[5]Spatial distribution of volume fraction, C_D, C_{TD} required

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

DERM model development/application

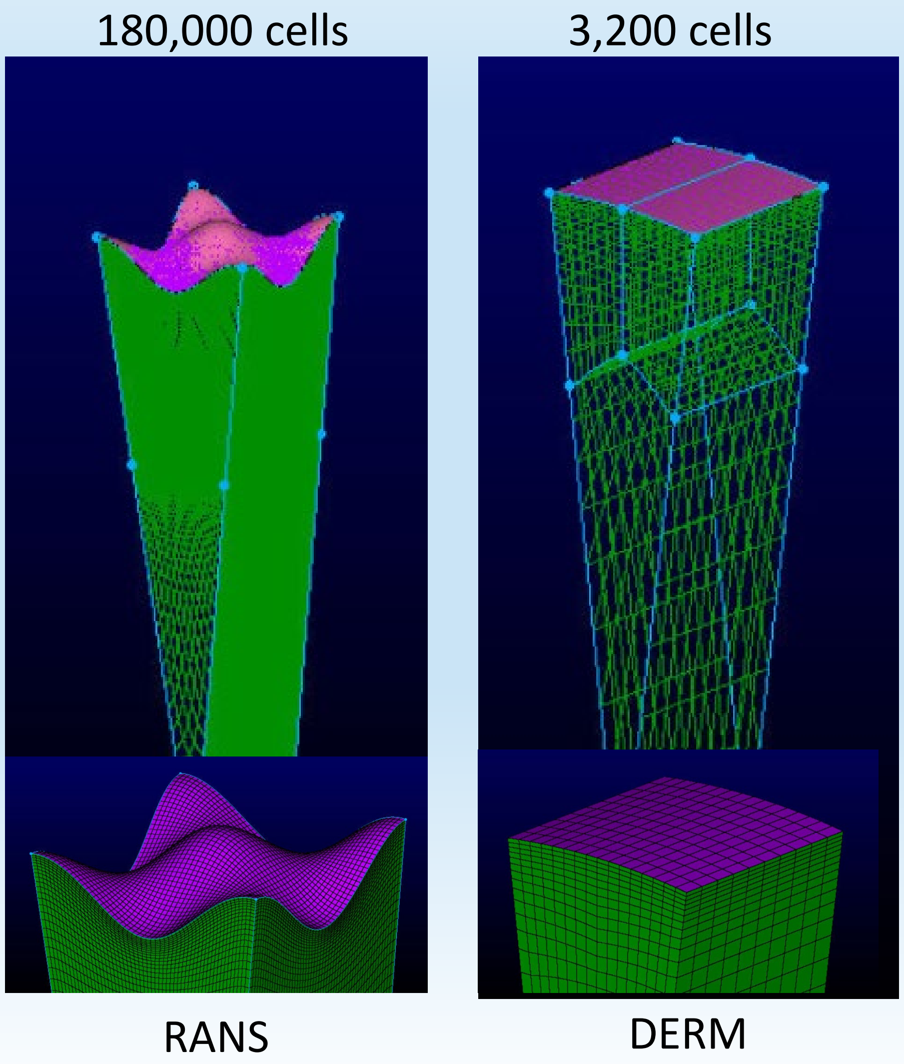
- Chan 2015 JFM studied numerous sinusoidal roughness morphologies in pies at varying Re_{τ}.

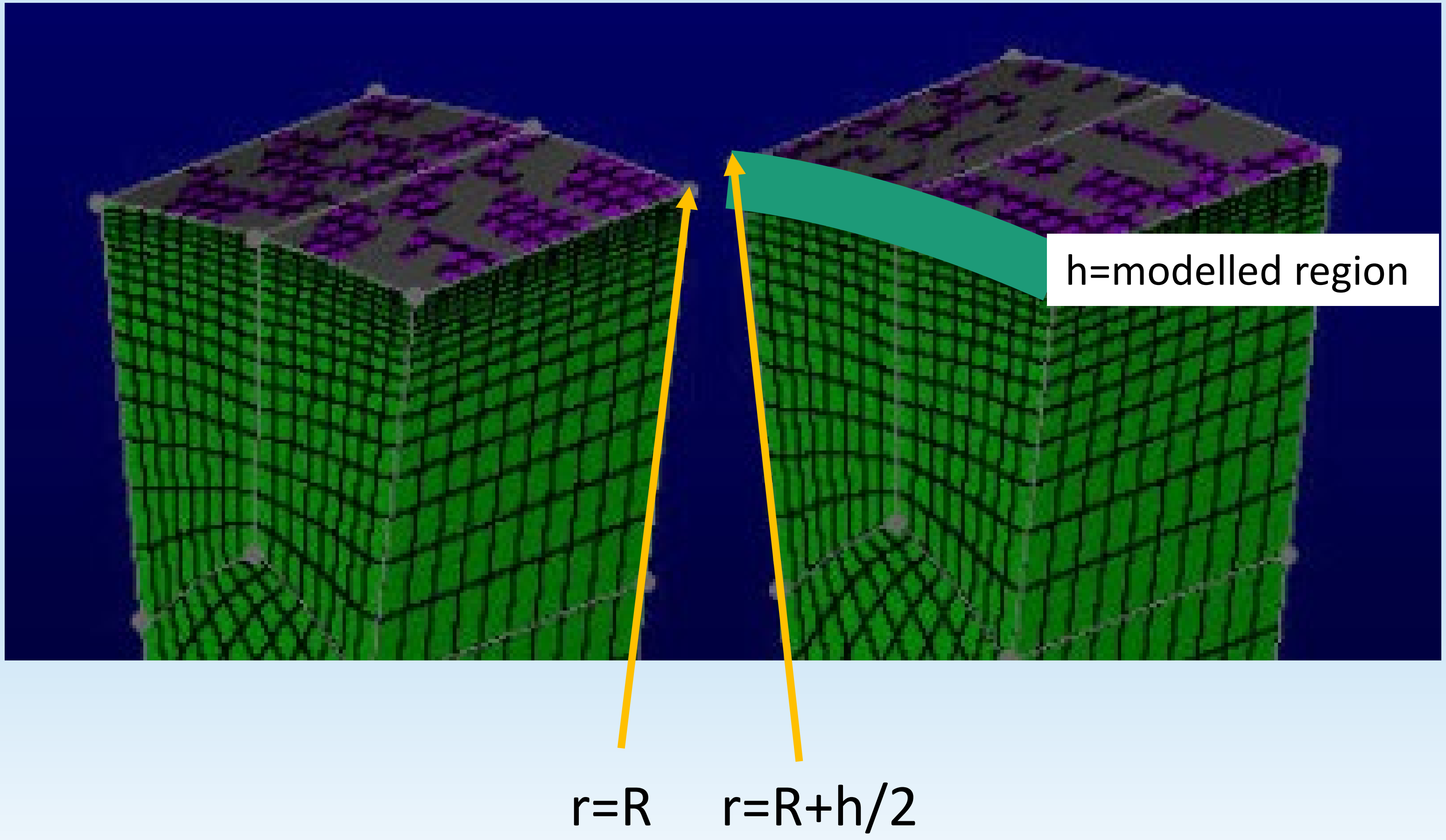




DERM model development/application

- Ideal calibration case for DERM:
  - Can be modelled in RANS using a **single** roughness element and cyclic boundaries
  - Trig functions likely to be AM shape family members
  - Symmetry of sin/cos enable limit behavior enforcement (smooth wall, porous wall, “true” sand grain roughness)




h=modelled region
r=R
r=R+h/2

DERM model development/application

- Chan Pipe 20_141

Wall pressure, axial velocity contours along streamwise stations

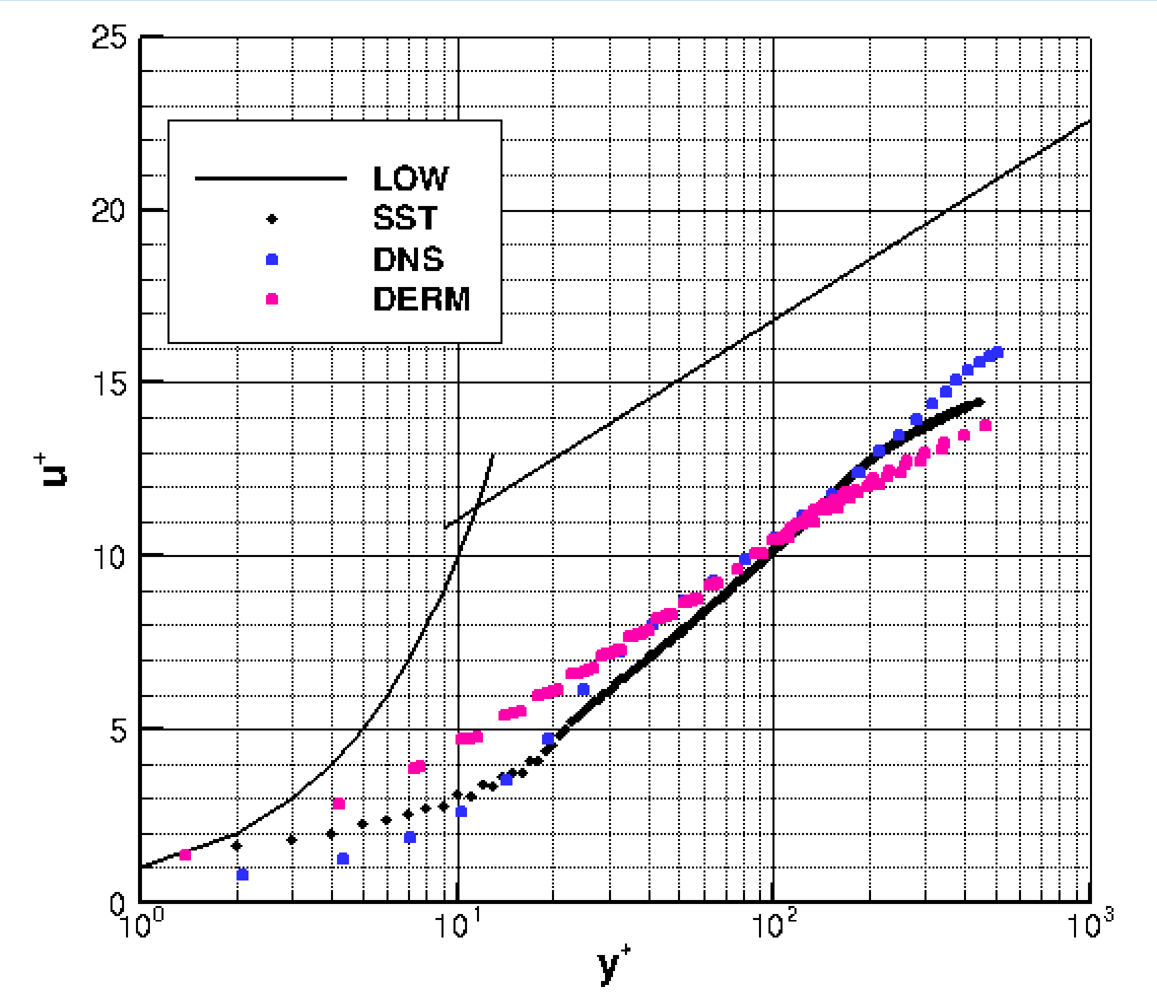
Wall pressure, vertical velocity contours along streamwise stations

Wall pressure, turbulent kinetics energy contours along streamwise stations

DERM model development/application

- Chan Pipe 20_141, Comparison of DNS, sublayer resolved RANS and DERM

Re_τ=540



Publications

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

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

Journal of Fluids Engineering

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

ASME Paper Number: GT2020-15630
Paper Title: Distributed Element Roughness Modeling of Additively and Conventionally Manufactured Turbine Coolant Passage Flow and Heat Transfer

Students on Project

- Sam Altland
  - Penn State, Mechanical Engineering
  - Passed PhD Candidacy Exam September 2020, most course work complete
  - 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
  - M.S. Thesis scheduled for December 2019
  - Performed x-array hot-film measurements in RIFT
- Gabriel Stafford
  - Baylor University, Mechanical Engineering
  - Began M.S. studies in Summer 2019
  - Working on infrared heat transfer system and validation measurements

Summary and Current/next steps

- Significant enrichment of RIFT database
  - 8 surfaces/combinations (top/bottom) thereof, including smooth and “surrogates”
  - 2-sensor hot film profiles + Δp ➔ f
  - Serves a validation basis for modeling
- RANS modeling of each of the combinations at $Re_D \cong$ 60,000:
  - Year 1 results against upskin Hastelloy better than average: only 6/8 configurations to date match f within 20%
  - Mean velocity profiles fairly accurate although τ_w has aforementioned discrepancies
  - Serves as a local supplement for DERM comparisons

Summary and Current/next steps

- DERM development is showing excellent promise:
  - Suite of DNS comparisons with "conventional" drag and dispersion modeling
  - Far more efficient than any volumetric RANS modeling approach ≅ same as surface parametrization
- Heat transfer coming soon!
  - RIFT
  - RANS
  - DNS/LES
  - DERM

Year 1 Activities and Progress
Test article configuration build and characterization

Arithmetic mean roughness

$R_a = \left[\frac{1}{N_P}\sum_{i=1}^{N_P}|Y'|\right]$

root-mean-square roughness

height $R_q = \left[\frac{1}{N_P}\sum_{i=1}^{N_P}(Y'^2)\right]^{\frac{1}{2}}$

Flack-Shulz eq sand height roughness

Stimpson eq sand height roughness

Streamwise autocorrelation

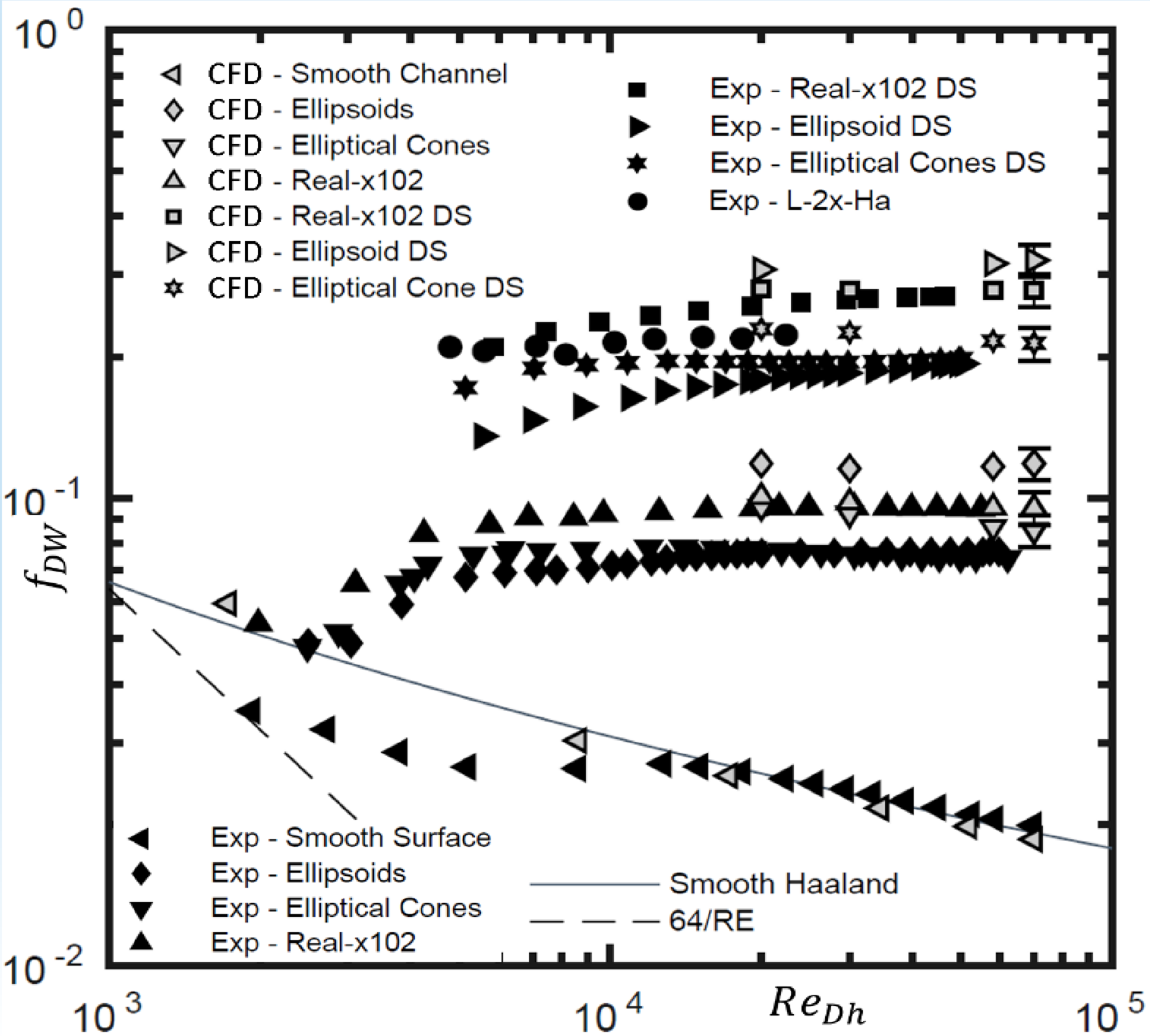
skewness, $Skw = \frac{1}{R_q^3}\left[\frac{1}{N_P}\sum_{i=1}^{N_P}(Y'^3)\right]$

Statistical and relative characteristics of the surfaces investigated

Metric	Real_x102	Ellipsoid Analog	Elliptical Cone Analog
R_a (mm)	1.887	2.075	**1.214**
R_q (mm)	2.436	2.419	1.504
$k_{s,F-S}$ (mm)	6.933	7.045	6.965
$k_{s,St}$ (mm)	30.85	34.24	18.73
λ_x (mm)	32.9	32.9	33.7
Skw	-0.276	-0.264	0.033

Year 1 Activities and Progress

Summary of friction factor measurements and CFD predictions



Double sided

Single sided

Smooth