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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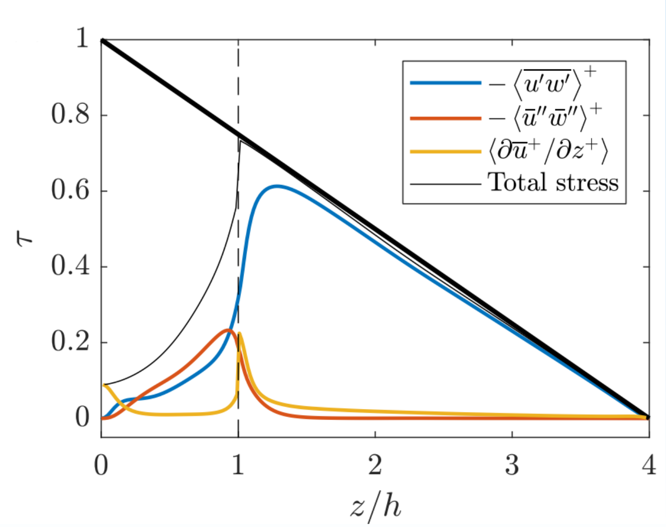

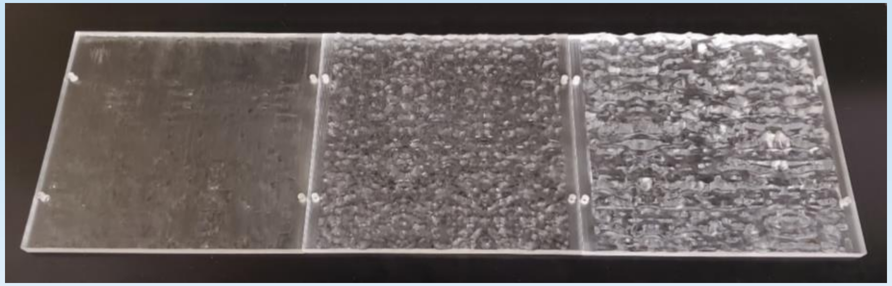

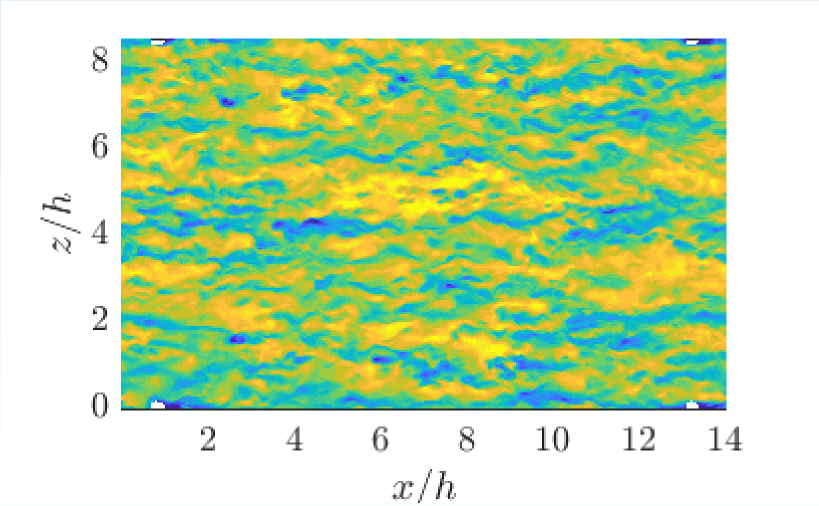

UTSR Program Review
9 November 2021

Contents

- Brief recall of background/objectives/technical approach/earlier progress
- Current activities and progress:
  - RIFT testing – heat transfer and Tomo-PIV
  - DERM model development/applications
  - DNS studies
- 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
- New generalized approach to roughness modeling
- 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 $\therefore$ 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, PIV
- 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

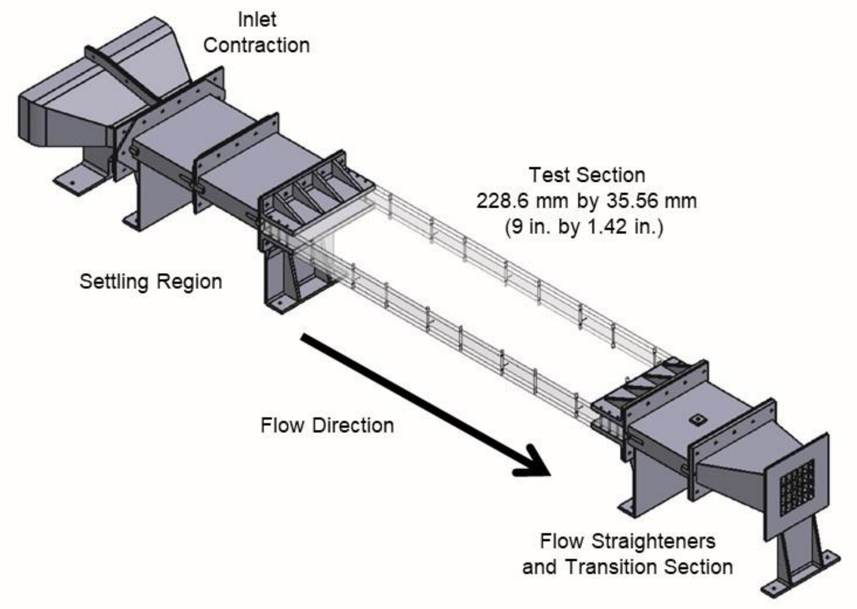
Develop CAD suitable for scale-up, CFD mesh generation, and statistical characterization

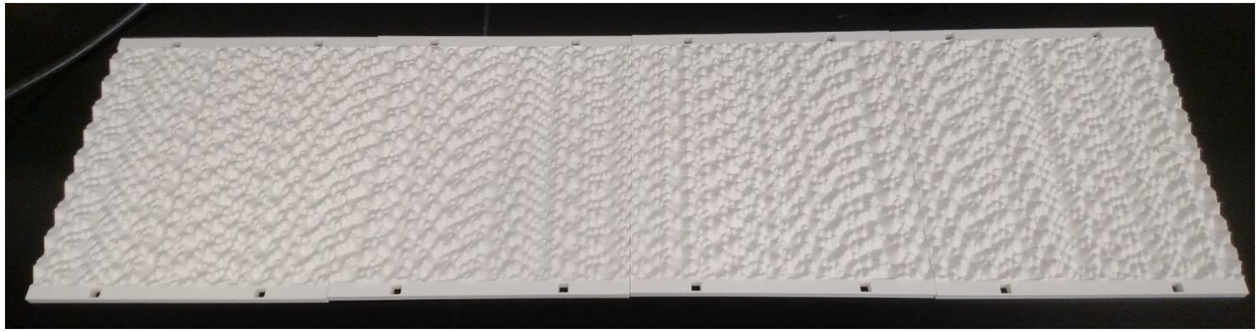
DERM model development
- Formulation
- Morphology parameterization
- DNS calibration
- At scale and up scale calibration

Application and Optimization

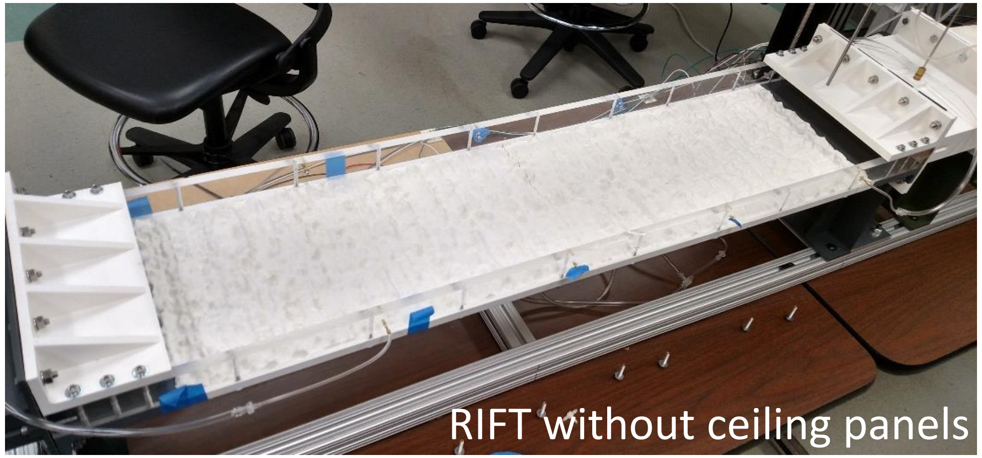
Roughness and Internal Flow Tunnel

- Adiabatic work **to date**:
  - 50x or 100x geometric scale
  - Panels printed using FDM
  - Channel flow with two walls
  - Bulk pressure loss measurements
  - Single wire and X-array anemometry
  - Tomo-PIV now





Ellipsoidal Cone Surface Panels



RIFT without ceiling panels

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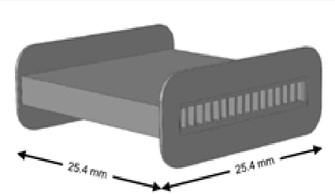
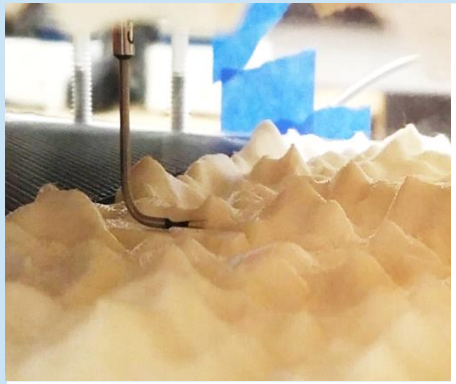
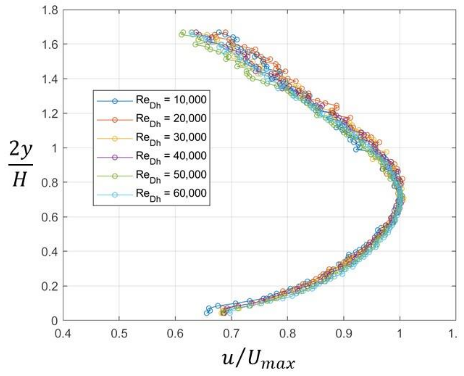
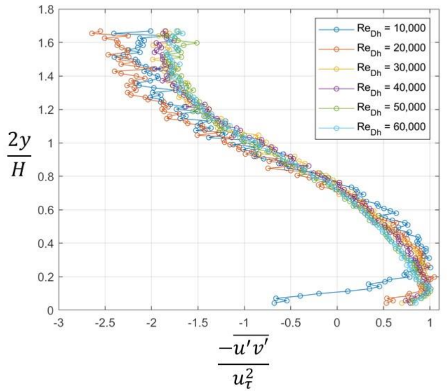
Roughness and Internal Flow Tunnel

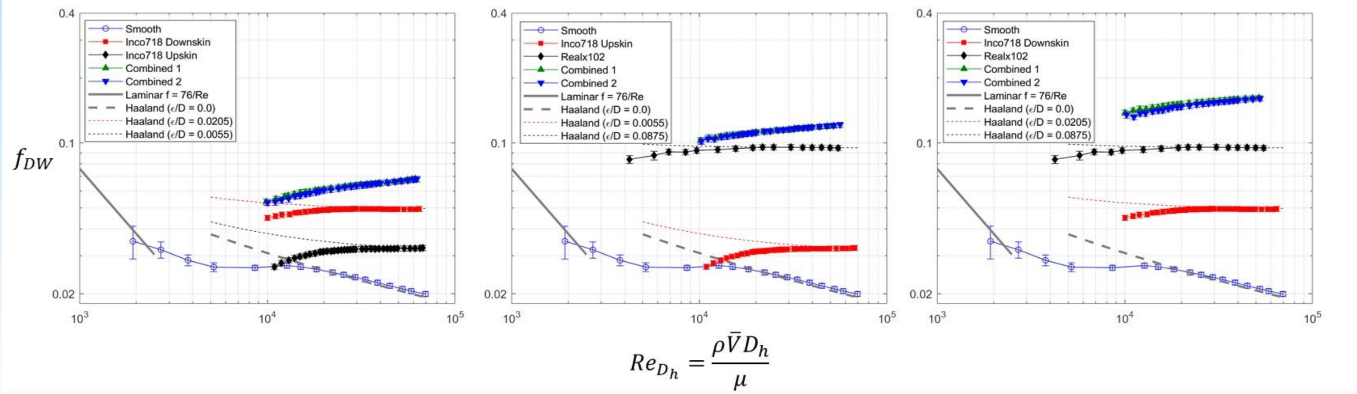


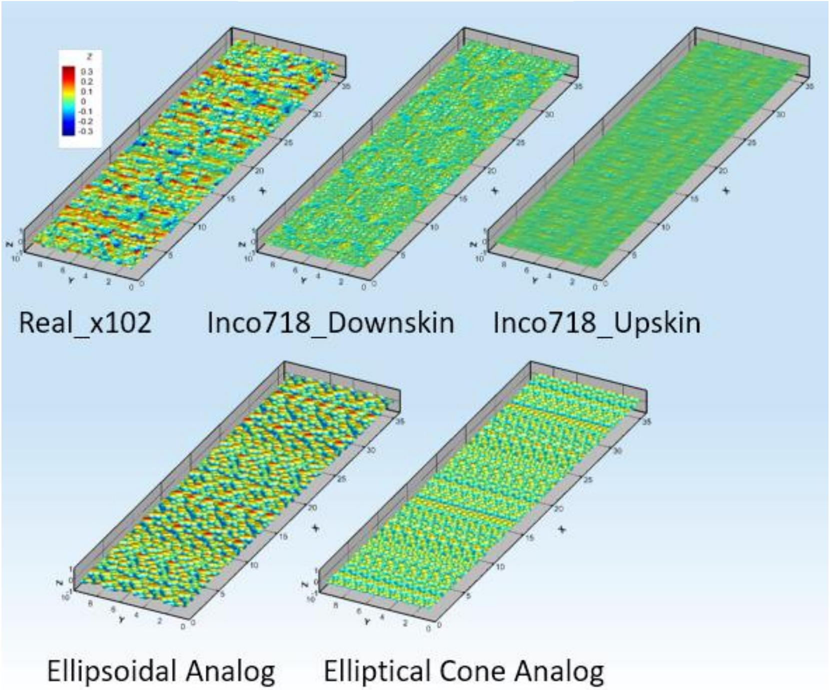
- Adiabatic work **to date**:
  - 8 upscaled engine scale START configurations
  - 2 surrogate analog configurations

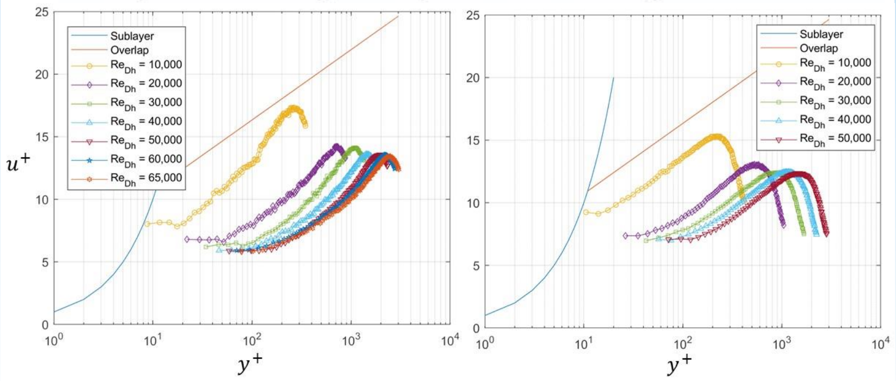






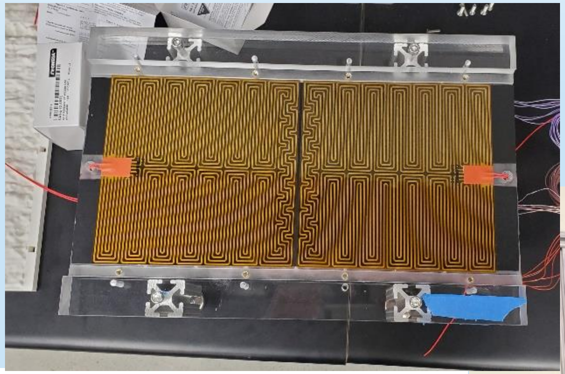


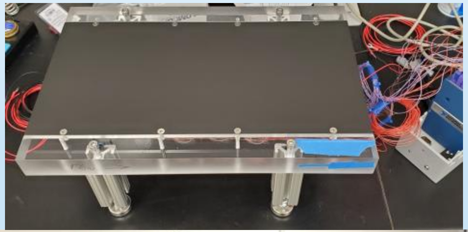


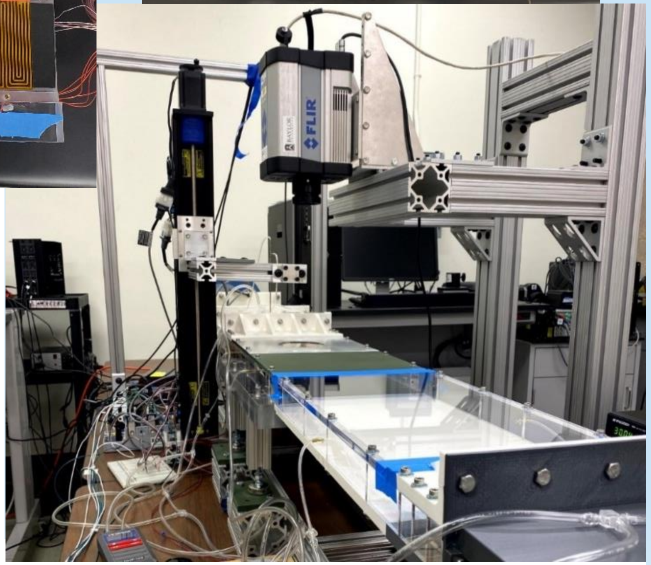


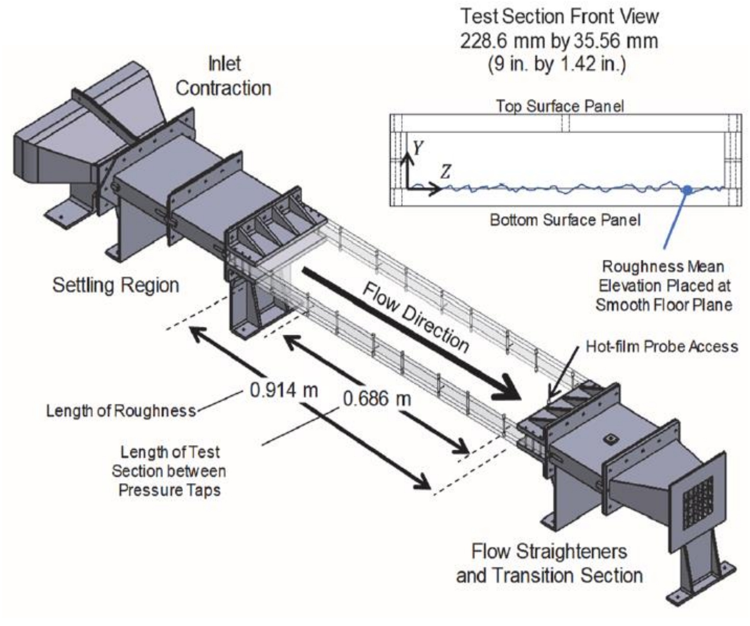
Heat Transfer Modifications and Surface Imaging

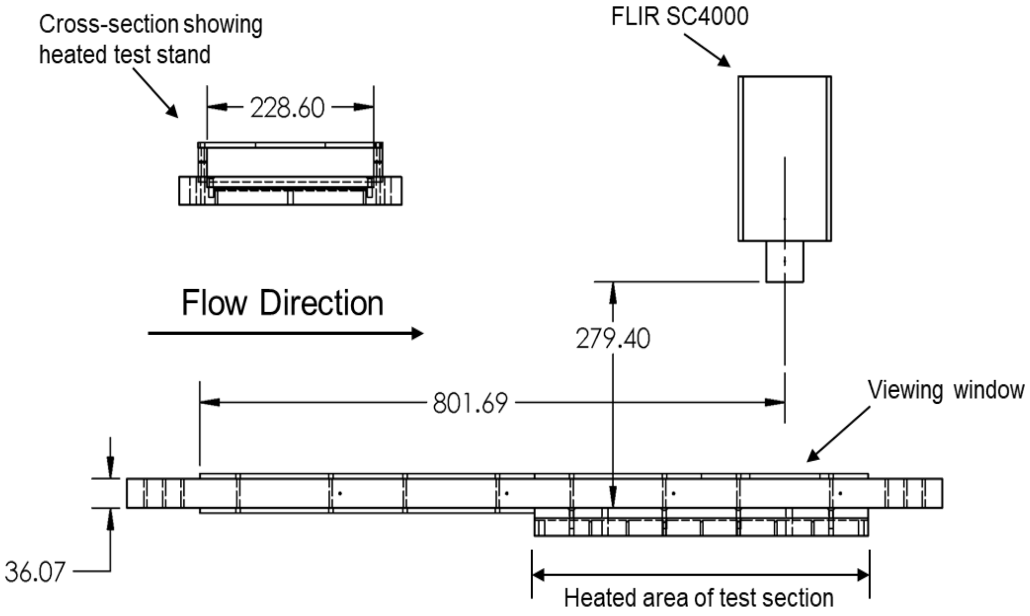
- RIFT Modified for HT Measurements
- IR Temperature Measurements

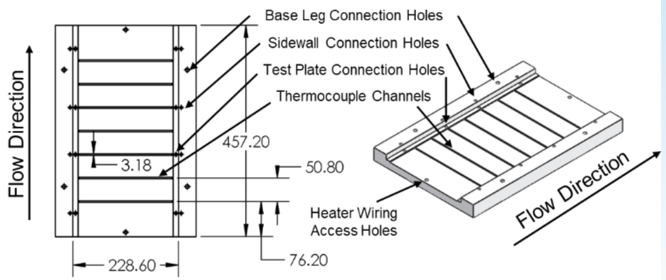






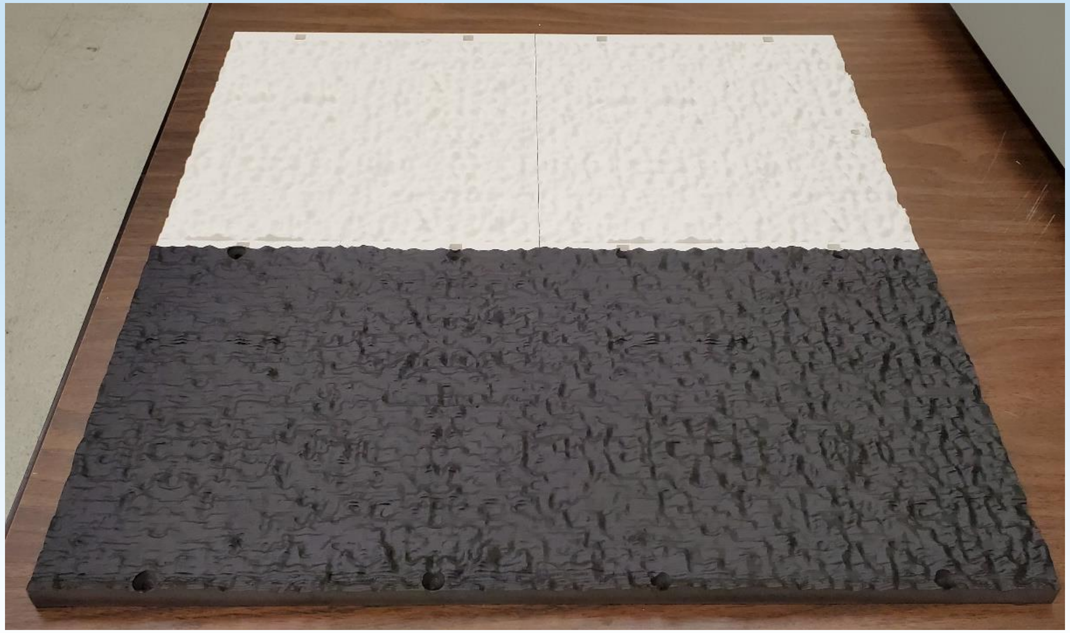


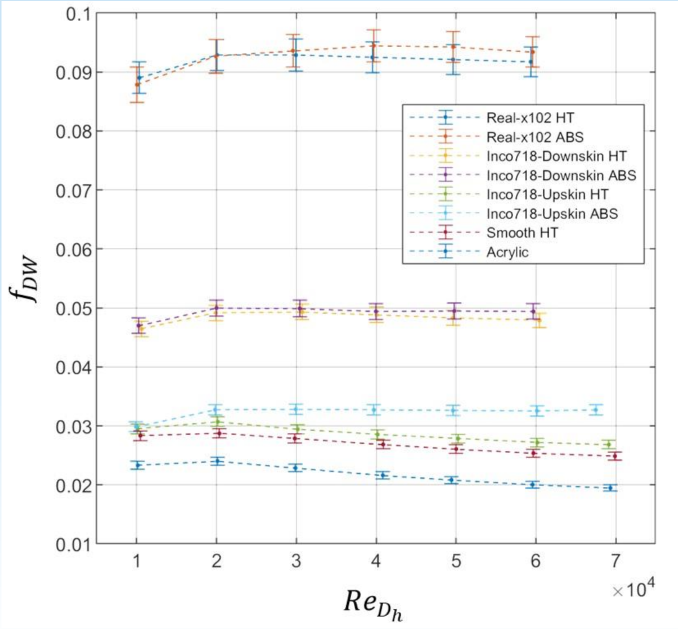


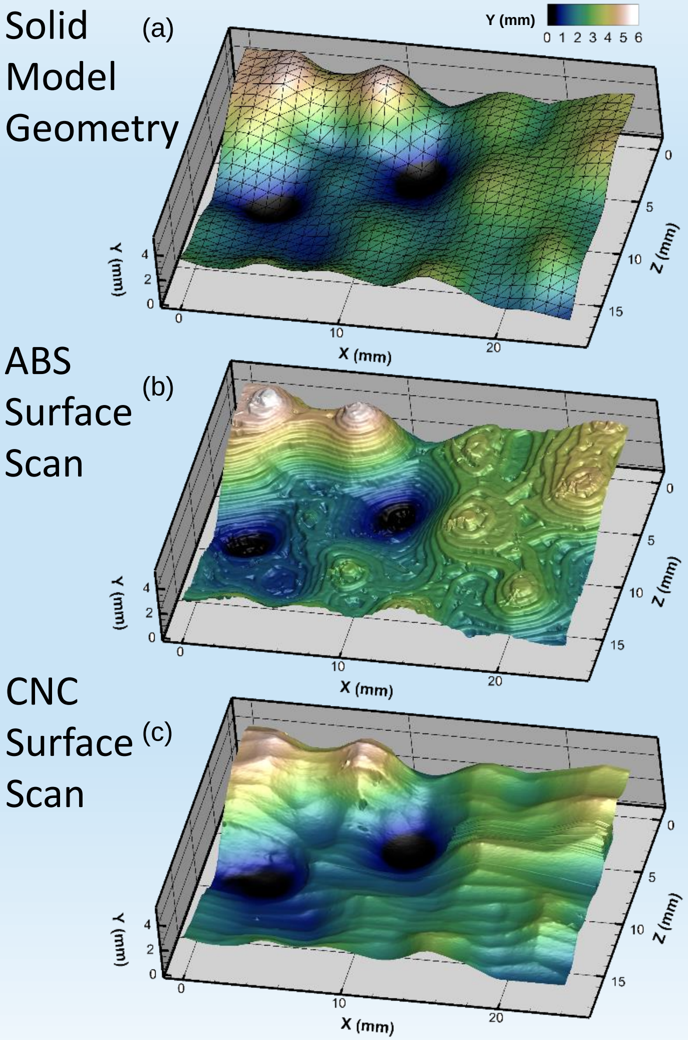


Heat Transfer Surface Friction Results

- 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 for surfaces with large roughness
  - Aluminum to smooth acrylic has most significant difference (paint)

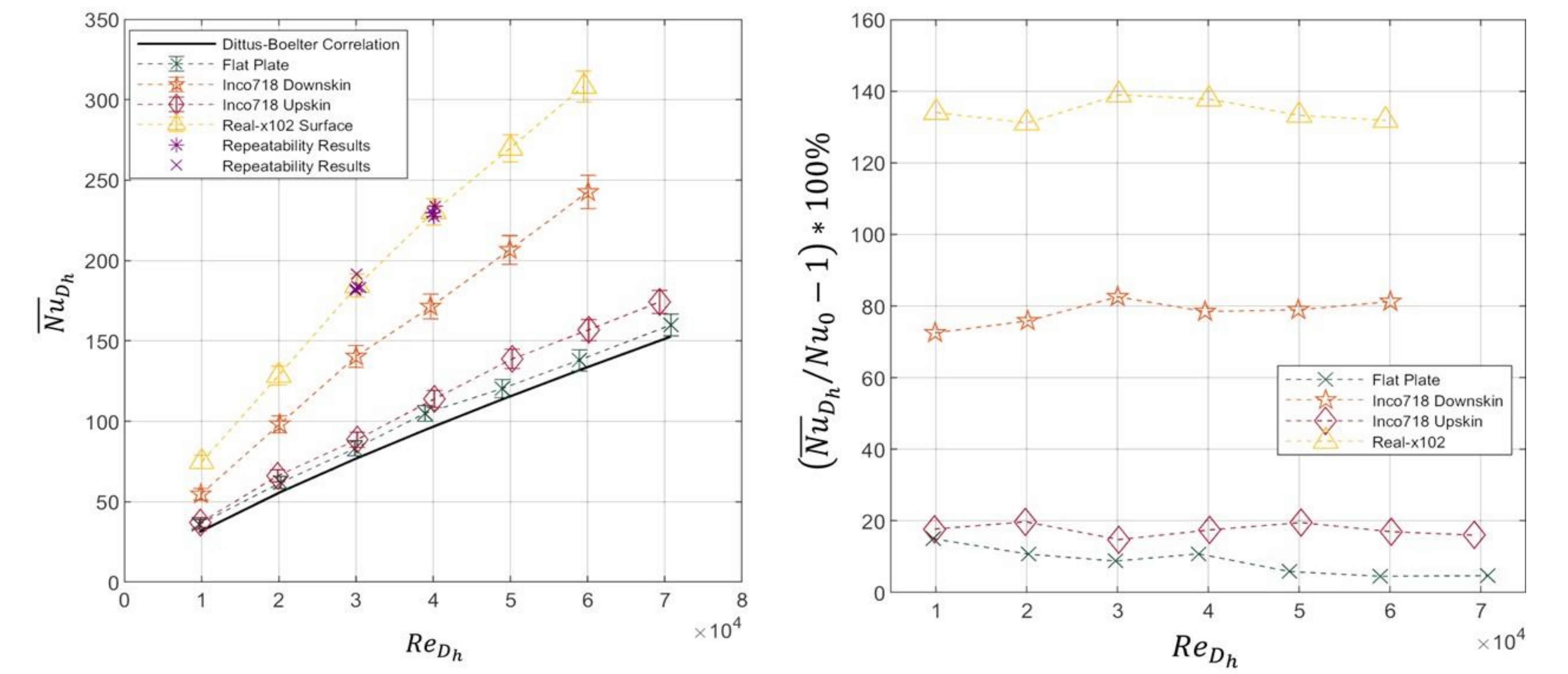






Average Nusselt Number Results and Enhancement

- Nusselt numbers follow Dittus-Boelter
- Enhancement of each surface generally constant



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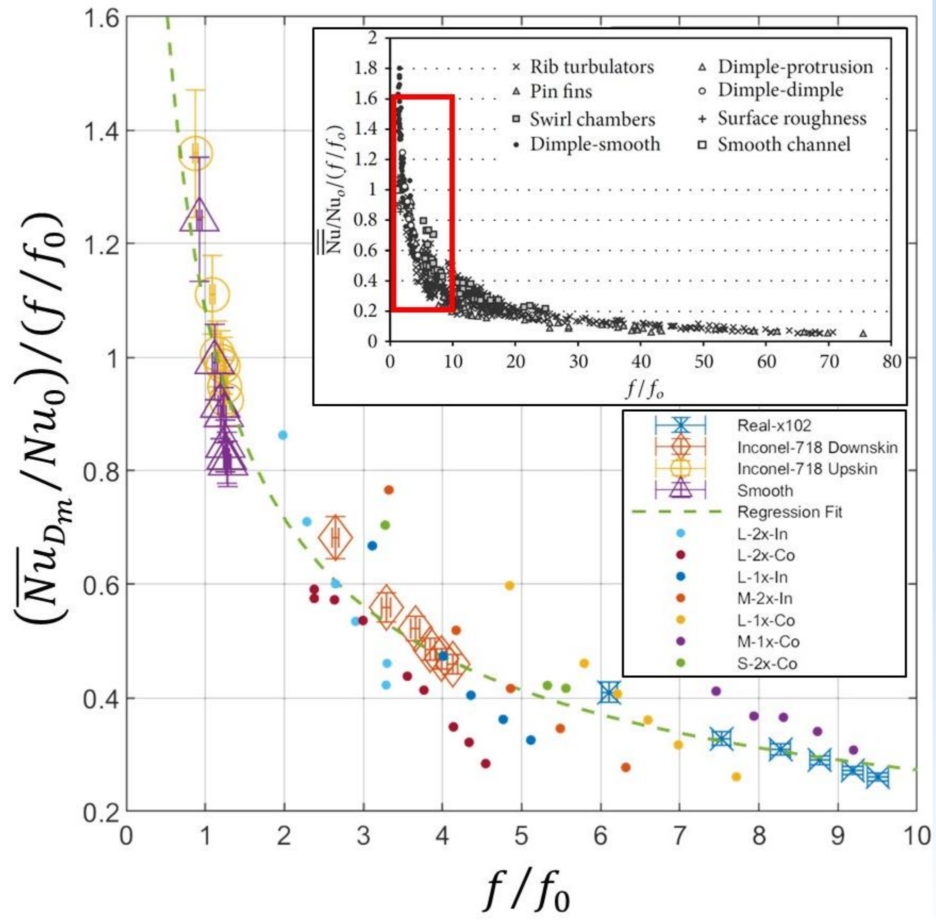
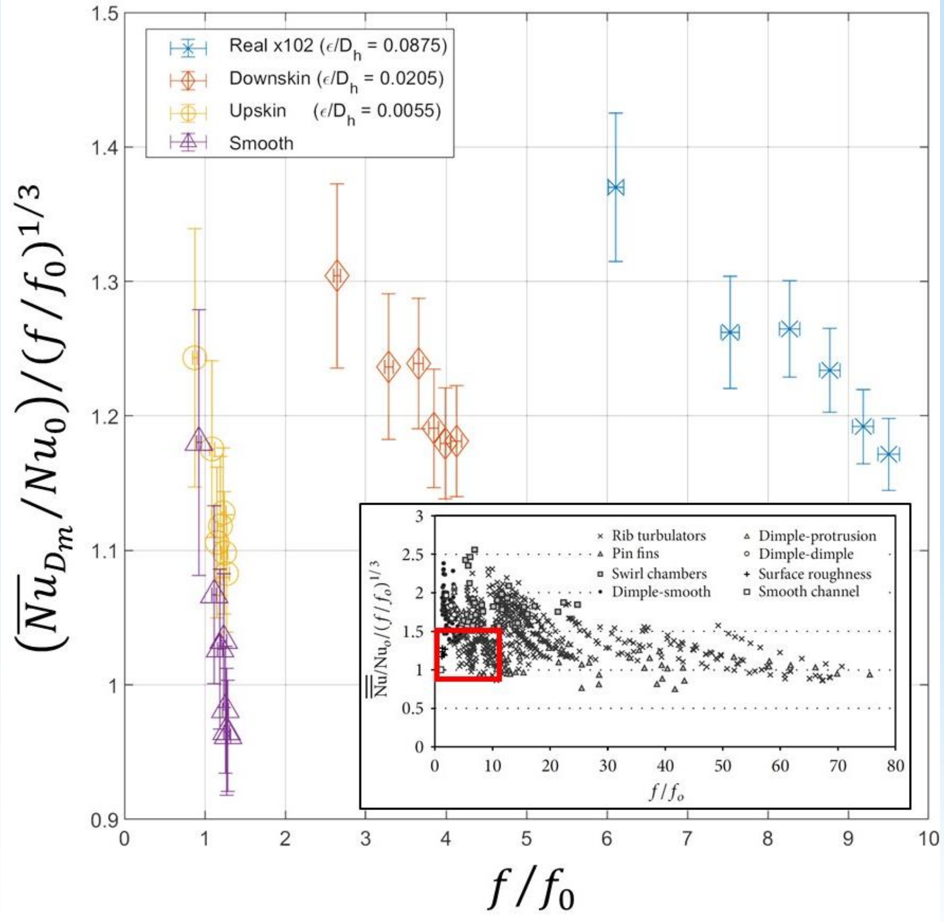
Reduced Convection Results

- Reynolds Analogy Performance Parameter



- Global Thermal Performance Parameter

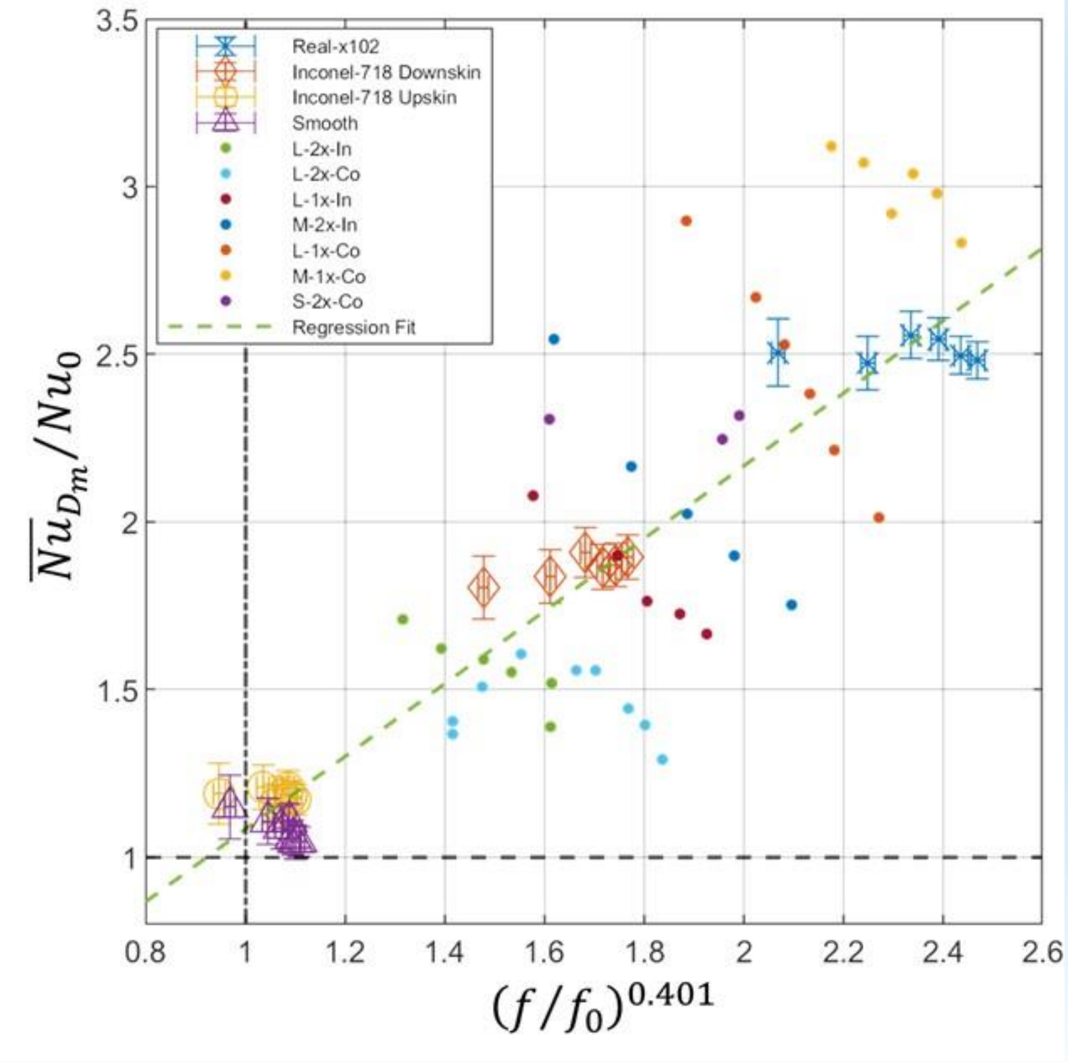


Correlation Development

- Norris-style correlation developed

$$\overline{Nu}/Nu_0 = a(f/f_0)^{b+1}$$

- RIFT: ±10%
- Stimpson et al. (2016): ±50%
- *Differences exist between engine-scale and lab-scale measurements*



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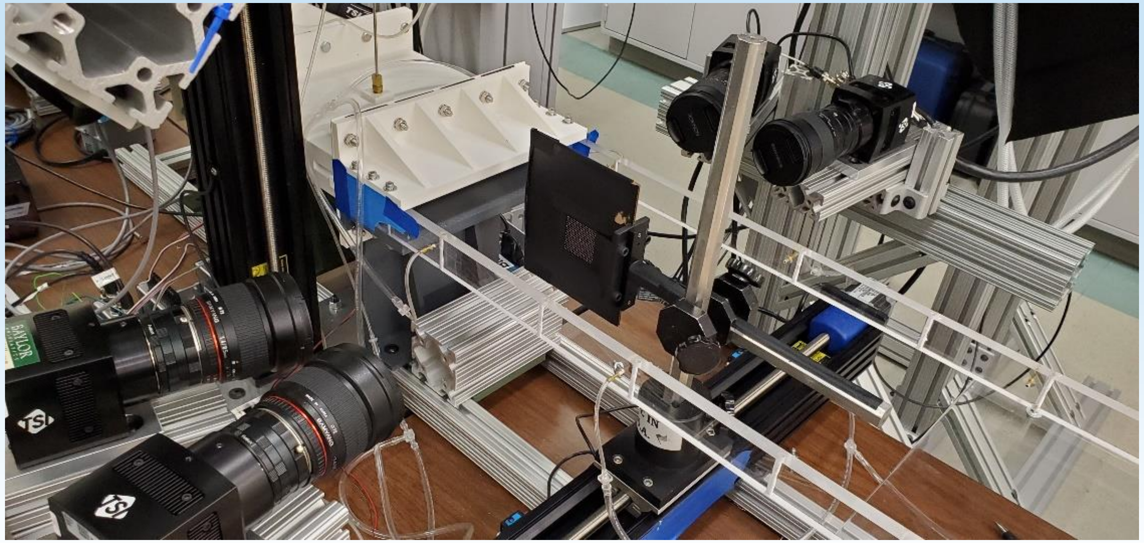
Current Work: Volumetric PIV

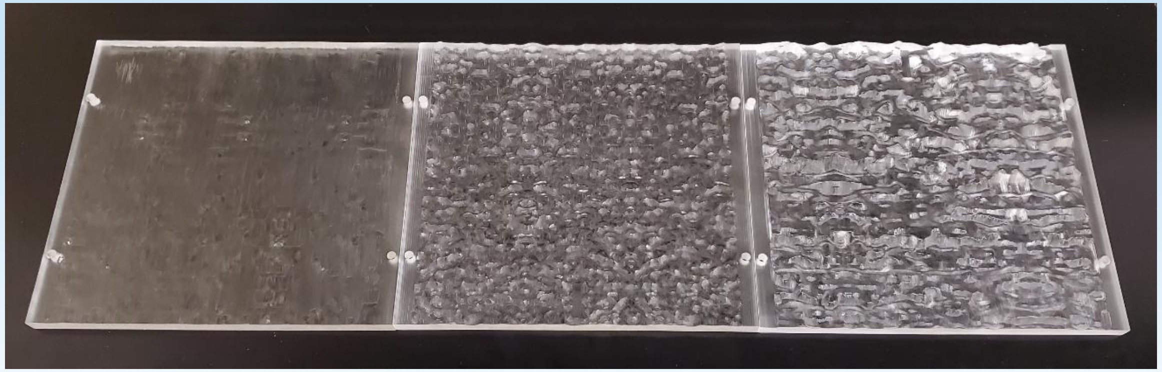
- Use of 4-camera, tomographic PIV 3D, 3- component system
- Extruded aluminum frame for system supply chain delay
- Started using DEHS seeder
- Switched to bubble generator (15 μm bubbles)



Current Work: Volumetric PIV

- Reduce laser reflections:
  - Refractive index matching not an option
  - Surfaces CNC machined from acrylic
  - Surface “cleared” using MAPP torch
- Recent laser repair required
- New “brain” installed
- System being recommissioned

Upskin Downskin Real_x102



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
  - Present approach is much more general than others that have appeared:
    - Sheltering model – not shape specific
    - Accommodates:
      - Turbulence transport
      - Wall-normal element projection contributions
      - Spatial dispersion

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

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
  - Smooth sublayer resolved RANS mesh – roughness not resolved
  - Volume fraction pre-processing per roughness morphology
  - Drag
  - Spatial dispersion stresses
  - Turbulence stresses

Modeling ← → Calibration

DERM Formulation

- DERM equations derived from space+time averaged Navier-Stokes equations[1,2]
  - Volumetric variable decomposition

$$\langle \varphi \rangle = \langle \varphi \rangle^f + \varphi^*$$

  - Leads to dispersive stress terms

$$\langle \varphi \psi \rangle = \beta \langle \varphi \rangle^f \langle \psi \rangle^f + \langle \varphi^* \psi^* \rangle$$

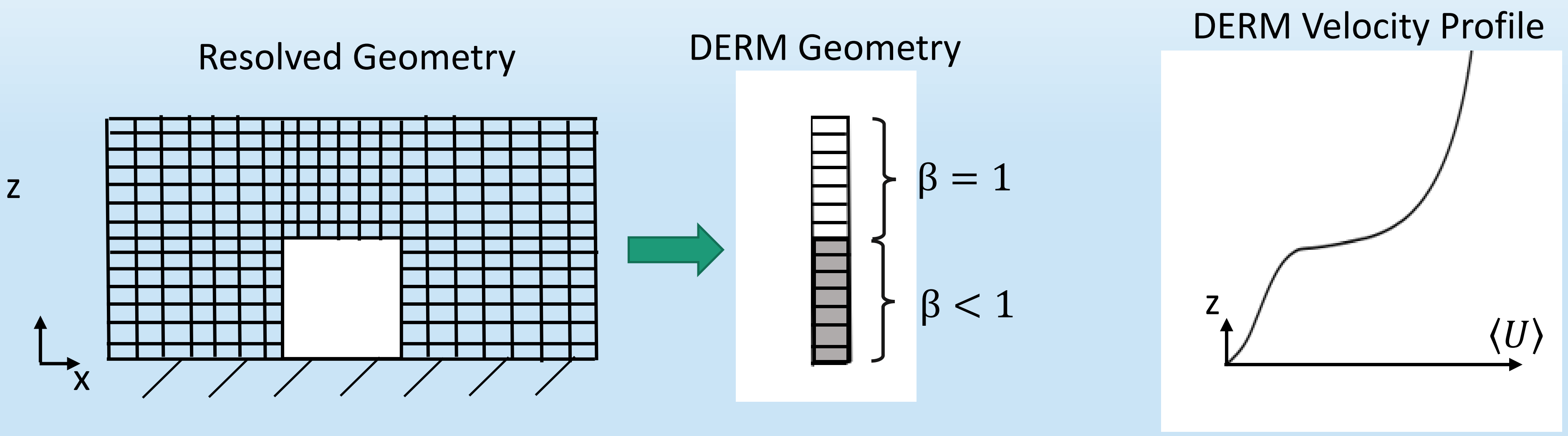
  - Steady incompressible DERM continuity and momentum equation

$$\nabla \cdot \beta \langle \underline{\overline{U}} \rangle^f = 0$$

$$\nabla \cdot \beta \langle \underline{\overline{u}} * \underline{\overline{u}} \rangle^f + \underbrace{\nabla \cdot \langle \overline{\underline{u}' * \underline{u}'} \rangle}_{\text{Reynolds Stress}} + \underbrace{\nabla \cdot \langle \underline{\overline{u}}^* * \underline{\overline{u}}^* \rangle}_{\text{Dispersive Stress}} + \frac{1}{\rho} \nabla \beta \langle P \rangle^f - \nu \nabla \cdot \nabla \beta \langle \underline{\overline{u}} \rangle^f + \underbrace{\underline{f}_D}_{\text{Drag}} = 0$$

1 Aupoix, B., 2016, "Revisiting the discrete element method for predictions of flows over rough surfaces," ASME J. Fluid Eng., 138, p. 031205.
2 Carpiste, G. H., Rotstein, E, and Whitaker, S., 1986, "A general closure scheme for the method of volume aveaging," Chem. Eng. Sci., 41(2), pp 227-235

DERM Formulation



- Volume averaging removes geometric variation (spanwise/streamwise)
  - Computes averaged flow quantities in the wall normal direction

1D DERM Momentum Equation

$$\frac{\partial}{\partial z}\left[\nu \frac{\partial \beta \langle U \rangle^f}{\partial z} - \langle u^* w^* \rangle - \langle \overline{u'w'} \rangle\right] - \frac{1}{\rho}\frac{\partial \beta P}{\partial x} + f_{DERM} = 0$$

$$\tau(z) = \nu \frac{\partial \beta \langle U \rangle^f}{\partial z} - \langle u^* w^* \rangle - \langle \overline{u'w'} \rangle + \int_z^h f_{DERM}\, dz - \frac{1}{\rho}\frac{\partial \beta P}{\partial x} z$$

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DERM Drag Force Treatment

- Most DERM models use a “convective drag” law

$$\boldsymbol{F_D = \rho C_d(z) A_f(z) U(z)^2}$$

- Determining drag coefficient for DERM is nontrivial
- Often curve fit from a suite of experimental data

[8] McClain 2004 (for Cones and Hemispheres)

$$C_d = \begin{cases} \left(\frac{Re_D}{1000}\right)^{-.125} \varepsilon^{.74} & if\ Re_D < 60{,}000 \\ .6\ \varepsilon^{.74} & if\ Re_D > 60{,}000 \end{cases}$$

[11] Chedevergne 2020 (Rounded Cones)

$$C_d = 3\frac{\xi}{\beta^4} \text{ with } \begin{cases} \xi = .2\ \ if\ \ \beta Re_D > 116883 \\ log\xi = (.58f - .86)\log(\beta Re_D) + 1.82 - f \end{cases}$$

Yang and Raupach[3,4] Drag Sheltering Model

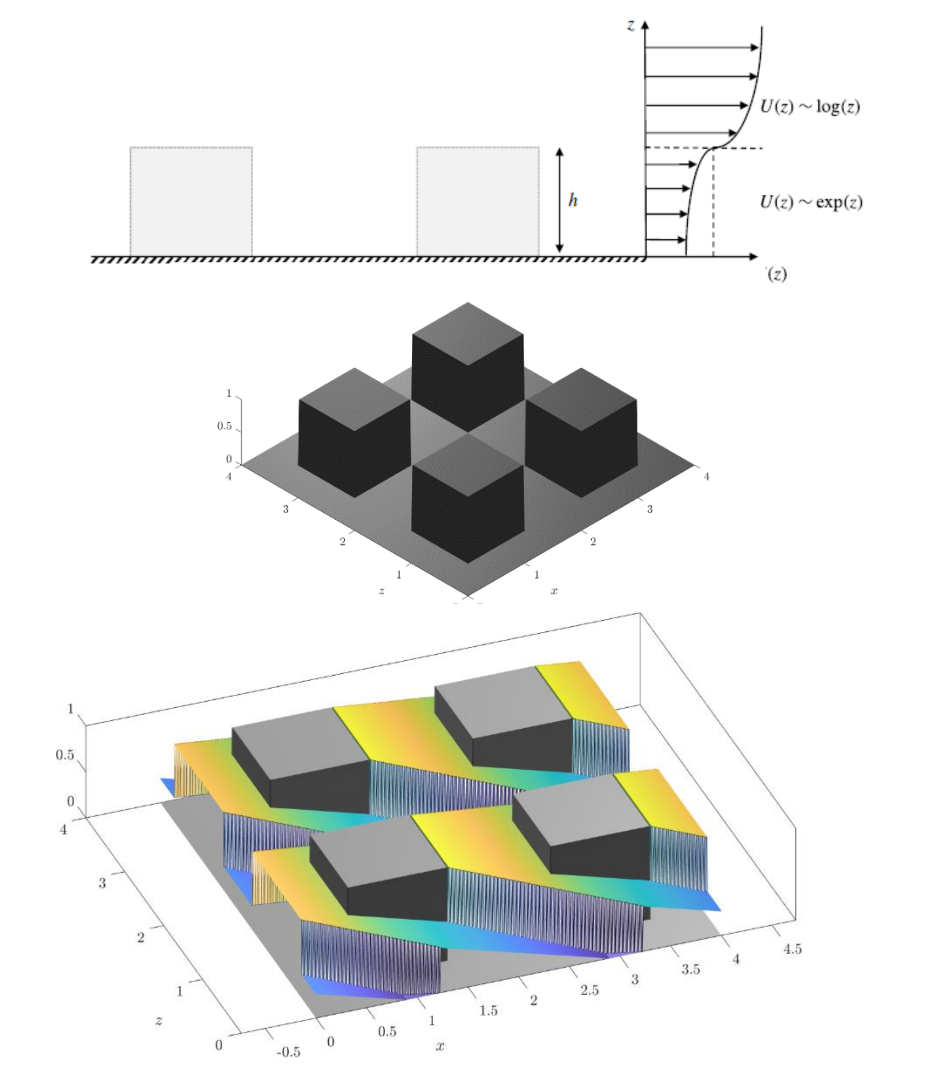
- Sheltering theory used to determine C_D
- Assumes a universal shape for mean velocity
  - Exponential in roughness layer
  - Logarithmic above

$$U(z) = \begin{cases} U_h e^{\frac{a(z-h)}{h}} & \text{for } 0 < z < h \\ \frac{u_\tau}{\kappa} log[(z-d)/z_o] & \text{for } h < z < \delta \end{cases}$$

- Estimates the attenuation of velocity in roughness region from
  - Basic flow conditions
  - Geometry of roughness
  - Attenuation used to calculated drag coef.

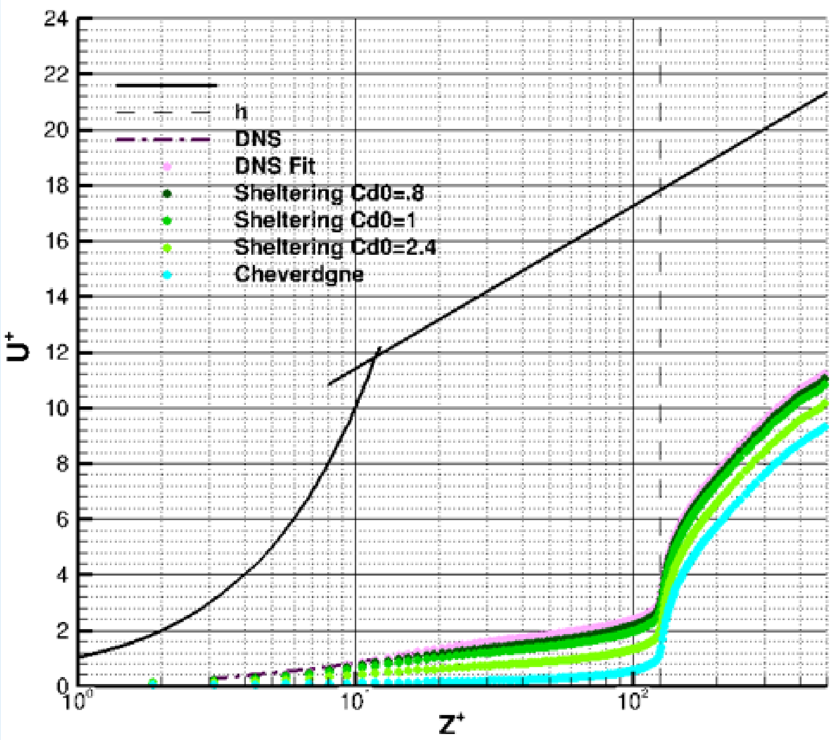
$$C_d(z) = C_0 e^{\frac{-(a-a_0)(z-h)}{h}}$$

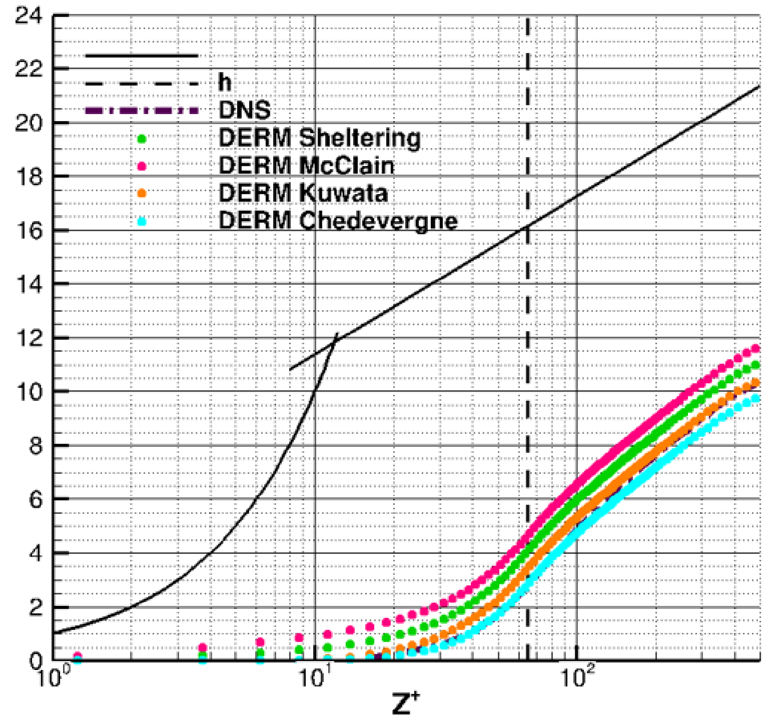
$$F_D = \rho C_d(z) A_f U(z)^2$$

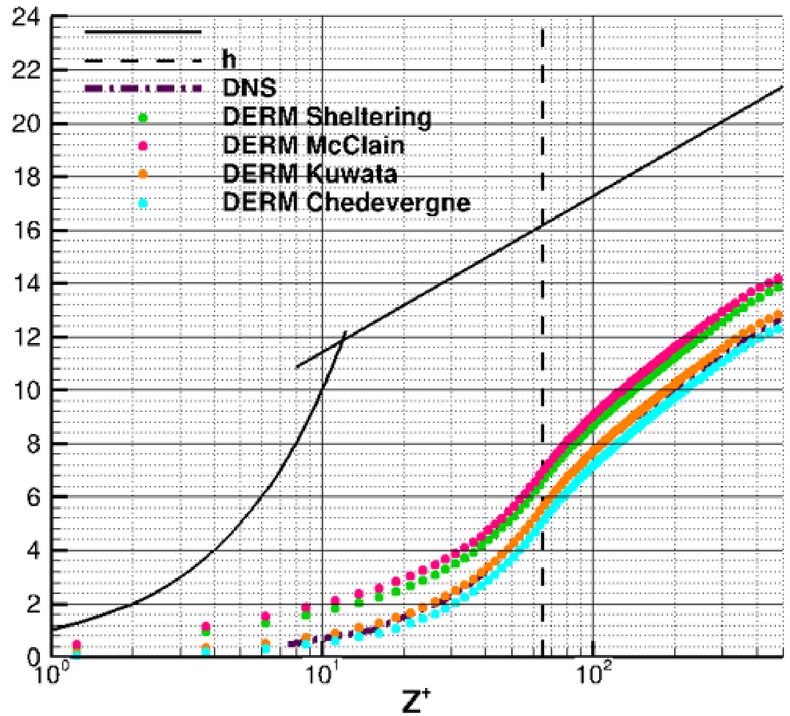


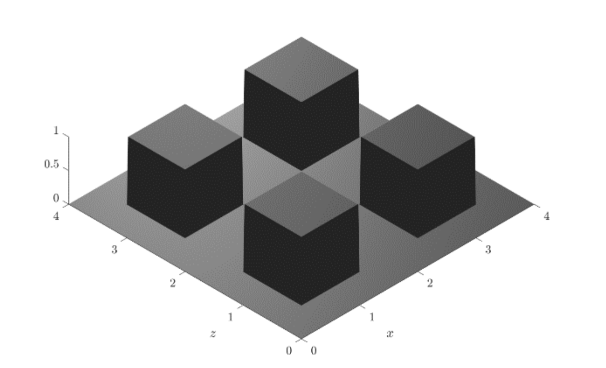
3 Raupach, M., 1992, “Drag and drag partition on rough surfaces,” Boundary-Layer Meteorol, 60, pp. 1–25.
4 Yang, X. I. A., Sadique, J., Mittal, M., and Meneveau, C., 2016, “Exponential roughness layer and analytical model for turbulent boundary layer flow over rectangular-prism roughness elements,” J. Fluid Mech., 789, p. 127–165.

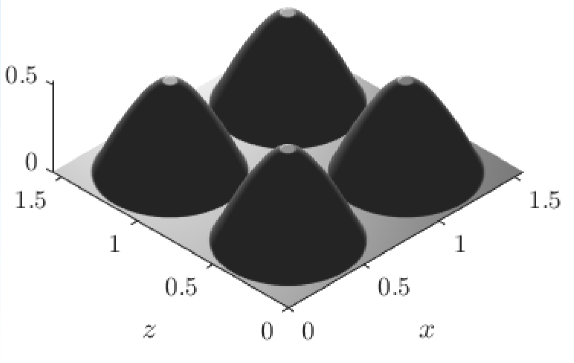
Validating with a suite of shape families, and legacy DERM drag models

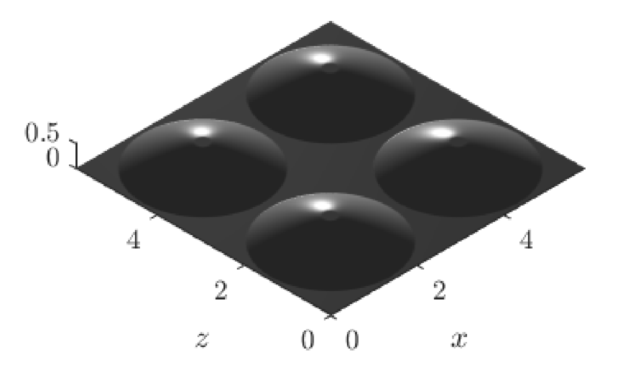








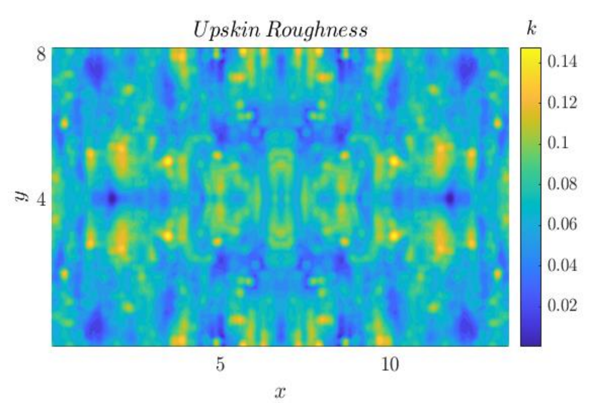


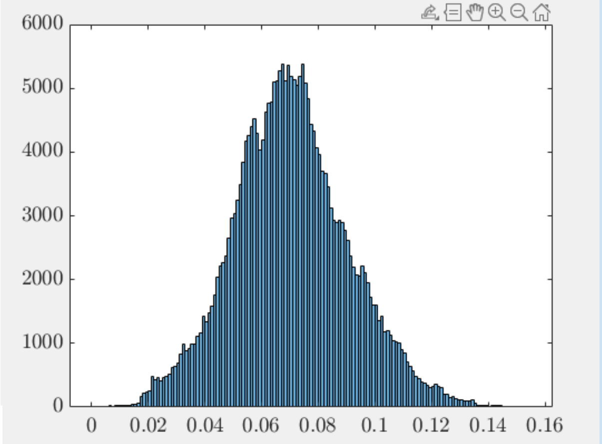


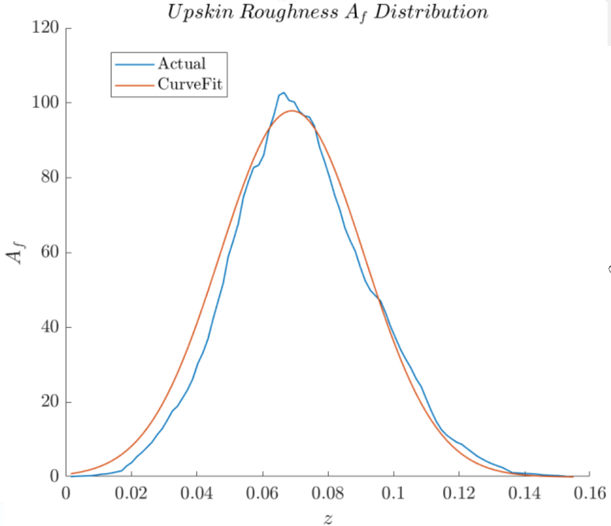
Application of DERM for Additive Surfaces

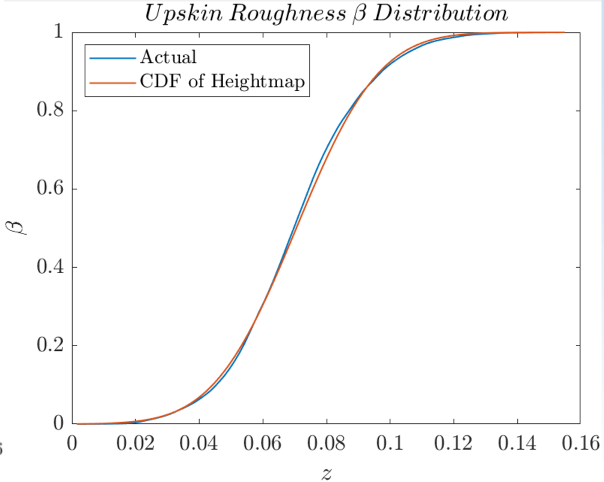
- Applying DERM to real additive surfaces
  - Validating with DNS, RANS and experimental data.
  - Necessary to show DERM has applicability to non-deterministic roughness fields

Volume Fraction Distribution

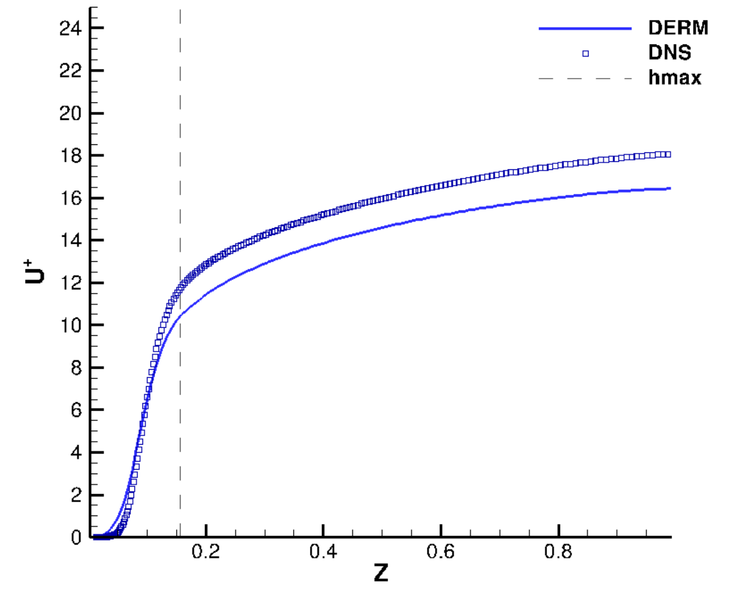




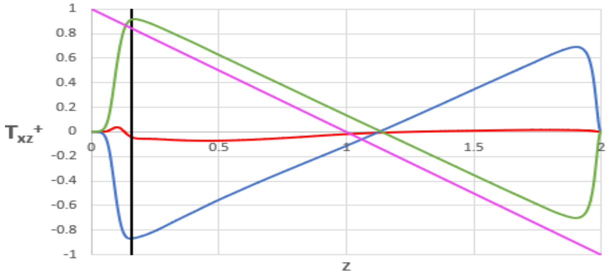


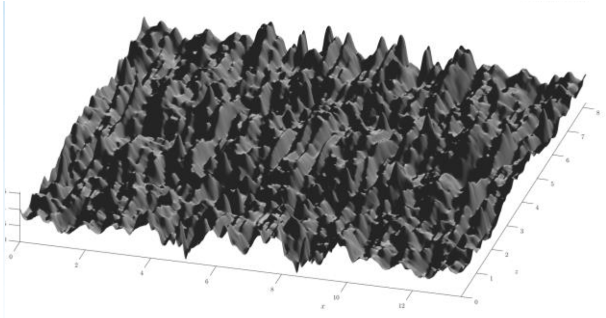


u/s-395 Mean Velocity Profile



u/s-395 Stress Profile





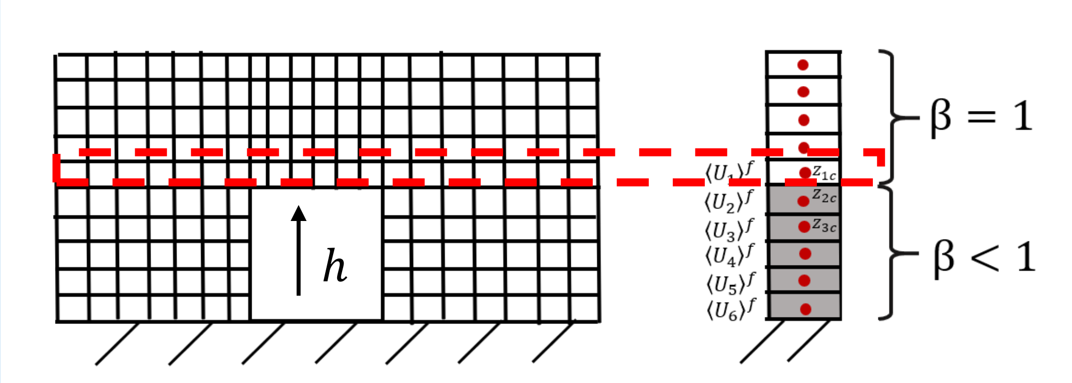
Wall Normal Area Projection Treatment

- Novel DERM element
  - Necessary for certain limit behavior predictions
  - Allows for improved drag partition prediction
  - Can predict cube arrays roughness
    - Legacy models fail for cubes

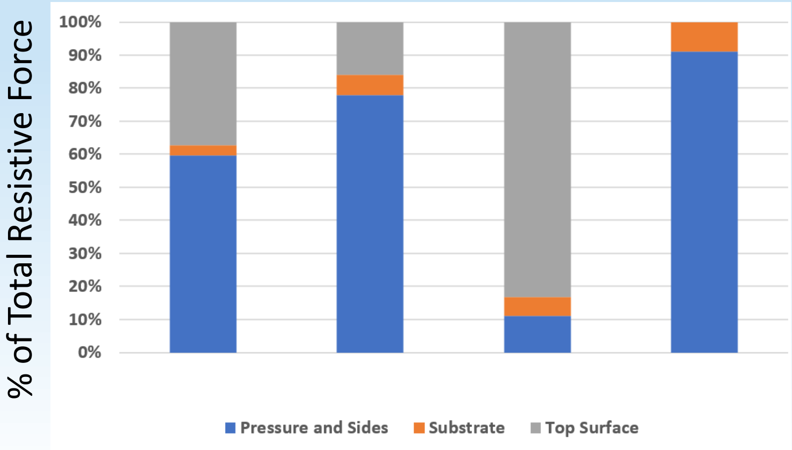
$$\tau_s = \mu\left(\frac{U_A}{z_{c1} - h}\right)$$

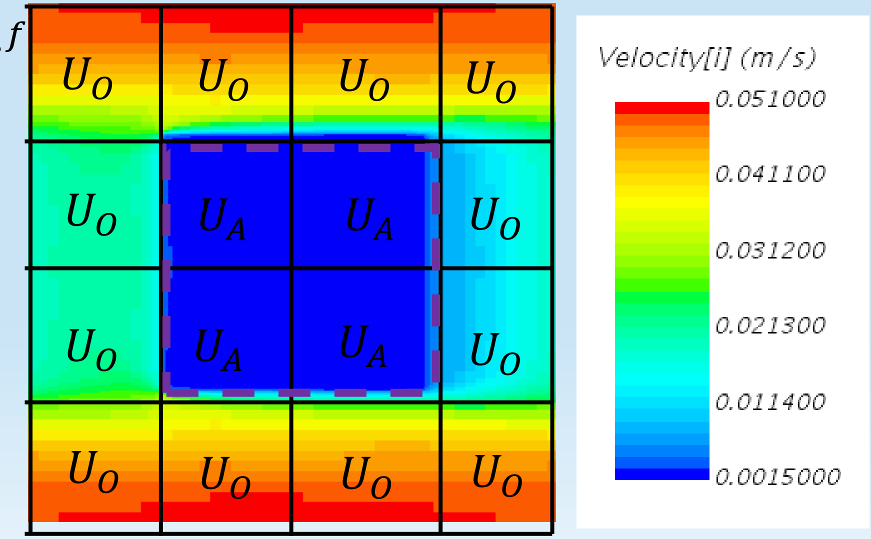
$$\langle U_1\rangle^f = \lambda U_A + (1-\lambda) U_O$$

$$U_O = \left(\frac{\langle U_2\rangle^f - \langle U_3\rangle^f}{z_{2c} - y_{3c}}(z_{1c} - z_{2c})\right) + \langle U_2\rangle^f$$



Laminar Aligned Cube Arrays





X Velocity in Cell Layer Directly above Cube from Resolved CFD

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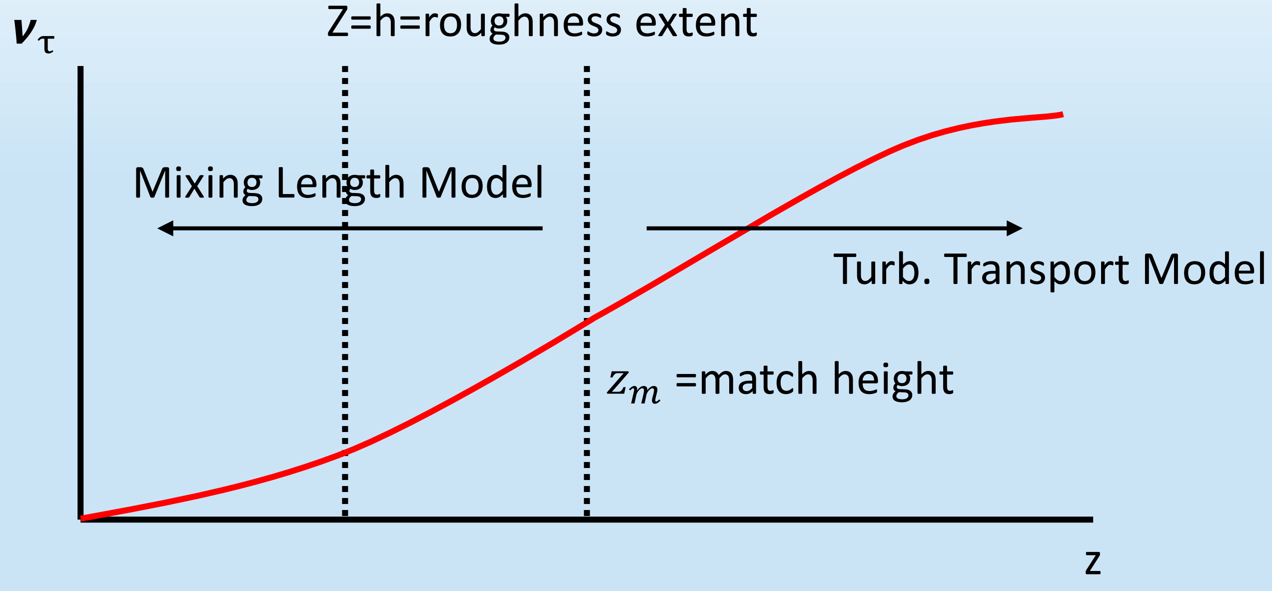
Reynolds Stress Treatment

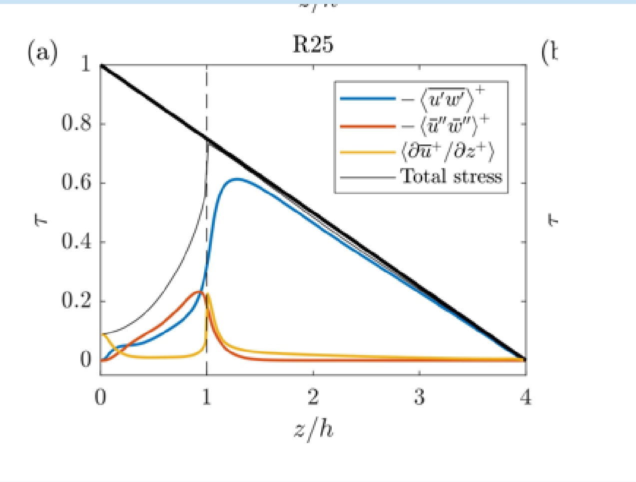
- Volume averaged Reynolds Stress $\langle\overline{u'w'}\rangle$ model required
  - Spatially averaged transport equations present challenges:
    - Covariances
    - Boundary Conditions

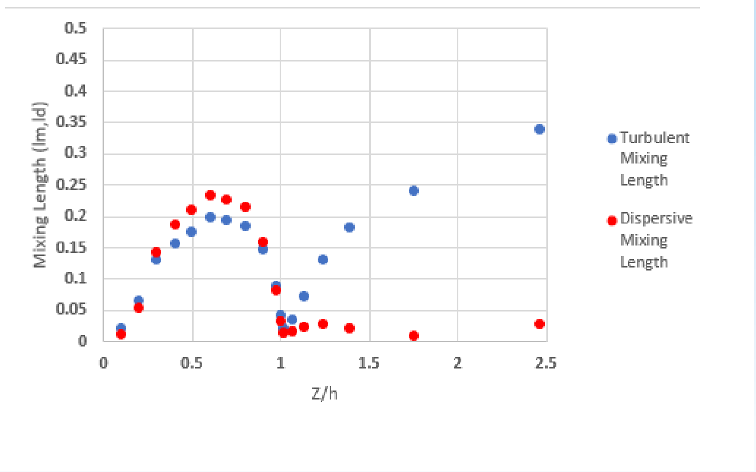
$$\langle\overline{u'w'}\rangle = \nu_\tau \frac{\partial \beta \langle \boldsymbol{U} \rangle^f}{\partial z}$$

$$\nu_\tau = l_D^2 \left(\frac{\partial \beta \langle \boldsymbol{U} \rangle^f}{\partial z} \right)^2$$

  - Eddy viscosity calculated using 2-layer approach
    - Mixing length in roughness region
    - 2-equation transport model above
    - Turbulence transport effects

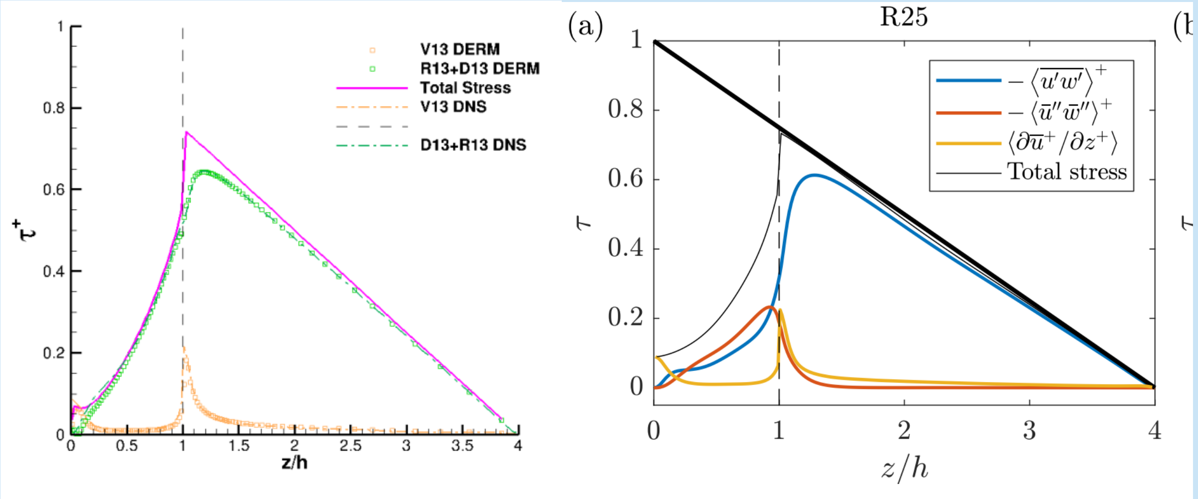




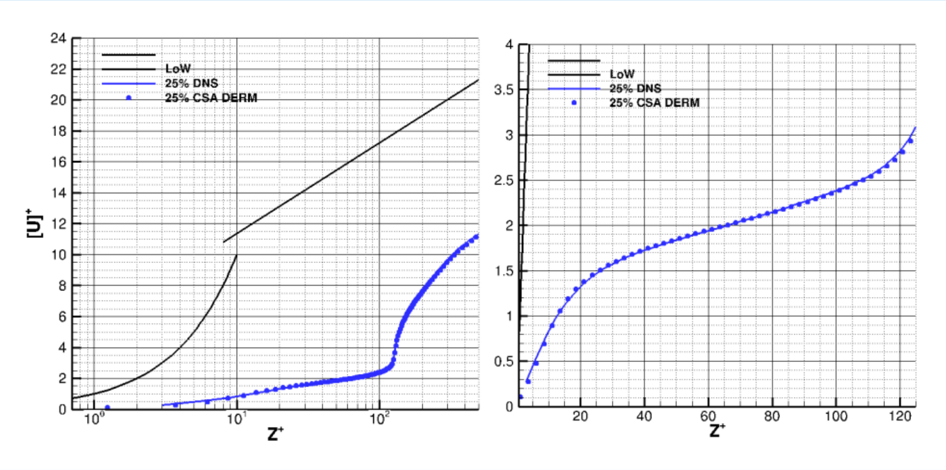


DERM Summary

- DERM can be applied to any geometry by
  - Conversion from 3D geometry to β distribution
  - Application of sheltering model to close drag term
  - Choice of models to close Reynolds and dispersive stress terms



$$\int \nabla\cdot(\nu+\sigma_\phi\nu_T)\nabla\beta\phi\ dV =$$
$$\int \nabla\cdot\beta(\nu+\sigma_\phi\nu_T)\nabla\phi\ dV + \int \nabla\cdot\phi(\nu+\sigma_\phi\nu_T)\nabla\beta\ dV =$$
$$\underbrace{\Sigma\Big[\big(\beta(\nu+\sigma_\phi\nu_T)\big)_f\big((\nabla\phi)_f\cdot n\big)A_f}_{\text{Existing VFlux}} + \underbrace{\Sigma\Big[\big(\phi(\nu+\sigma_\phi\nu_T)\big)_f\big((\nabla\beta)_f\cdot n\big)A_f\Big]}_{\text{New DERM VFlux}} \qquad (2.30)$$



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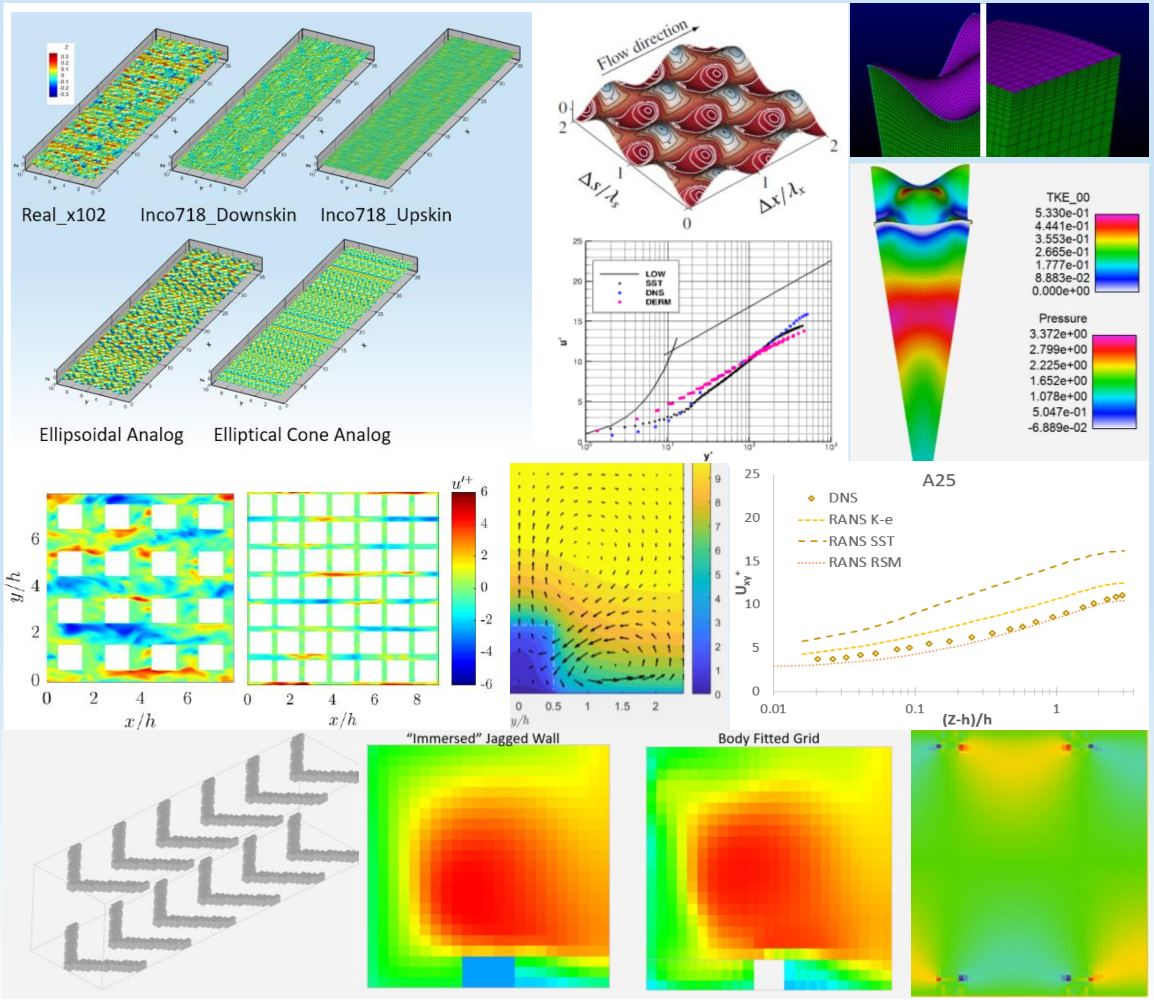
DERM model development/application

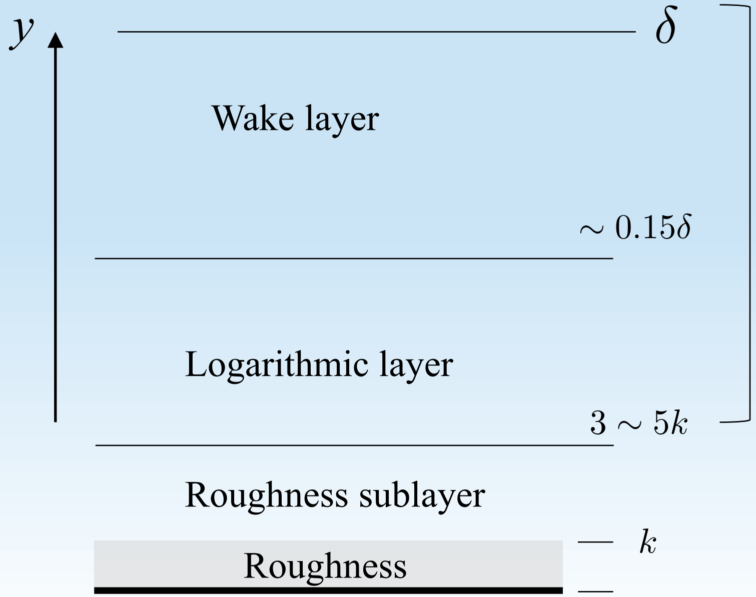
- Numerous configuration have been studied
  - 8 engine scale START configurations
  - Surrogate ellipsoid, elliptical cone surfaces
  - Sinusoidal
  - Cube arrays
    - Aligned and staggered
    - Range of coverage densities: <1% → 100%
  - Wedges (Han)
- Matrix of EFD+DNS/LES/RANS for calibration
- Using in house and some open-lit DNS/LES/RANS
- Two DERM model sets evolved → Model Set 2 summarized above



DNS Studies

- Open research questions
  - Large horizontal inhomogeneity ➔ how representative are measurements at single streamwise and spanwise location
  - Does the logarithmic layer survive the large-scale roughness?

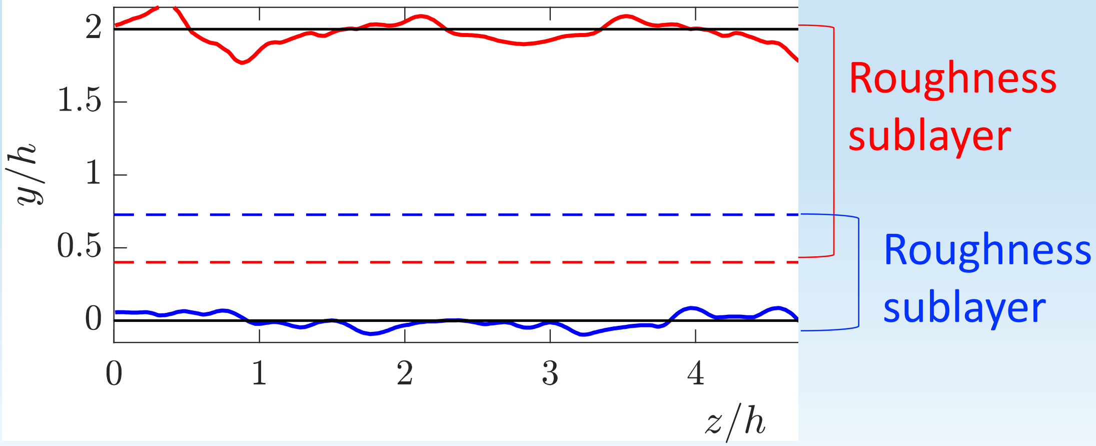
Conventional view



Mean flow homogeneous

Mean flow inhomogeneous

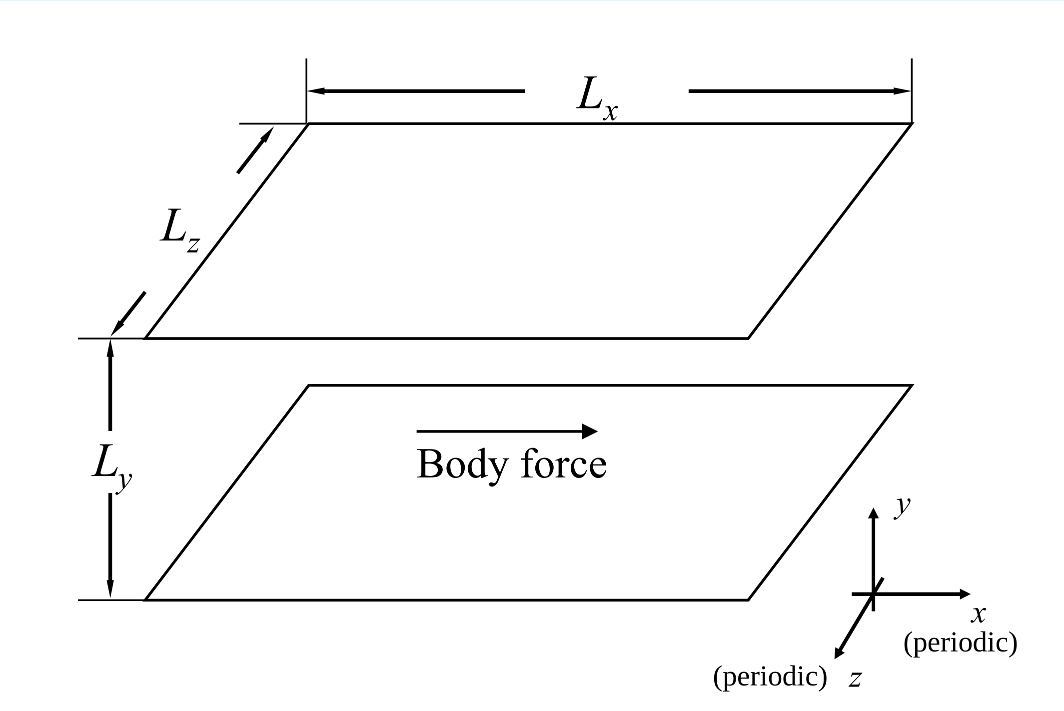
Additively manufactured cooling passage



Roughness sublayers overlap

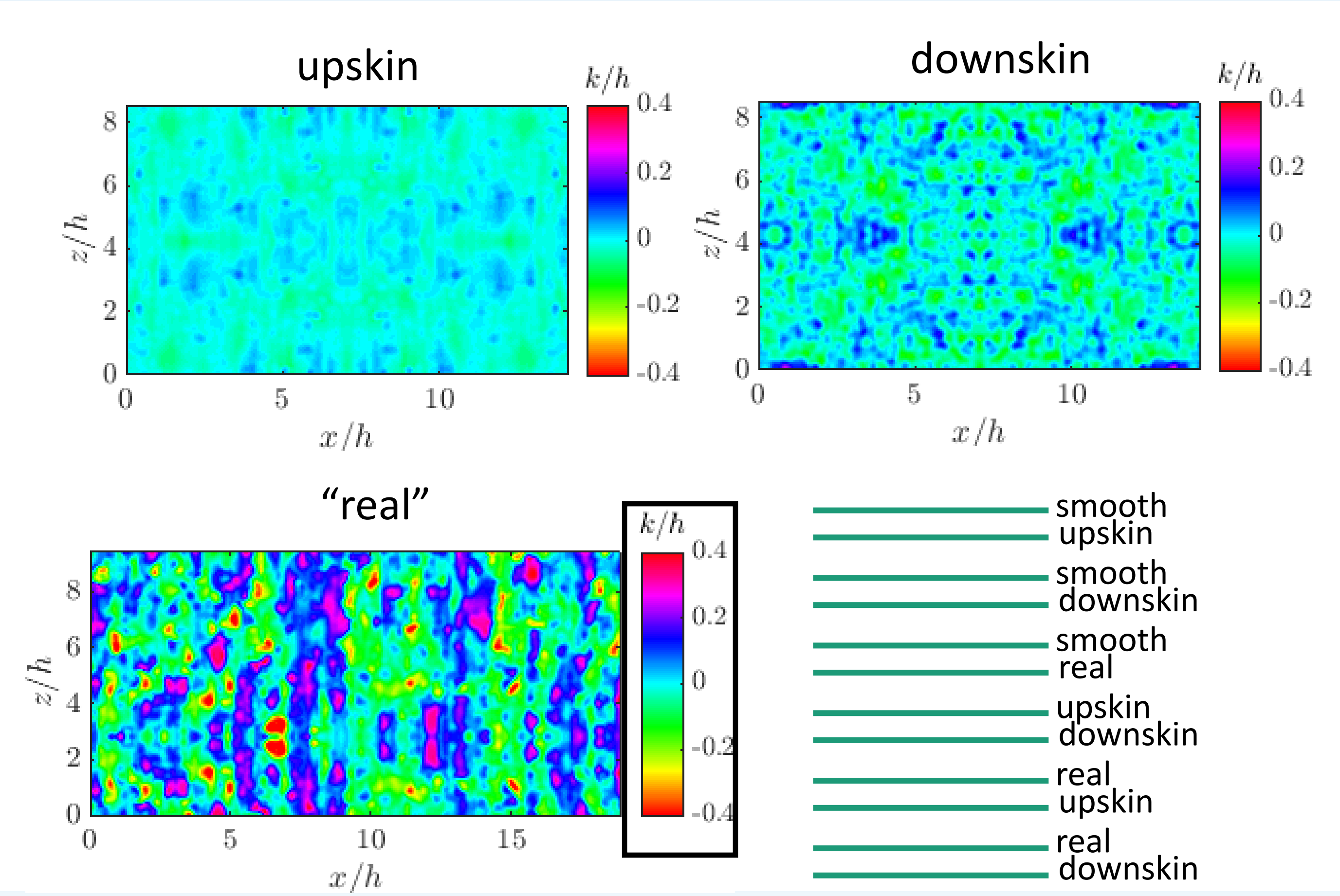
DNS Studies

- Flow configuration



Periodic in x, z
Axial body force ➔ $\mathrm{Re}_\tau = 395$
Mesh resolved roughness

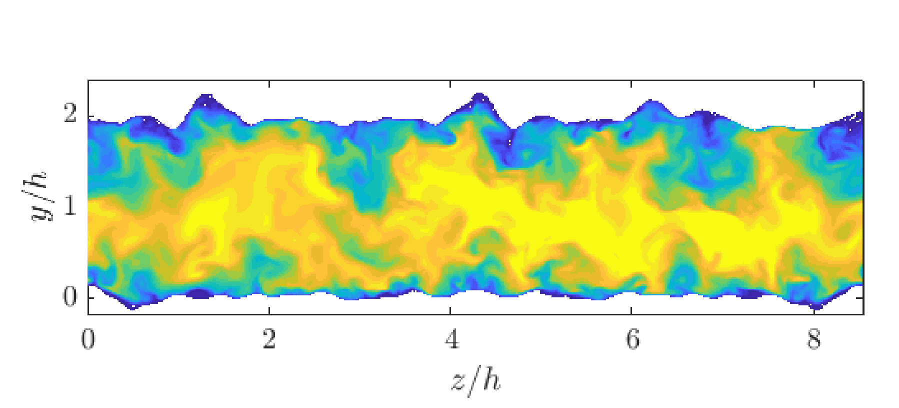
- Rough walls: START Lab Configurations

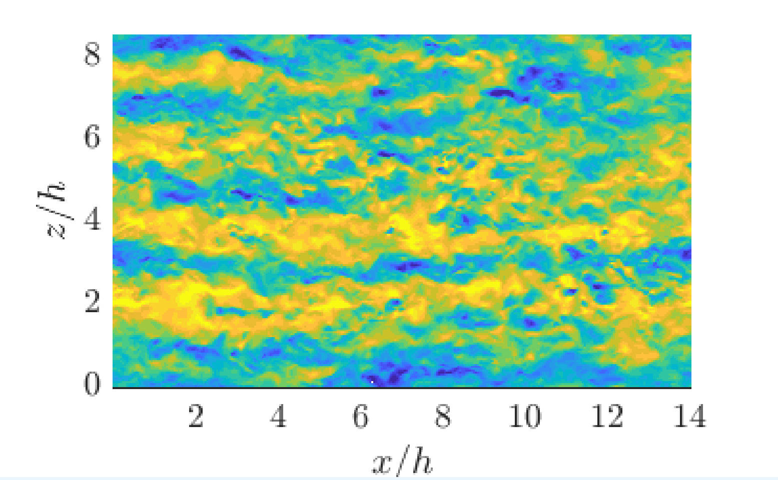


6 channel configurations per RIFT studies

DNS Studies

- Code
  - Pseudo-spectral code LESGO
  - Spatial discretization: spectral in x, z directions, 2nd order finite difference in y
  - 2nd order Adam-Bashforth in time
- Roughness resolved via immersed boundary method
- Grid resolution: $\Delta x^+ = 6, \quad \Delta y^+ = 1 - 5, \quad \Delta z^+ = 6$
- Computational domain: $L_x \approx 4\pi, \; L_z \approx 3\pi, \; L_y = 2$
- Statistically converged mean velocities and stresses





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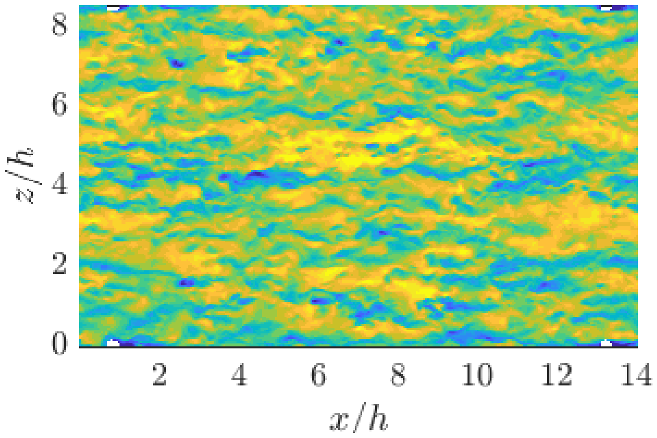
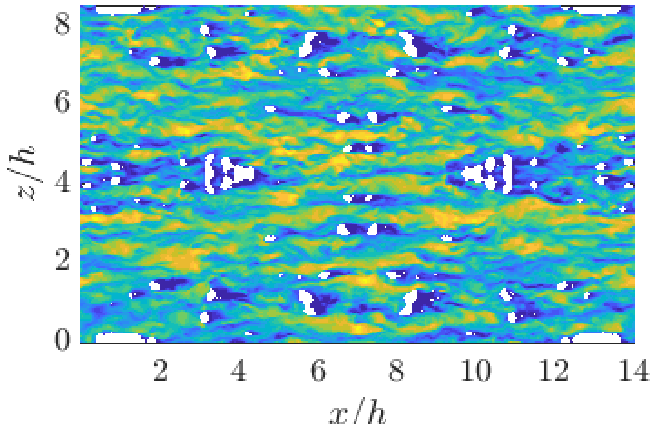
DNS Studies

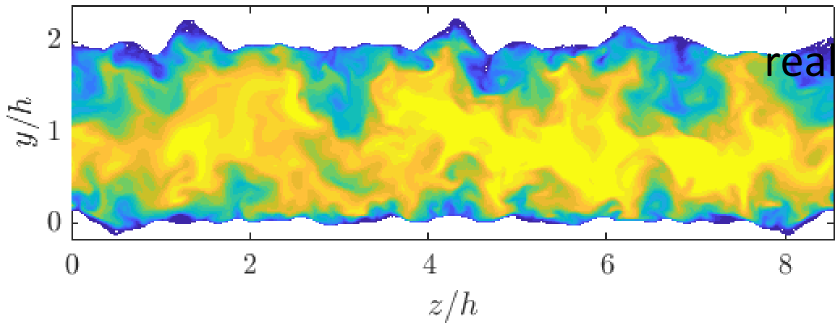
- Instantaneous flow fields, r/d-395

Down skin, roughness top

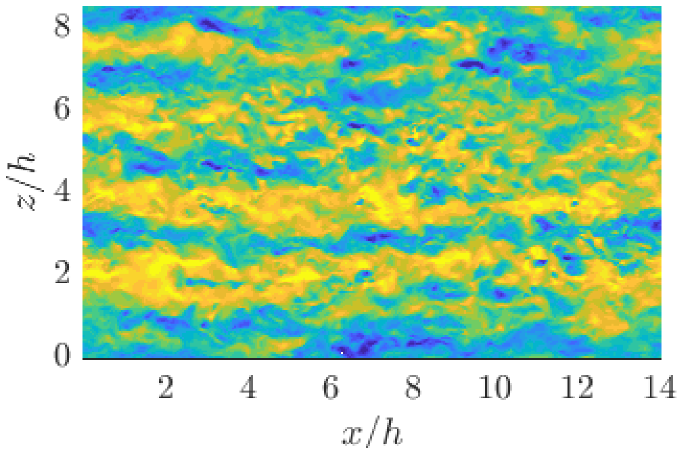


Down skin, 0.5k from the roughness top

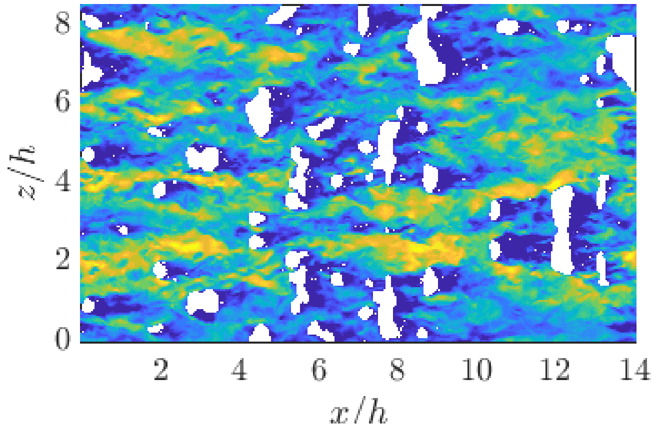




real, roughness top



real, 0.5k from the roughness top



Streaks survive

Statistically Inhomogeneous flow

Wakes behind roughness

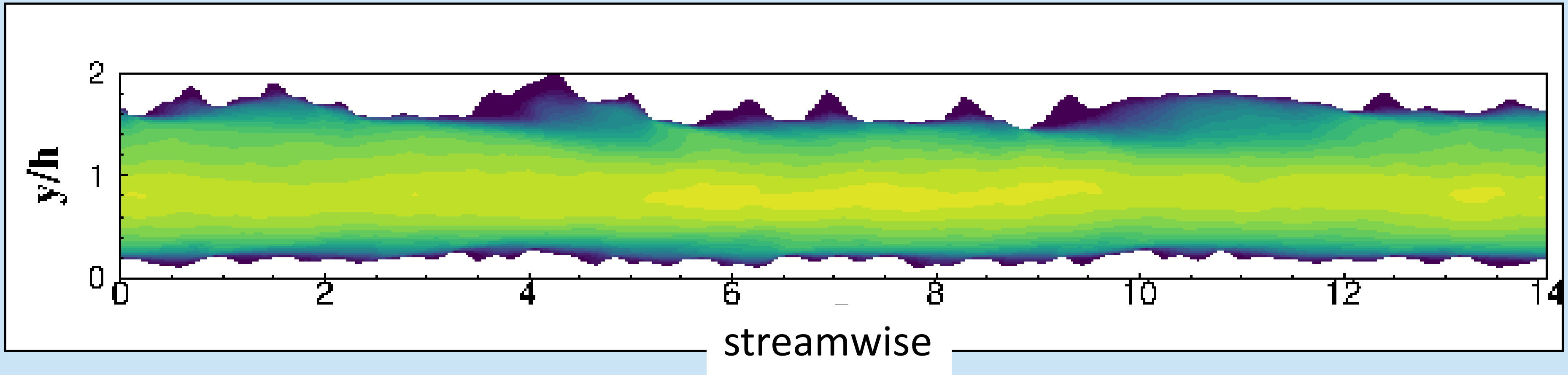
High momentum pathways between roughness

DNS Studies

- Mean flow inhomogeneity

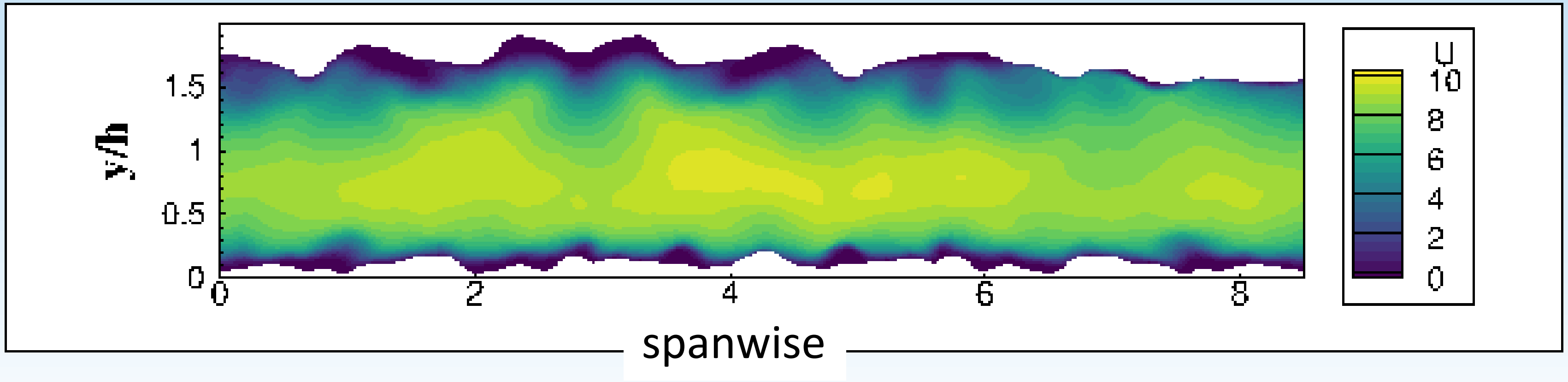
real

down skin



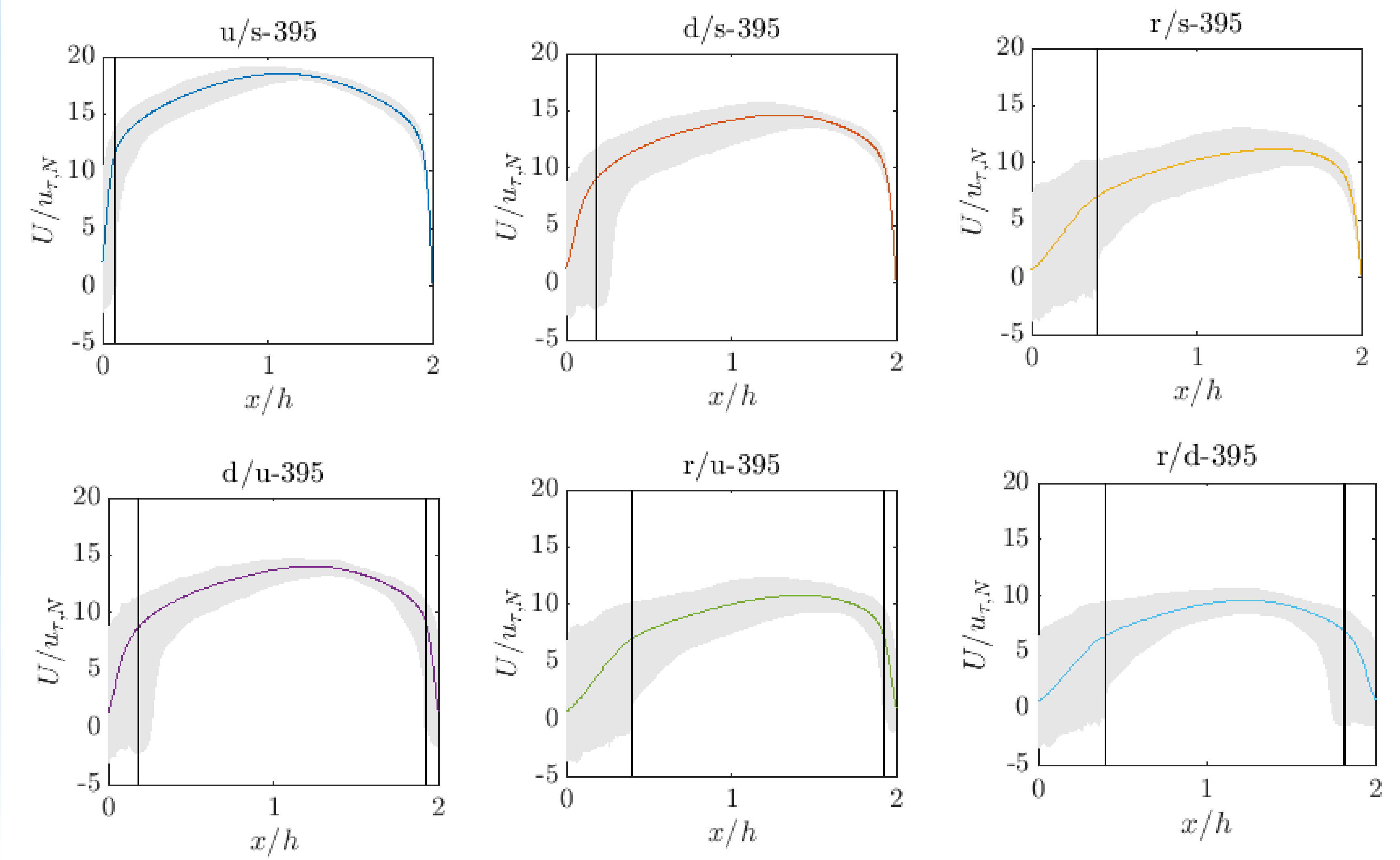
real

down skin



DNS Studies

- Mean flow inhomogeneity



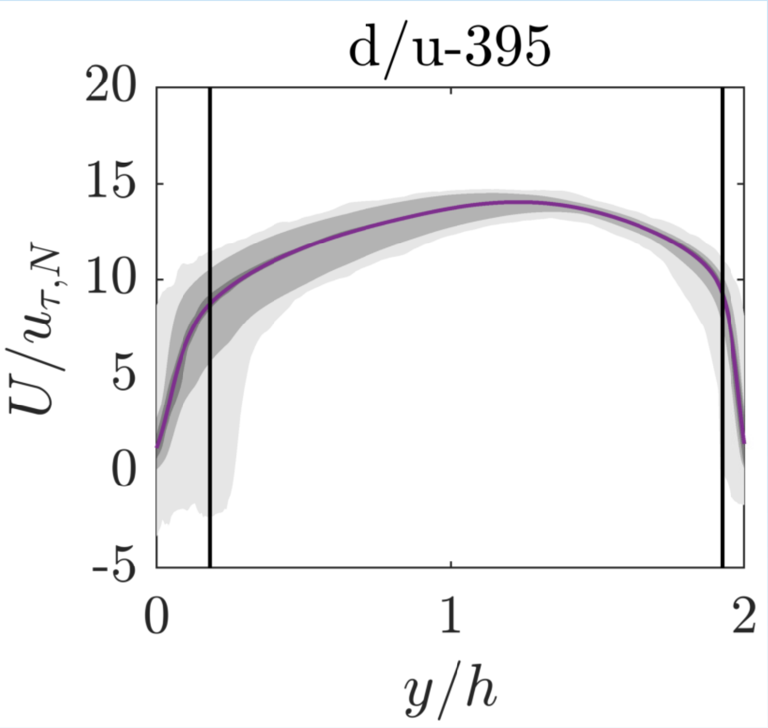
Range of time-averaged values

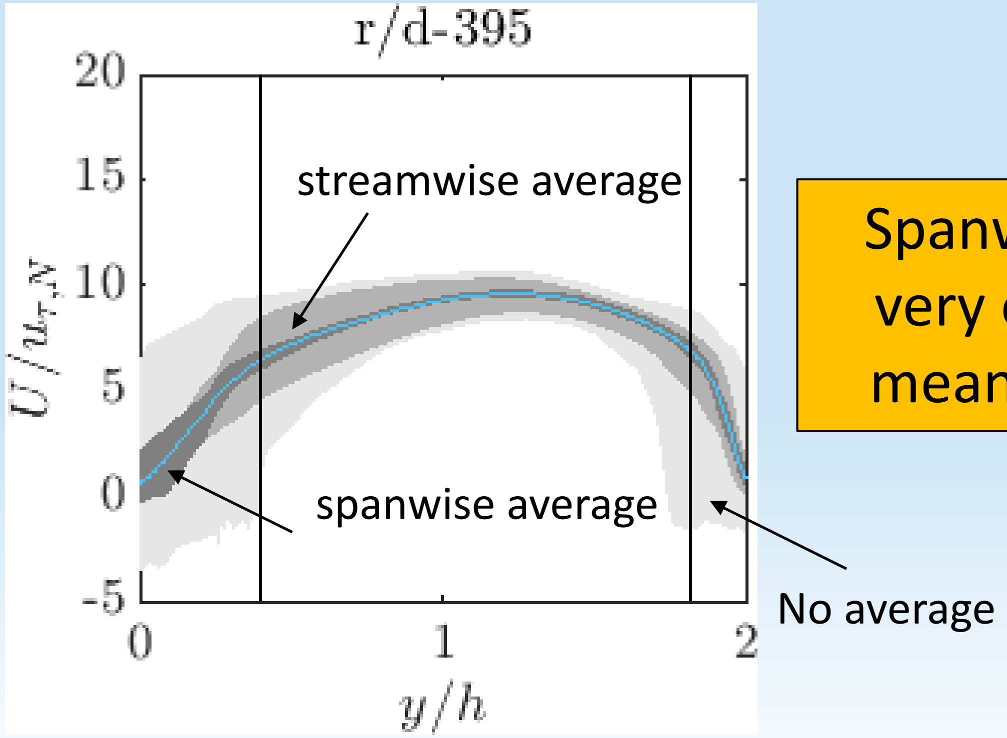
Overlap of the two roughness sublayers

Single point measurements not good representation of mean flow

DNS Studies

- PIV allows for average along a plane
- How much spatial average is needed and in what directions?





Spanwise spatial averaging very effective in removing mean flow inhomogeneity

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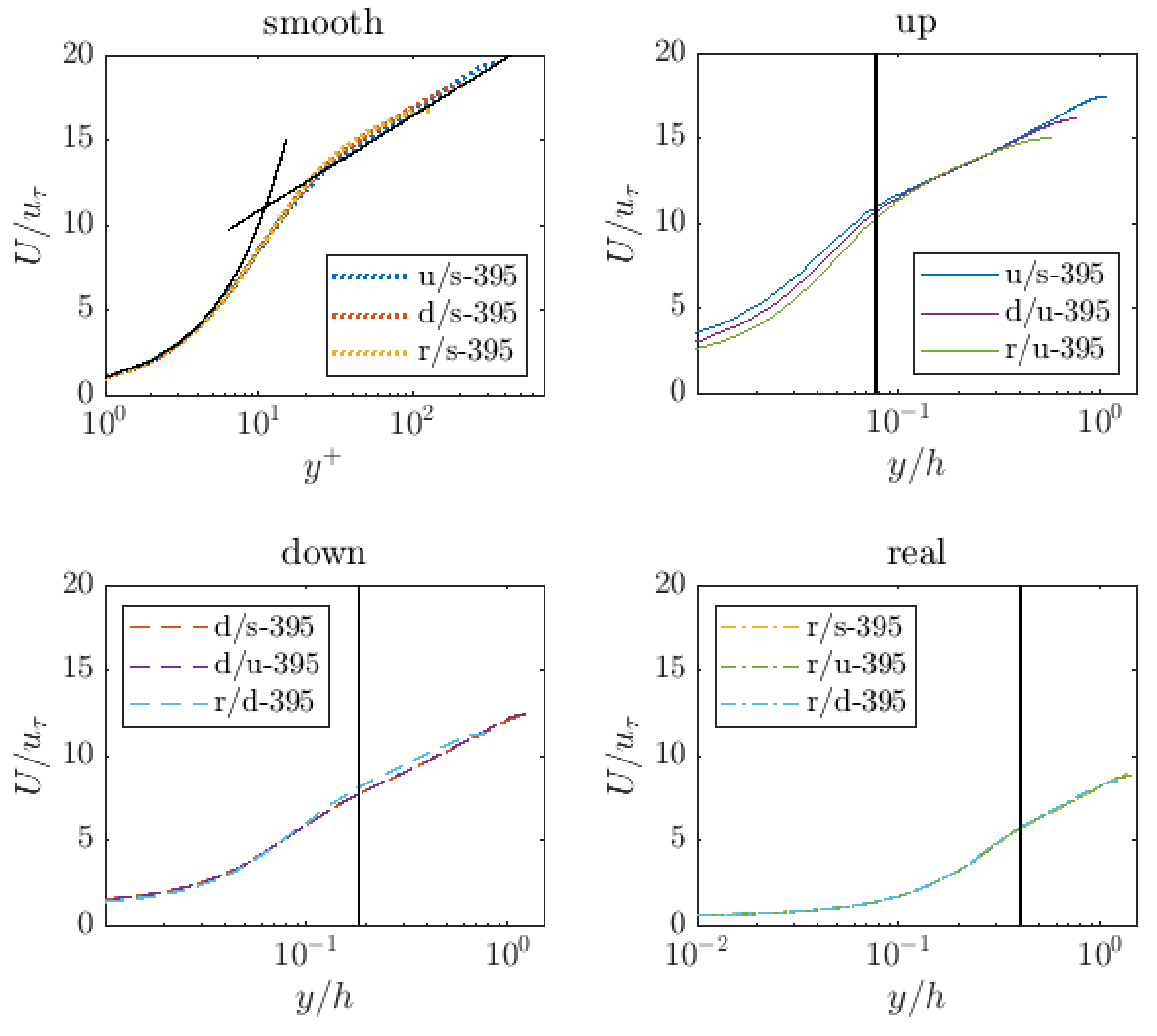
DNS Studies

- Mean flow universality



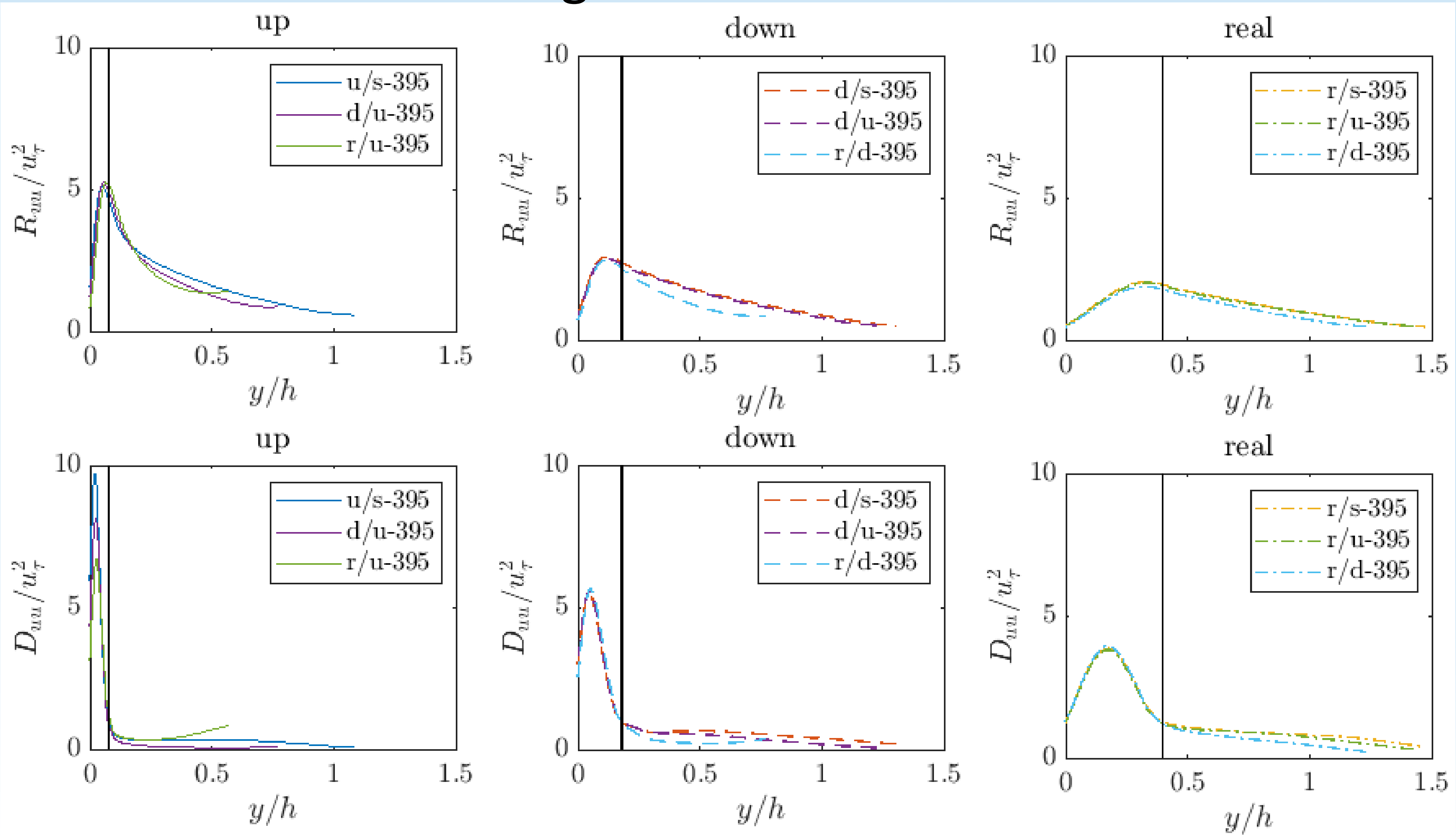
Log-layer survives despite large roughness

Mean flow above rough wall is universal irrespective of roughness on opposite side
➔ this despite roughness sublayer overlap

Supports use of DERM sheltering model

DNS Studies

- Although mean flow exhibit universality, Reynolds Stress and dispersion do not
- This renders modeling of these terms non-trivial



$$u = U + u' + u''$$

Temporal fluctuation

Spatial variation of the temporal mean

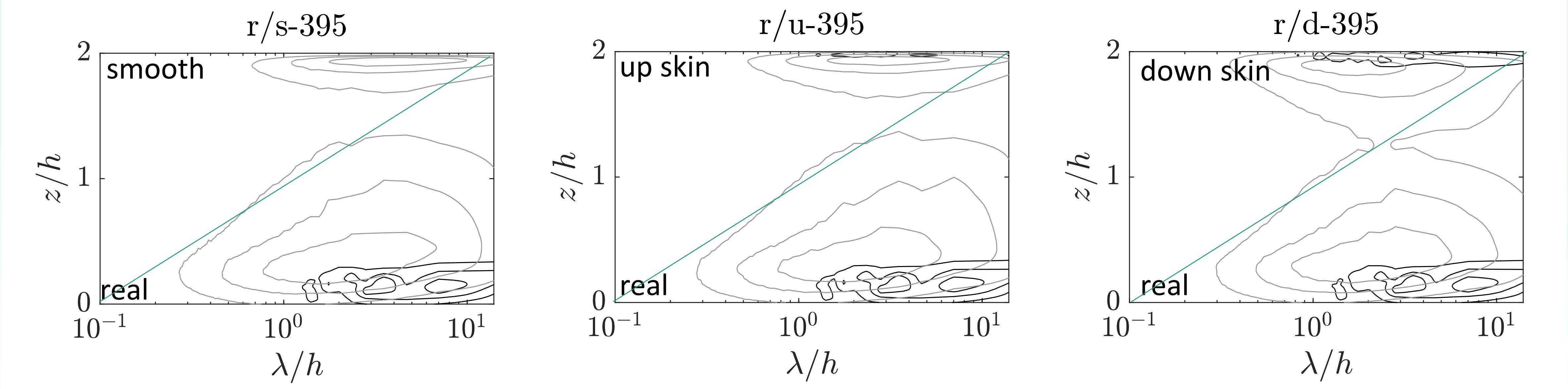
DNS Studies

- Turbulence spectra are of interest to both DERM and RWTBL communities
  - u'' is most energetic z<h → Mean flow universality
  - u' is most energetic z>h
    - Does not seem to be strongly affected by roughness on the opposite side.
    - This calls for more in-depth research.

Temporal fluctuation
Gray lines

Spatial variation of the temporal mean
Black lines

$$u = U + \boxed{u'} + \boxed{u''}$$



DNS Studies

- Conclusions
  - Roughness of scale ~ half channel height ➔ horizontal mean flow inhomogeneity
    - Measurements at single streamwise and spanwise location not a good representation of mean flow due to horizontal mean flow inhomogeneity
    - Spanwise spatial averaging effective in removing inhomogeneity
  - Logarithmic layer survives large scale roughness
  - Mean flow in log layer is universal irrespective of roughness on opposite side
  - However, universality is not found in the underlying turbulence

Students on Project

- Sam Altland
  - Penn State, Mechanical Engineering, PhD, Expected Graduation May 2022
  - Passed Comprehensive Exam July 2021
  - Passed PhD Candidacy Exam September 2019, 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, 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"

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. ***ASME Journal of Turbomachinery***, July 2021, Vol. 143(7): 071013, doi:10.1115/1.4050389.

Title: Flow over Closely Packed Cubical Roughness, ***Journal of Fluid Mechanics*,** Vol. 920, 2021, doi:10.1017/jfm.2021.456.

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

ASME Paper: GT2021-59684
Title: Convection in Scaled Turbine Internal Cooling Passages with Additive Manufacturing Roughness, Accepted ***ASME Journal of Turbomachinery***.

ASME Paper: FEDSM2021-65494
Title: Modeling of Cube Array Roughness; RANS, LES and DNS. Accepted ***Journal of Fluids Engineering***.

APS-DFD 2021: 2021- E26.00001
Title: A Distributed Element Roughness Model for Deterministic Roughness Morphologies using the Double Averaged Navier Stokes Equations.

ASME Paper Number: GT2022-81218
Title: Application of a Distributed Element Roughness Model to Additively Manufactured Internal Cooling Channels
Abstract submitted.

Title: Flow in Additive Manufactured Rough Channels
Manuscript in Preparation, ***Flow***.

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Summary and Current/next steps

- Nearing end of project
- Progress to date:
  - RIFT
    - Adiabatic
    - Convection
    - 3D Tomo-PIV ← Covid and supply-chain delays – to be completed Feb 2022
  - DERM formulation development
  - DNS, LES, RANS for DERM calibration of numerous roughness morphologies
  - DERM calibration
  - Winding down → more publishing of EFD, DERM/DNS/LES/RANS elements