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

Year 1 Research Progress

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Background/Objectives

- 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

Background/Objectives

- 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

Background/Objectives

- 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

Background/Objectives

- 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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Overview of 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

Technical Approach

- Task 1 - Engine scale cooling passage manufacture, scan, and testing
- Task 2 - Advancement, validation, application of DERM
  - 3D volume fraction statistical field representations of PBF roughness fields
  - Shape parameterizations and scale synthesis
  - Interfacial momentum and heat transfer models, using DNS and LES of measured and synthesized roughness
  - Calibrate and validate DERM model for representative turbine cooling passage configurations using engine scale data and using up-scaled data
- Task 3 – Up-scale flow/heat transfer experimental measurements
- Task 4 – Development and application and experimental validatation of optimization methodology in context of DERM

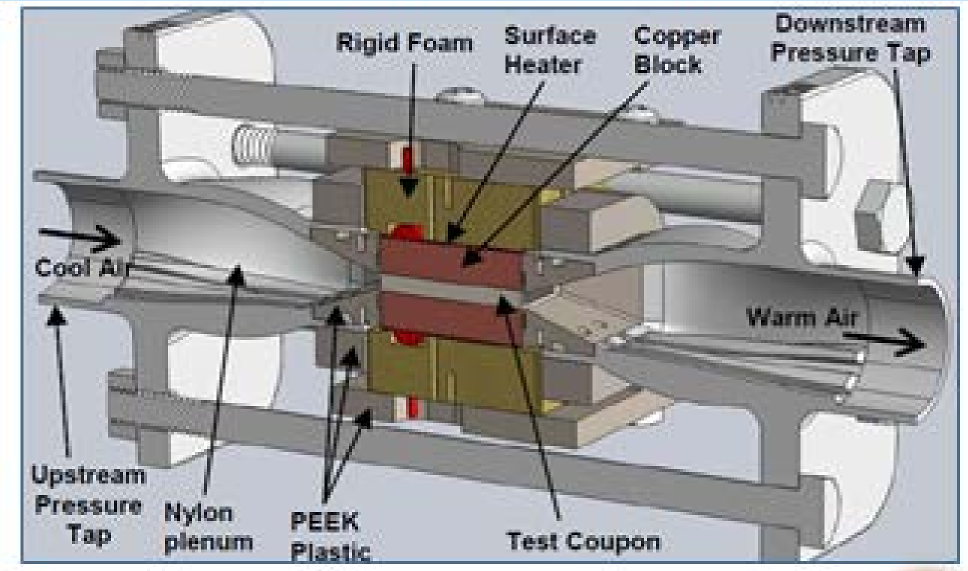
Year 1 Activities and Progress

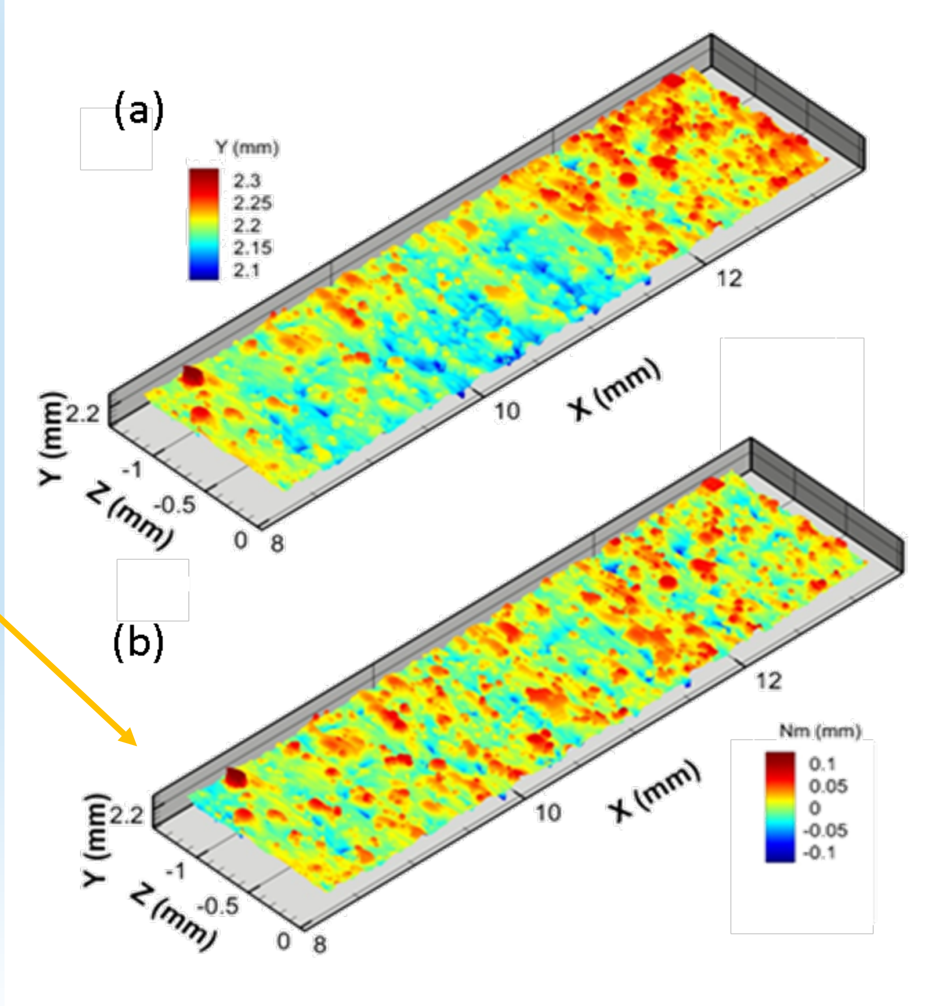
Test article configuration build and characterization

- L-PBF creation of engine scale coupon with straight passages and characterize with CT
- CAD model of the AM surface with geometric imperfections removed:
  - Extract only bottom channel surface (upskin) here
  - Stream-wise and spanwise variations in the point cloud that are at length scales much larger than individual roughness elements)
  - 2D, self-organizing-map with Z-axis regression (2D-SOM-ZR) approach of McClain Upscale (100x) with 3D printing for C_f and hot film anemometry
  - Upscale surrogate surfaces which replicate statistics and hydraulic characteristics of the original AM surface (Clemenson)
- Total of 4 configurations: 1 engine scale, 3 upscale

Year 1 Activities and Progress
Test article configuration build and characterization

- Engine scale coupon (Realx102)
  - CT to 4 μm (sacrificial coupon – same build parameters as tested in START small scale rig
  - 2D-SOM-ZR for long wavelength variation removal





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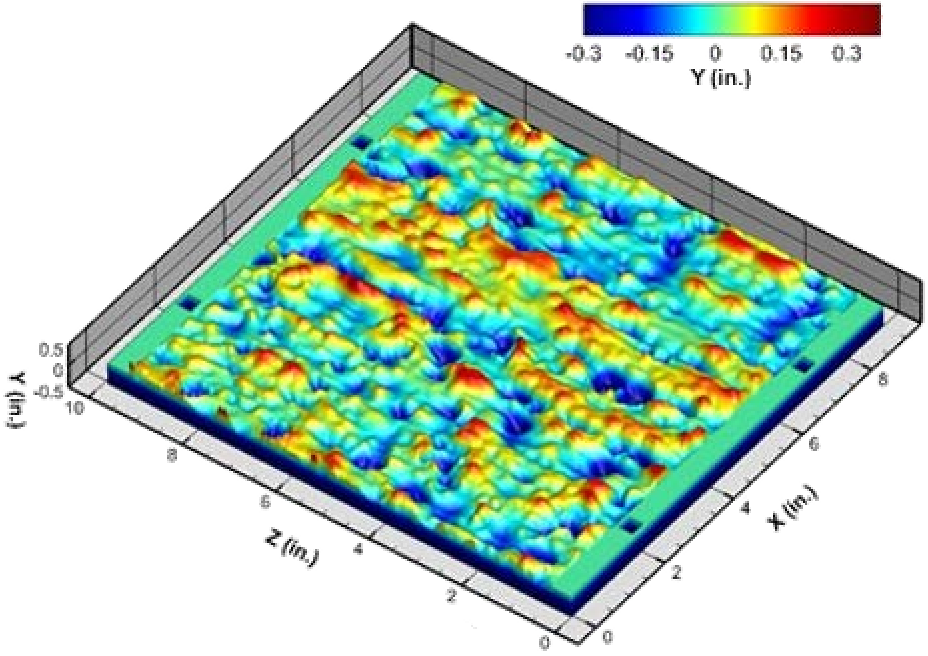
Year 1 Activities and Progress
Test article configuration build and characterization

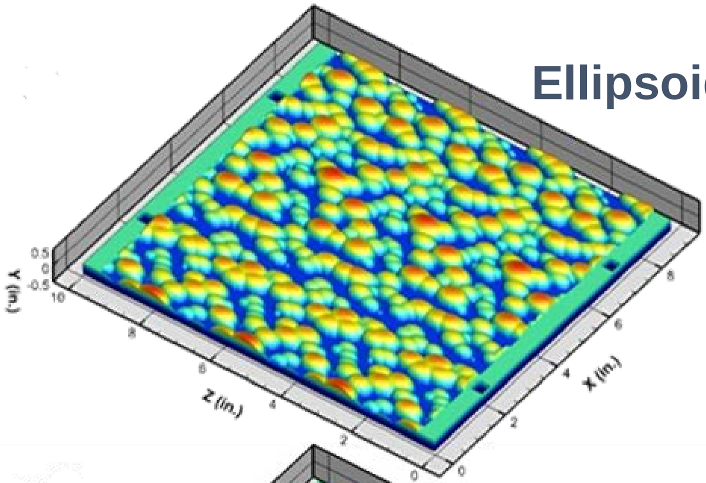
- Surrogate surfaces based on icing work by McClain and his team:
  1. Analog surface must be multi-spectral
     - Generate a random pattern of selected roughness elements that is then scaled to match root-mean-square roughness height, R_q
  2. The primary shear and convective enhancements are caused by vortex shedding from the individual roughness elements and the interaction of the vortices with the next downstream roughness elements
     - Match the dominant wavelength in the stream-wise autocorrelation between the original and analog surface

Year 1 Activities and Progress
Test article configuration build and characterization

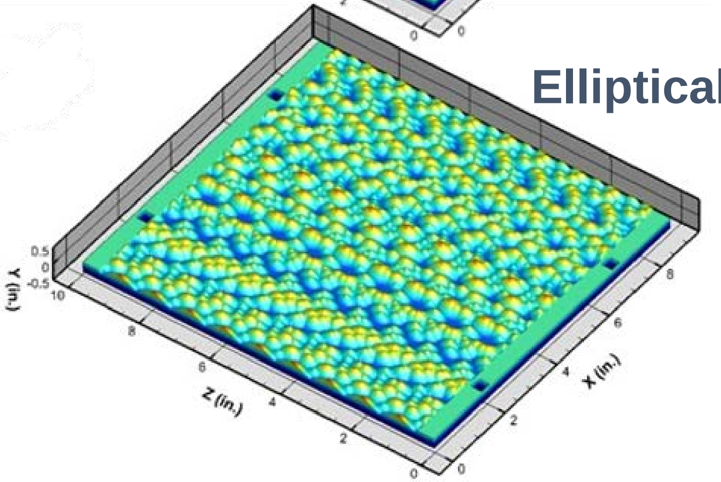
Realx102



Ellipsoid Analog



Elliptical Cone Analog



Year 1 Activities and Progress

Test article configuration build and characterization

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

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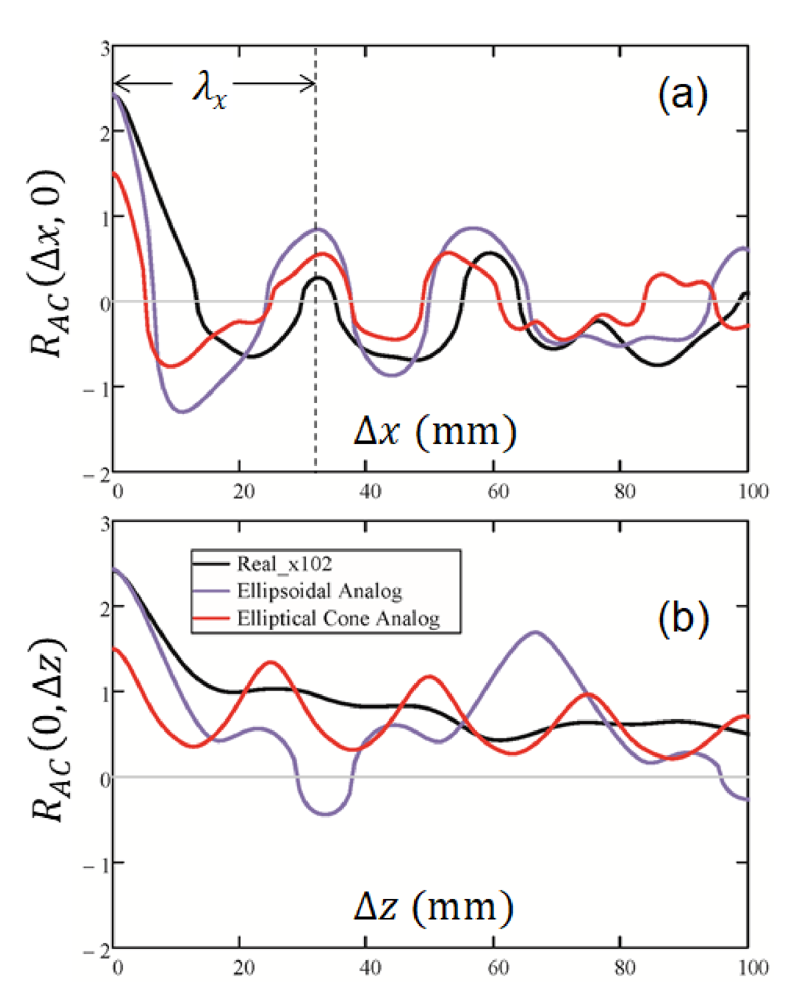
Year 1 Activities and Progress
Test article configuration build and characterization



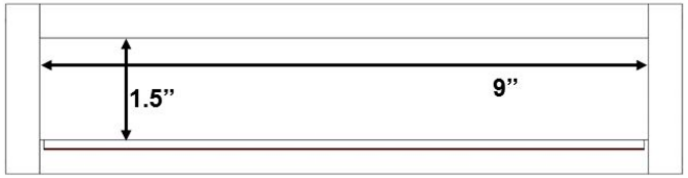
Streamwise autocorrelation results look pretty good for both surrogate surfaces

Spanwise autocorrelation results look not as good for both surrogate surfaces

In both cases evidence of striations inherent in the PBF build are evident

Year 1 Activities and Progress
Up-Scale Experiments

Roughness Internal Flow Tunnel (RIFT)

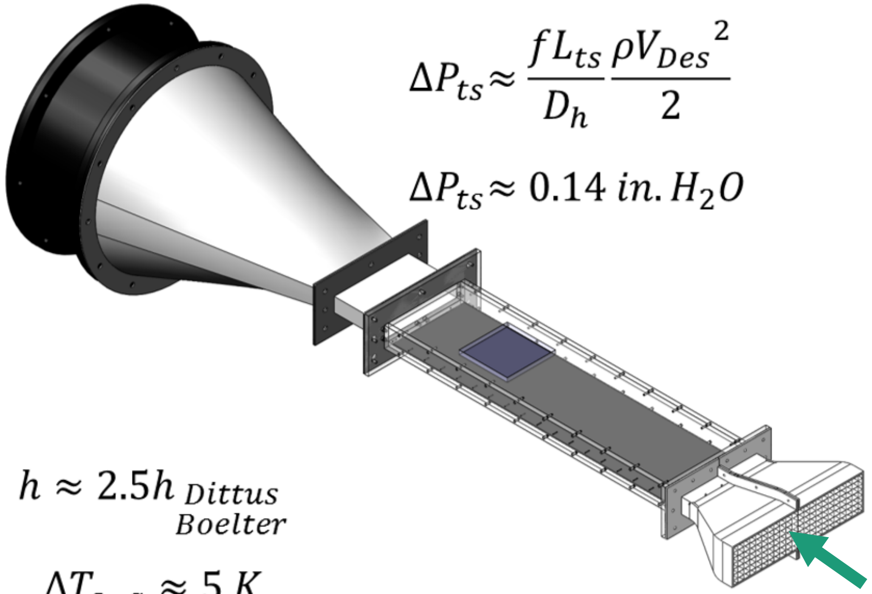


Channel Cross Section

$$Re_{D_h} = \frac{\rho D_h V_{Des}}{\mu} = 30{,}000$$

$$V_{Des} = 7.1\, m/s$$

$$Q_{Des} = 130\, cfm$$

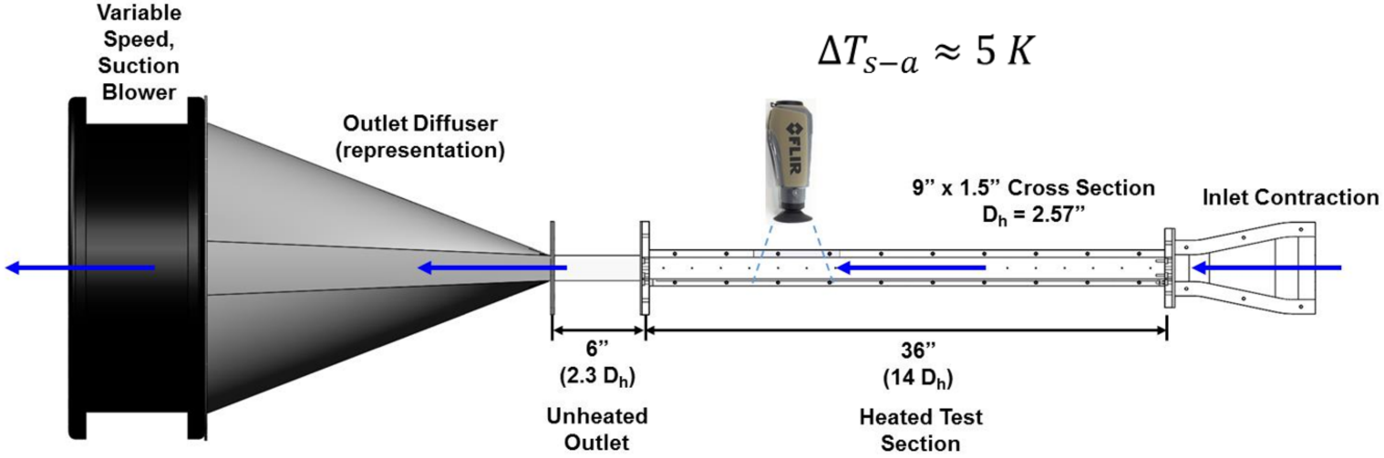


$$\Delta P_{ts} \approx \frac{f L_{ts}}{D_h} \frac{\rho V_{Des}{}^2}{2}$$

$$\Delta P_{ts} \approx 0.14\ in.\, H_2O$$

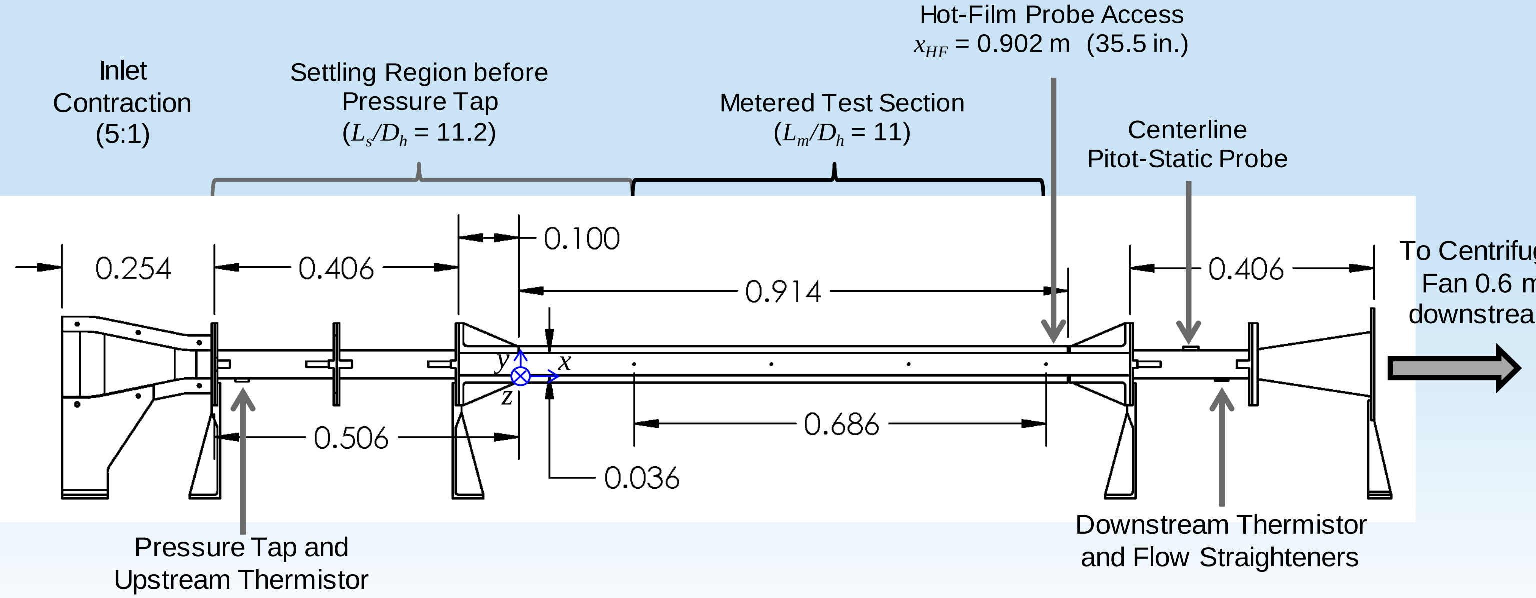
$$h \approx 2.5 h_{\substack{Dittus\\Boelter}}$$

$$\Delta T_{s-a} \approx 5\, K$$



Year 1 Activities and Progress
Up-Scale Experiments

- 6:1 aspect ratio (> 2.2:1 for as built)
- Tests with roughness panels on one side and both sides
- Δp at 4 axial locations, 9” apart in test section
- Hot film for velocity profiles
- PIV coming soon
- q” coming soon



Year 1 Activities and Progress
Up-Scale Experiments

Experiemntal results follow in a few slides
– present CFD method here first so results can be presented together

Year 1 Activities and Progress
CFD modeling: DNS

- Computational platform for DNS, LES and DERM: NPHASE-PSU
  - Segregated pressure based finite volume scheme
  - Fully unstructured
  - DNS 4th order central for advection, viscous and ∇p
    - Structured meshes
    - Extended stencils for high order
  - Demonstrated scalability to 3000 cores:
    - Re_τ appropriate for turbine cooling passages quite feasible in 2018
    - Smooth wall statistics in a few days on $\cong$1000 cores for $Re_\tau \cong 500$
- Computational platform for RANS: OVERREL, STAR-CCM, NPHASE-PSU

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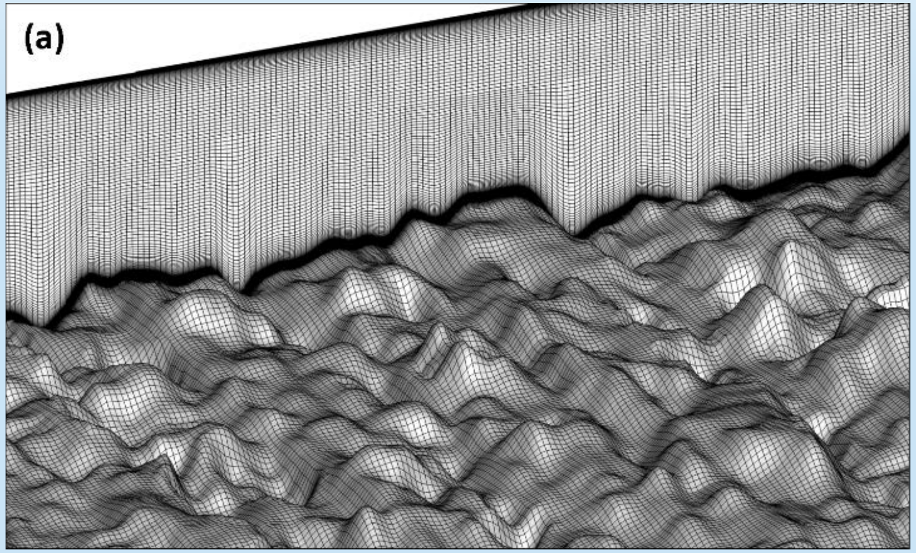
Year 1 Activities and Progress
CFD modeling: RANS

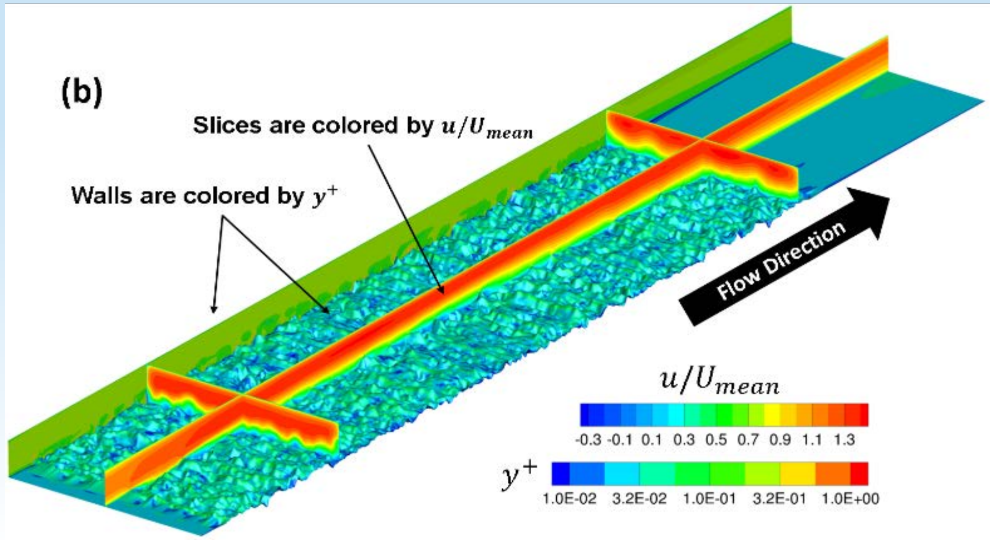
- Explicit resolution of roughness with RANS
- In-house 2nd/3rd order FV code (OVERREL)
- 53,000,000 cells ➔ sublayer resolved
- Spalart-Allmaras turbulence model
- Steady state analysis
- CFD for all 7 experimentally studied cases:

1: Smooth walls

2-4: **1**-sided roughness: Xeal_X102, Ellipsoid Analog, Elliptical cone analog

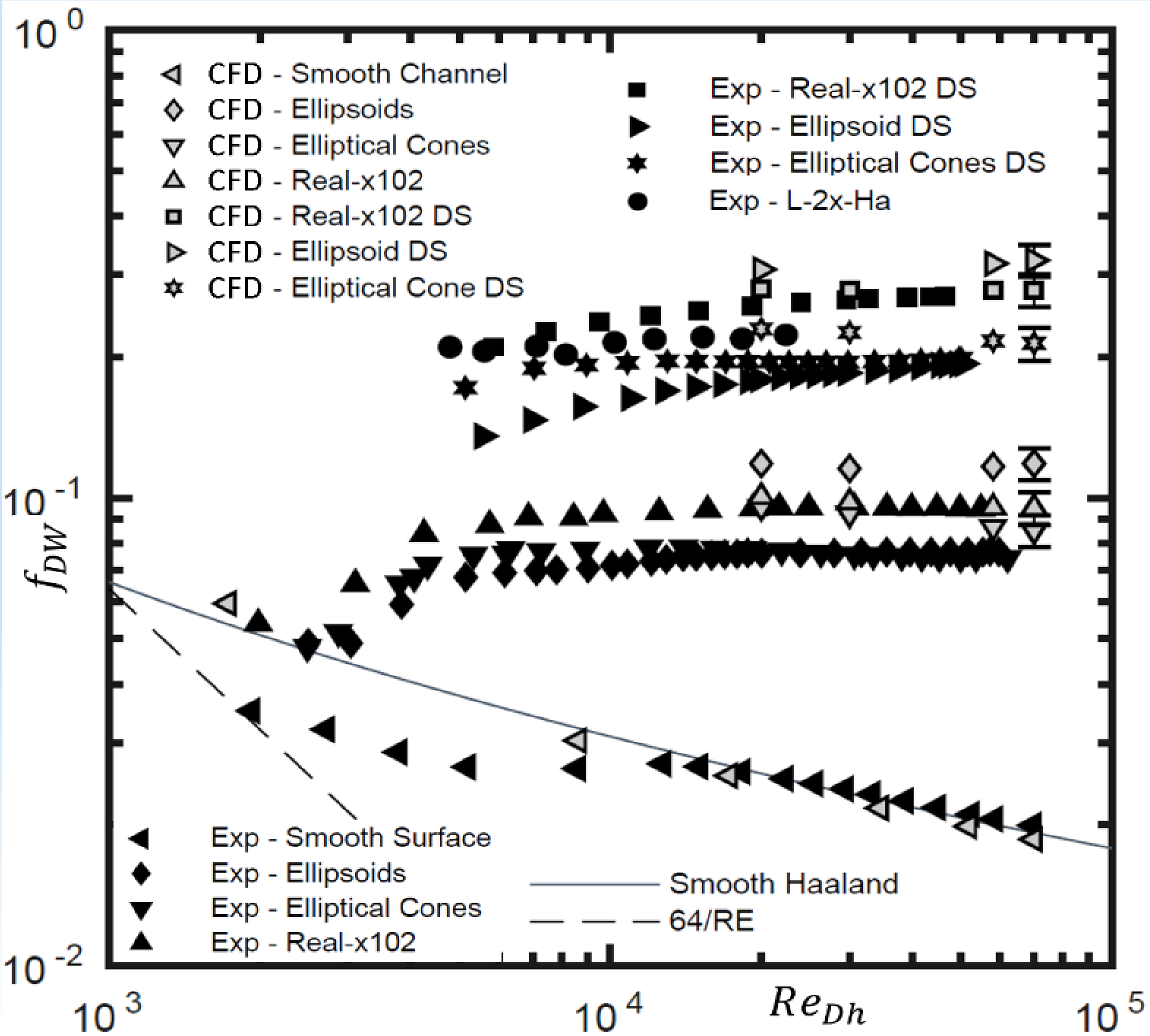
5-7: **2**-sided roughness: Xeal_X102, Ellipsoid Analog, Elliptical cone analog





Year 1 Activities and Progress

Summary of friction factor measurements and CFD predictions



Double sided

Single sided

Smooth

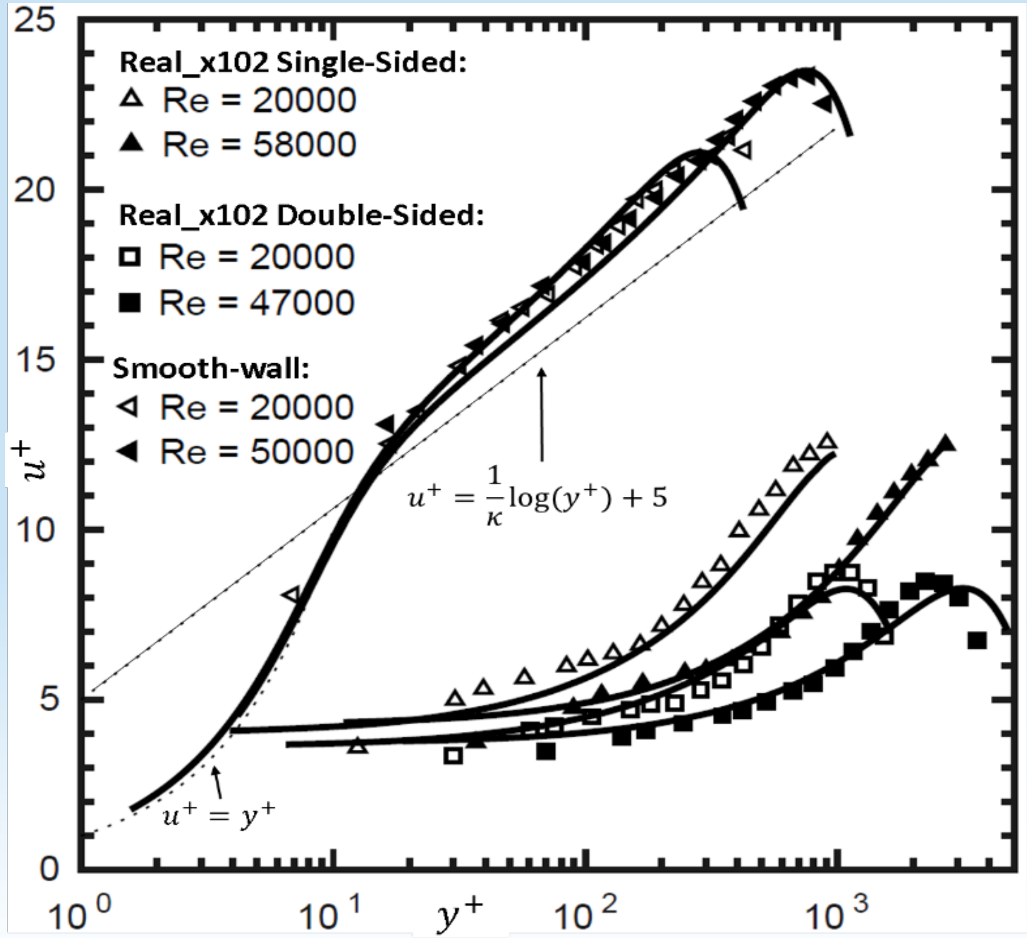
Year 1 Activities and Progress

Equivalent sand-grain roughness height computed from the friction factor at the highest Reynolds number of each double-sided run case

	Real_x102 DS	Ellipsoid Analog DS	Elliptical Cone Analog DS
k_{s,F_S} (mm)	6.933	7.045	6.965
$k_{s,St}$ (mm)	30.85	34.24	18.73
$k_{s,measured}$ (mm)	25.06	16.80	17.37
$k_{s,OVER-REL}$ (mm)	25.93	30.28	20.79

Year 1 Activities and Progress

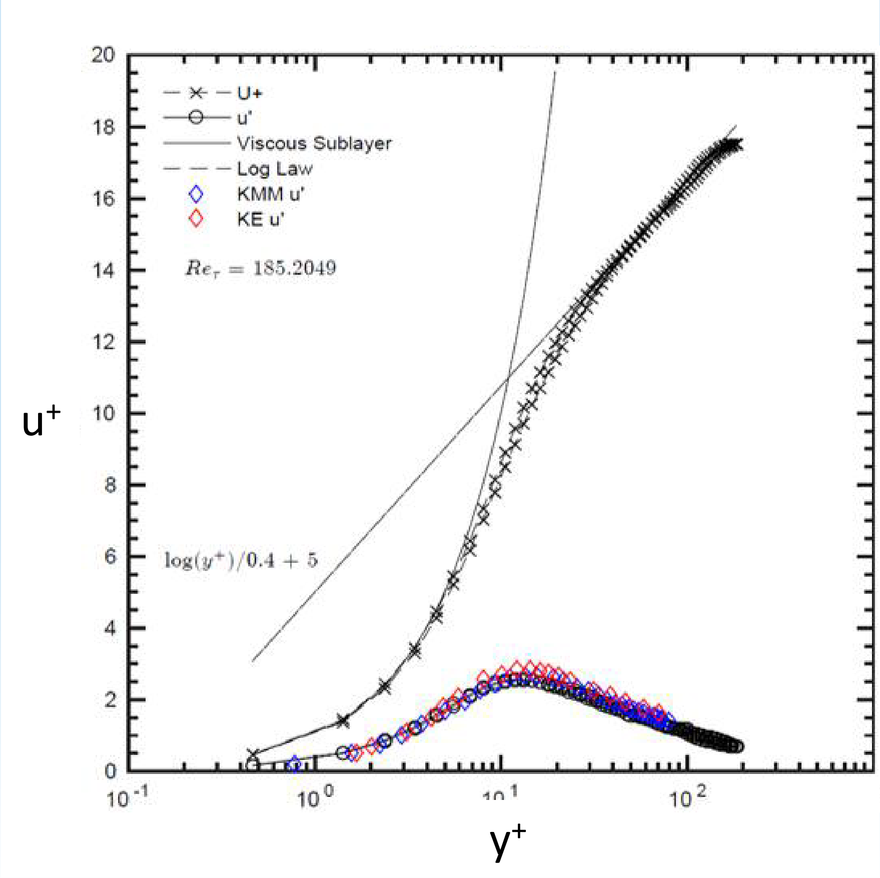
Velocity profiles for the smooth-walled and single- and double-sided Real_x102 flow cases over a range of Reynolds numbers expressed in inner variables. Symbols: measurements. Curves: CFD

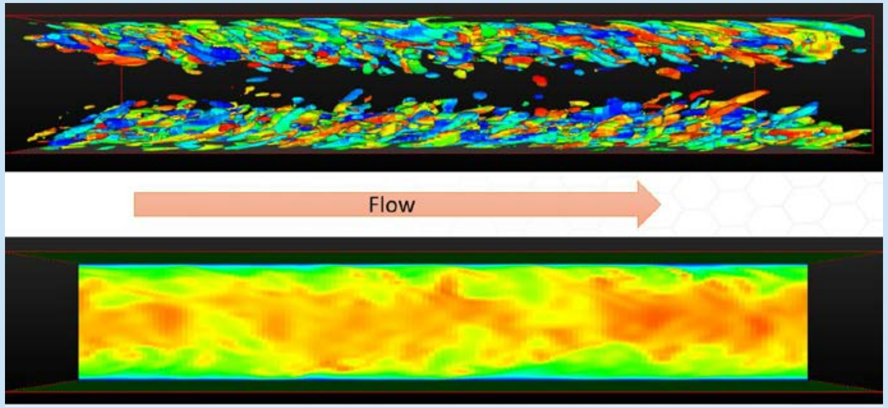


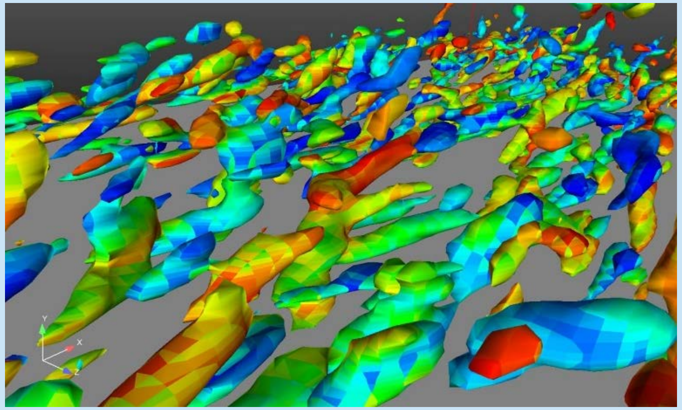
Year 1 Activities and Progress

CFD modeling: DNS

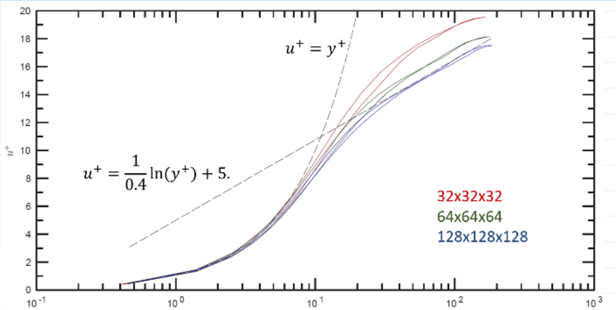
- Baseline smooth wall validation, $Re_\tau = 185$

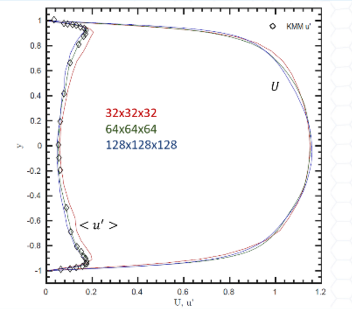


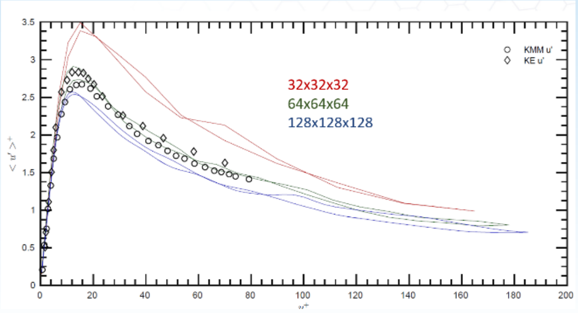




mesh studies



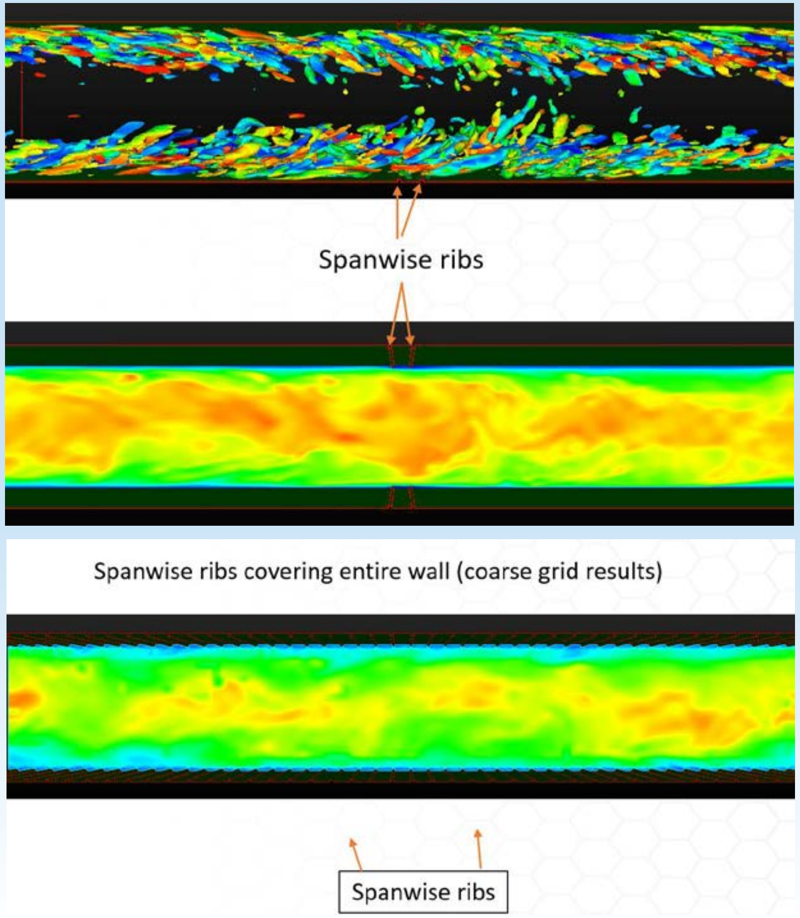


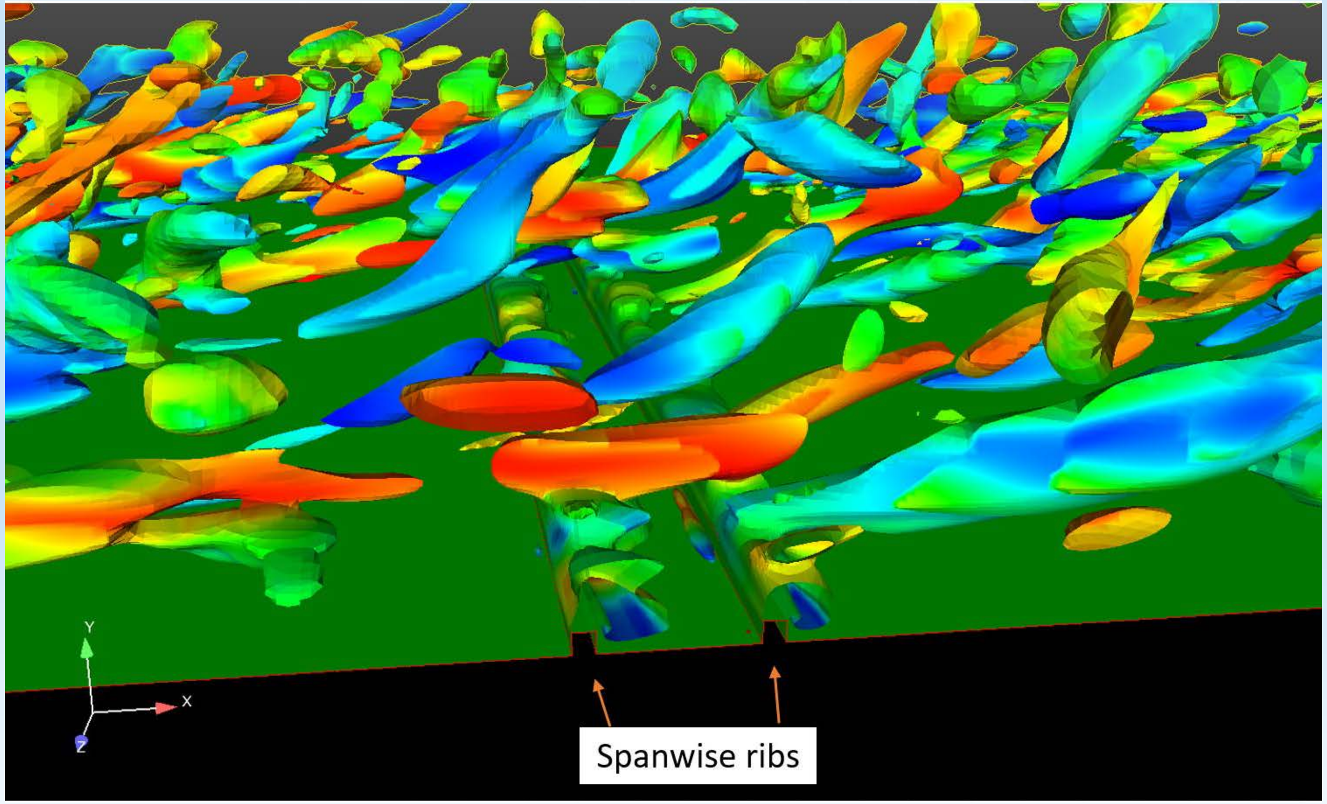


Year 1 Activities and Progress

CFD modeling: DNS

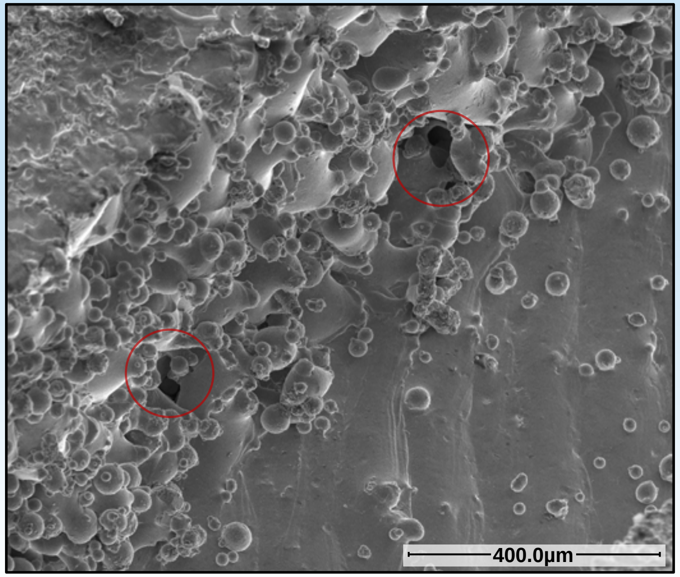
- Baseline rough wall studies





Year 1 Activities and Progress
DERM model development

- Computational platform for DERM: NPHASE-PSU
  - Full-two fluid formulation
  - Accommodate multiphase data-structures and interfacial momentum and heat transfer
  - Each "field" is represented by a given component of the synthesized roughness morphology, e.g.,
    - Field 1: ellipsoids a/b=1.2, surface penetration, surface density, orientation parameters
    - Field 2➔n: shape variations
    - Field n+1➔m: striation, feathering and wave structures associated with down-skin vs. up-skin build



Year 1 Activities and Progress

DERM model development

Double-Averaged Conservation Equations for a Newtonian Fluid

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = -\frac{1}{\beta}\rho u_i \frac{\partial \beta}{\partial x_i}$$

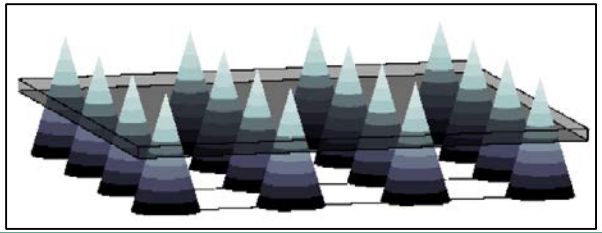
Mass Conservation

$$\begin{aligned}\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j + P\delta_{ij} + \frac{2}{3}\delta_{ij}\rho k - 2(\mu+\mu_t)S_{ij} + \frac{2}{3}(\mu+\mu_t)\frac{\partial u_k}{\partial x_k}\delta_{ij}\right) \\ = \frac{\mathbf{1}}{\boldsymbol{\beta}} \boldsymbol{f_i^p} - \frac{1}{\beta}\left(\rho u_i u_j + P\delta_{ij} + \frac{2}{3}\delta_{ij}\rho k \right. \\ \left. -2(\mu+\mu_t)S_{ij} + \frac{2}{3}\delta_{ij}(\mu+\mu_t)\frac{\partial u_k}{\partial x_k}\right)\frac{\partial \beta}{\partial x_j}\end{aligned}$$

Momentum Conservation

$$\begin{aligned}\frac{\partial \rho e_0}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j h + \left(\mu + \frac{\mu}{\sigma_k}\right)\frac{\partial k}{\partial x_j} - \left(\frac{c_p\mu}{Pr} + \frac{c_p\mu_t}{Pr_t}\right)\frac{\partial T}{\partial x_j} \right. \\ \left. -2u_i(\mu+\mu_t)S_{ij} + \frac{2}{3}(\mu+\mu_t)u_j\frac{\partial u_k}{\partial x_k} + \frac{2}{3}u_j\rho k\right) \\ = \frac{\mathbf{1}}{\boldsymbol{\beta}} \boldsymbol{f_i^p u_i} + \frac{\mathbf{1}}{\boldsymbol{\beta}}\boldsymbol{f^q} - \frac{1}{\beta}\left(\rho u_j h + \left(\mu + \frac{\mu}{\sigma_k}\right)\frac{\partial k}{\partial x_j} - \left(\frac{c_p\mu}{Pr} + \frac{c_p\mu_t}{Pr_t}\right)\frac{\partial T}{\partial x_j}\right. \\ \left. -2u_i(\mu+\mu_t)S_{ij} + \frac{2}{3}(\mu+\mu_t)u_j\frac{\partial u_k}{\partial x_k} + \frac{2}{3}u_j\rho k\right)\frac{\partial \beta}{\partial x_j}\end{aligned}$$

Energy Conservation



$\boldsymbol{\beta}$ = Void fraction

$\boldsymbol{d}$ = Element diameter

$$\int_{\Omega} \boldsymbol{f_i^p} = \delta \mathbf{F} = -\mathbf{u}\frac{2\mu}{\pi d^2}\beta(1-\beta)Re_d C_d \mathrm{vol}(\Omega)$$

$$\int_{\Omega} \boldsymbol{f^q} = \delta Q = 4\frac{k_f}{d^2}Nu_d \beta(1-\beta)(T_r - T_f)\,\mathrm{vol}(\Omega)$$

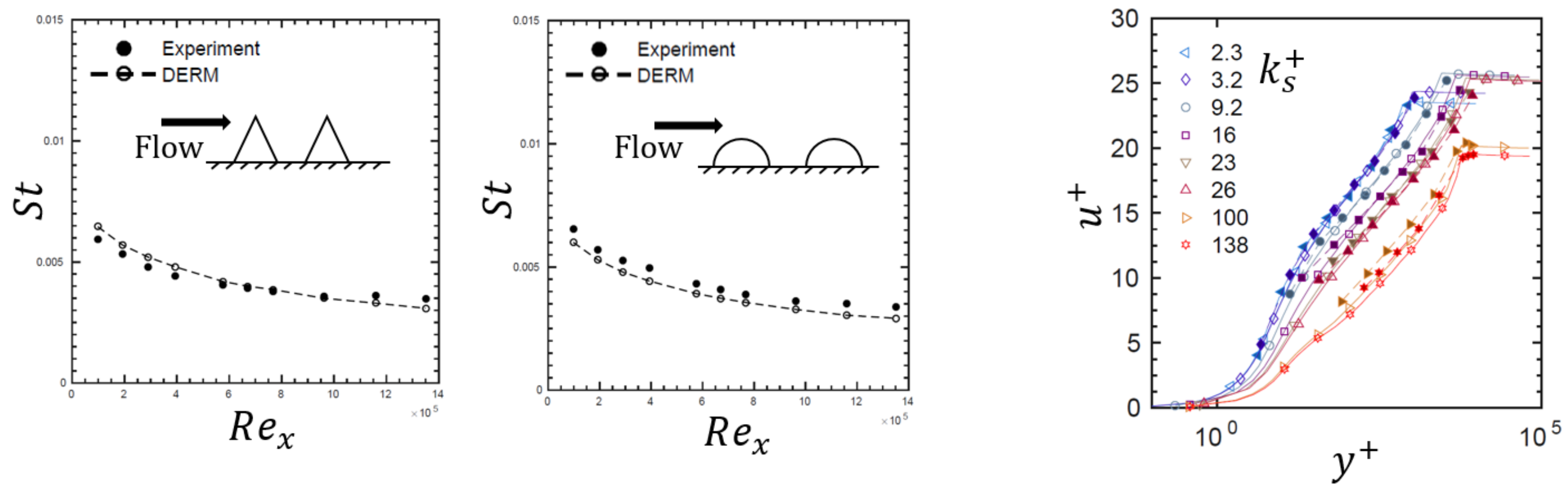
$$\mathrm{Re_d} = \frac{\rho d|u|}{\mu}$$ Roughness Reynolds Number

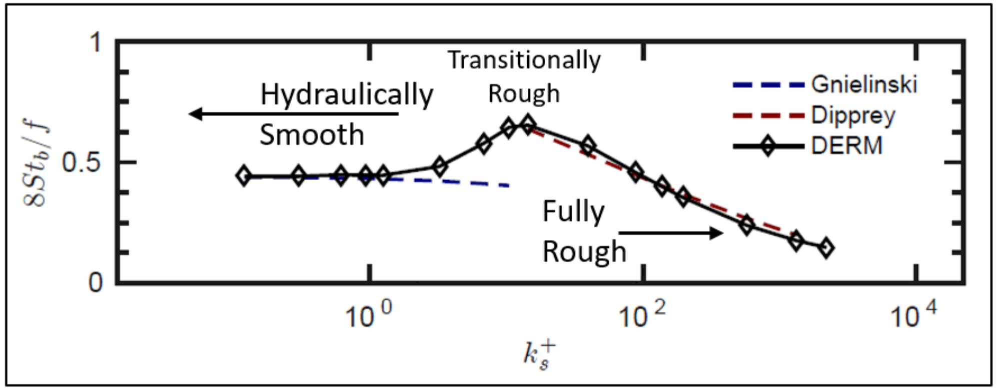
$$C_d = \begin{cases}\left(\frac{Re_d}{1000}\right)^{-0.125} & \text{if } Re_d \le 60000 \\ 0.6 & \text{otherwise}\end{cases}$$

$$Nu_d = \begin{cases}1.7Re_d^{0.49}Pr^{0.4} & \text{if } Re_d \le 13776 \\ 0.0605Re_d^{0.84}Pr^{0.4} & \text{otherwise}\end{cases}$$

Year 1 Activities and Progress
DERM model development

Legacy capability of DERM has been demonstrated for icing





Fully-developed roughened pipe flow

Periodic inflow/ outflow

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DERM model development

- Technology elements:
  - Rich shape families to characterize roughness (vs. cones, hemispheres)
  - Mathematically formal 3D averaging procedure consistent with modern Eulerian multiphase flow modeling (vs. 2D slices)
  - Drag model, viscous dissipation and turbulence attenuation/amplification are key – we do not have dispersion, virtual mass, surface tension, etc…
  - Heat transfer is as important as friction!
  - Shear and heat flux apportionment
  - Significant departure from equilibrium TBL
  - Resolution of sublayer and buffer layer

Students

- PSU PhD student Sam Altland started 6/18
- GE Cost share he spent summer 18 at GE Global Research as an intern working on working on flow testing (Δp and q”) for additively manufactured turbine-relevant specimens
- Research role in project:
  - Model development/calibration/validation/application
    - DNS
    - DERM
    - Optimization
  - Engine scale coupon testing (Δp and St)
    - GE
    - PSU
  - Possible activity in part manufacture and CT/OP/SEM

Students

- Baylor MS student Emily Cinnamon
- Baylor cost shared
- Research role in project:
  - Design, validation and implementation of the convection measurement version of the Roughness Internal Flow Tunnel (RIFT)

Personnel

- Leslie Wright left Baylor in Spring and has left the project
- Mike Kinzel left Penn State ARL in Summer and remains involved pro-bono on the DERM modeling

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Publications

Proceedings of ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition
GT2019
June 17-21, 2019, Phoenix, Arizona, USA

GT2019-90931

FLOW IN A SCALED TURBINE COOLANT CHANNEL WITH ROUGHNESS DUE TO ADDITIVE MANUFACTURING

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ABSTRACT

Additive manufacturing (AM) approaches such as Laser Powder Bed Fusion (L-PBF) are being explored to reduce manufacturing costs of gas turbine components. Surfaces of additively manufactured components exhibit distinctive roughness characteristics that significantly affect the pressure losses and heat transfer. For this study, a coupon with a vertical internal flow passage was created using L-PBF and characterized using x-ray tomography. The roughness pattern was extracted using the spanwise-planar extraction approach. Also, two surfaces consisting of distribution of ellipsoids were created to capture the important statistical characteristics of the original rough surface. The resulting roughness geometries were scaled

passages for gas turbines can be designed and optimized in ways not possible with cored-casting approaches.

AM offers significant design advantages but also presents unique challenges for engine-scale cooling channels. The most relevant AM approaches are laser powder bed fusion (L-PBF) approaches. The process creates surface roughness because of the layered-powder structure that differs depending on the material, build parameters, and the orientation of the surface during the manufacturing process.

The roughness inherent to L-PBF cooling channels is especially important to the resulting pressure-loss and heat transfer because of its large size in relation to the channel dimensions. The equivalent sand-grain roughness height for an

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Publications

71st Annual Meeting of the APS Division of Fluid Dynamics

Sunday–Tuesday, November 18–20, 2018; Atlanta, Georgia

Session M32: DNS, LES and Hybrid RANS Applications
8:00 AM–10:10 AM, Tuesday, November 20, 2018
Georgia World Congress Center Room: B404

Abstract: M32.00002 : Direct Numerical Simulation of Additively and Conventionally Manufactured Internal Turbine Cooling Passages*
8:13 AM–8:26 AM

← *Abstrac*

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Summary

- Elements of project:

1. Up scaling of manufactured and tested L-PBF channels
2. 100x wind tunnel testing: $\Delta p/C_f$ and velocity profiles for 7 configurations
3. Fully resolved roughness RANS – large calculations

Generally, engine scale, up-scale and RANS agree fairly well, abeit most robustly with real geometry. Not so great for surrogate surfaces. But of course resolved RANS is infeasible for design.

4. DNS has been stood up in code and validated for these channels and roughness morphologies have been introduced.
5. DERM has been stood up in code – runs 100s of times as fast as roughness resolved RANS.

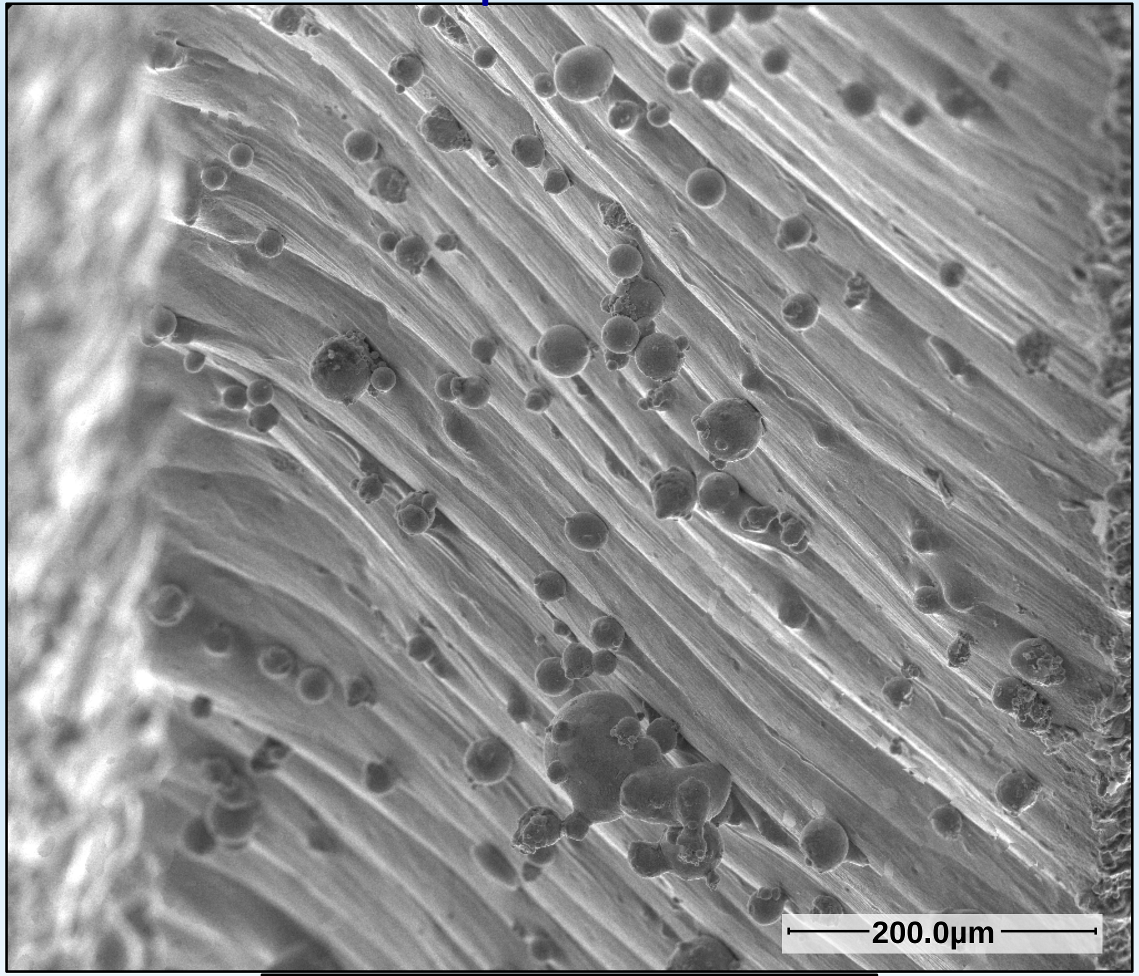
Current/next steps

- Advancing DNS towards “as built” and surrogate roughness morphologies
- Heat transfer and PIV in Baylor channel
- DERM:
  - Start with ellipsoidal surrogate since this can be formulated i/t/o analytical volume fraction field
  - Develop more accurate and calibrated model for different built parameters/roughness morphologies
- Manufacture and study other more parts/build parameters
- Optimization work not yet begun but will once we have a reliable DERM tool in hand

BACKUP

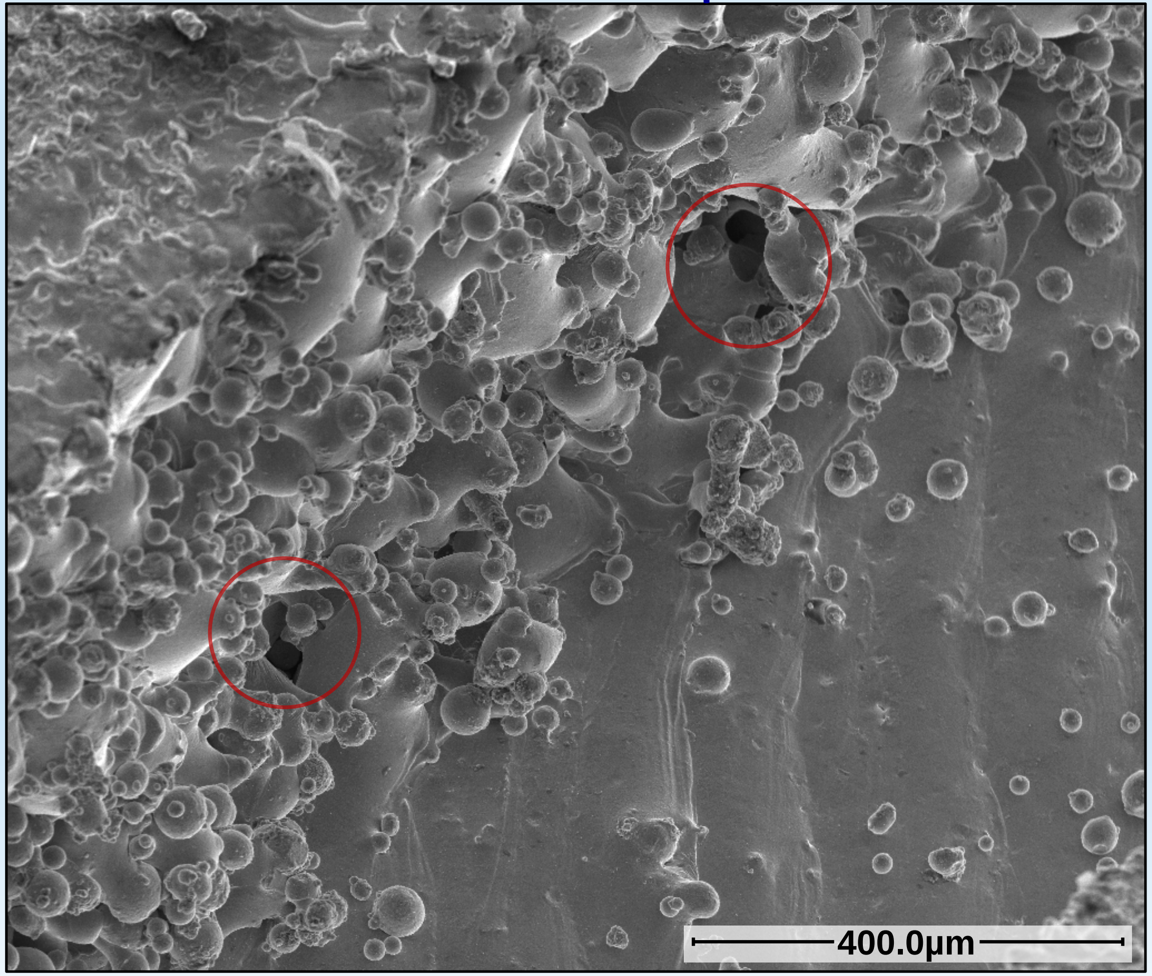
As-built AM surfaces have high levels of roughness with different characteristics

Upskin Surface



Partially melted powder particles and layer striations

Corner of Downskin and Upskin Surface



Large dross formations and high level of partially melted powder particles

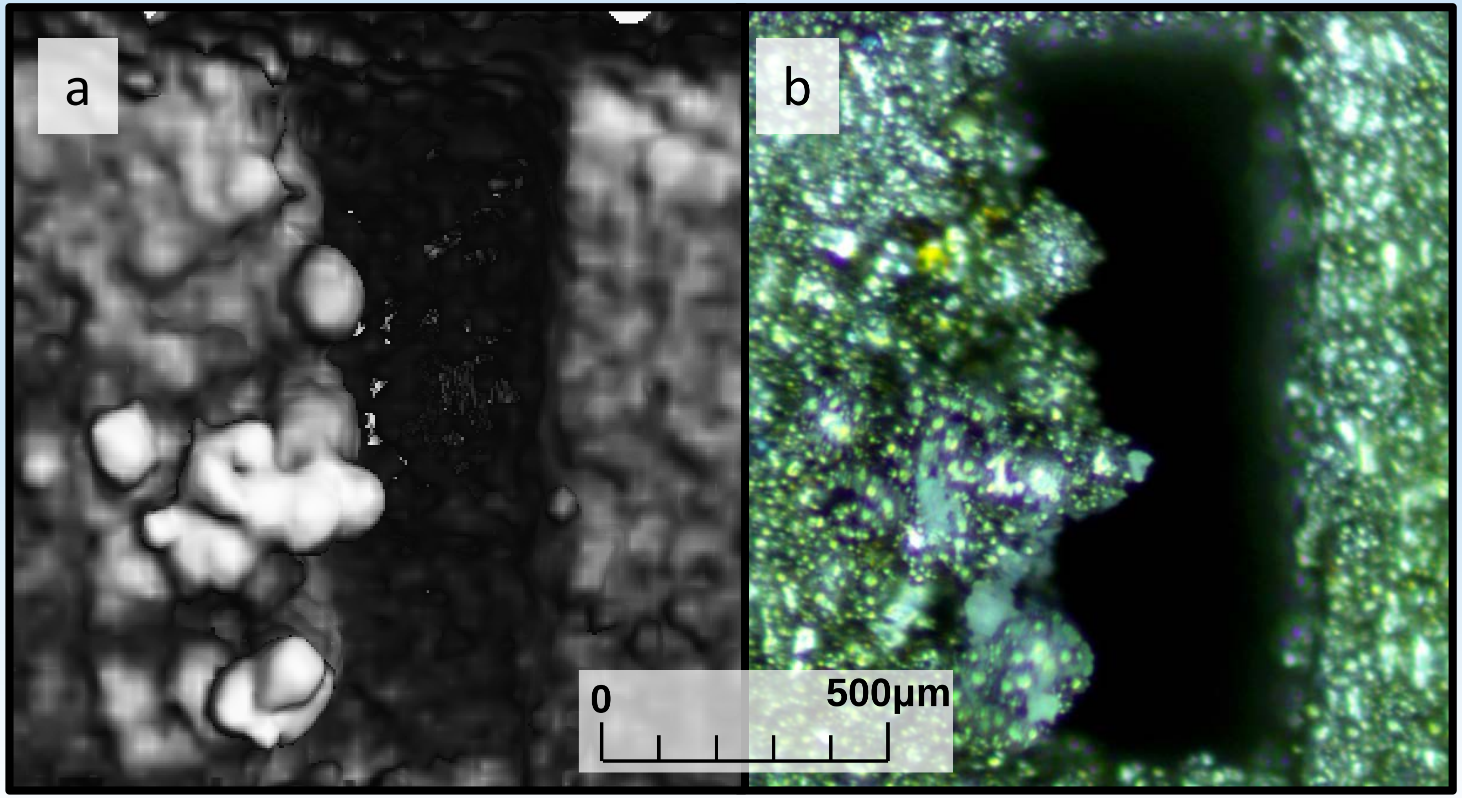
PennState Mechanical Engineering

BAYLOR UNIVERSITY

An industrial CT scanner is used to characterize the geometry of each coupon

v|tome|x m	VG Studio
CT Scanner	Surface determination
Voxel size: 23-32 µm	accuracy: ± 2-3 µm

CT Scan **Light Microscope**

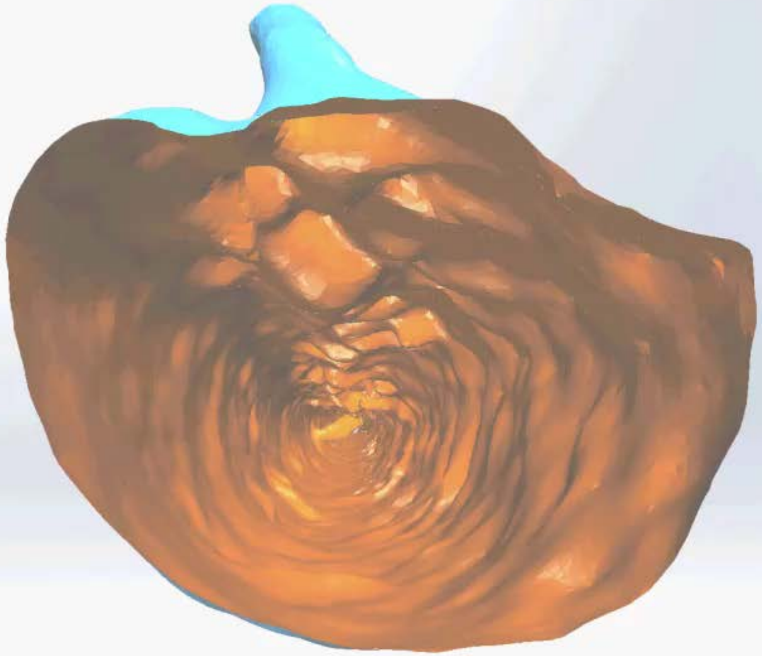


CT scans of cylindrical channels

Vertical

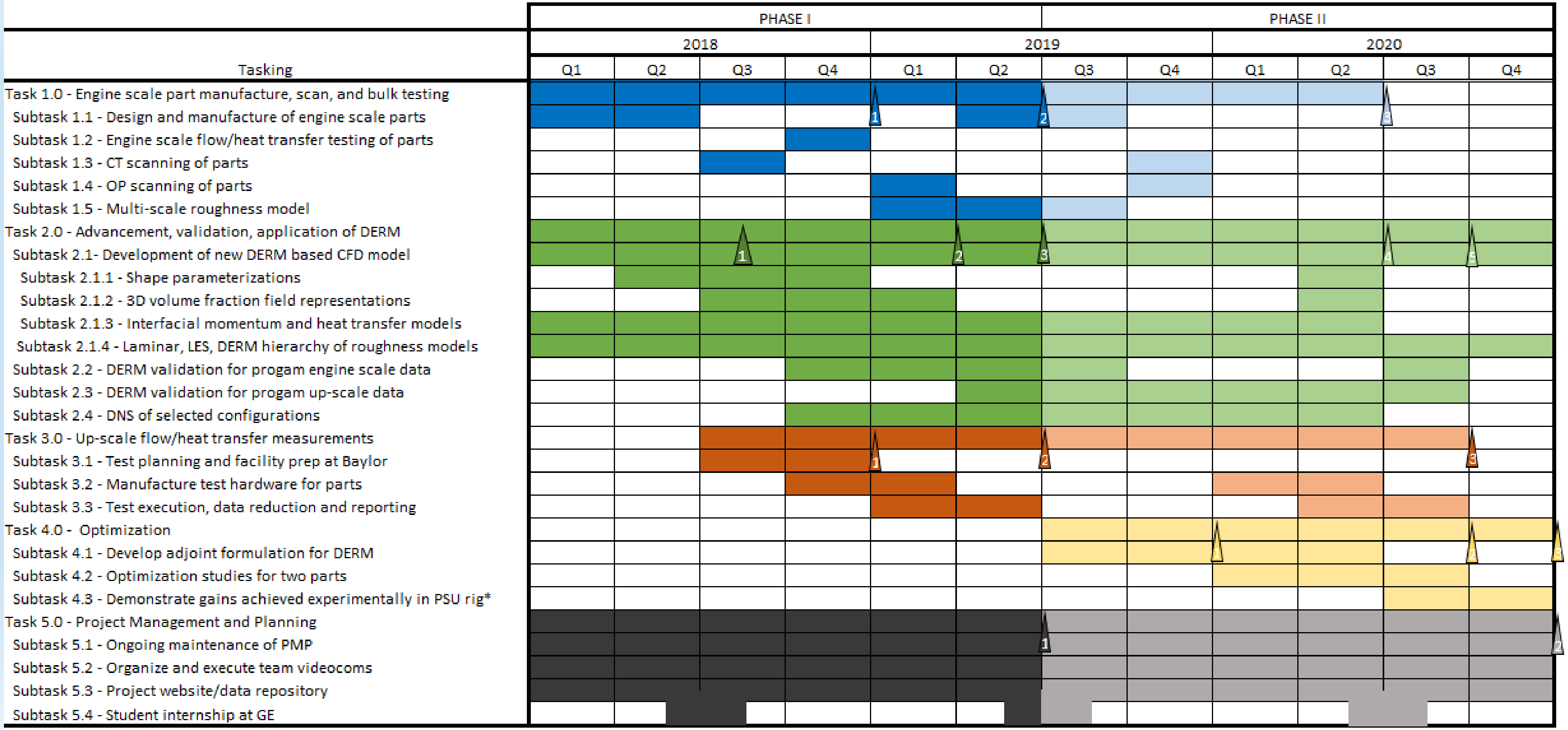
R_a = 8.4µm

Horizontal



R_a = 16.1µm

SCHEDULE



*Note per discussion in "Technical Background and Detailed Technical Approach" that Task 4.3 will be carried out only if resources become available through successful attempts to do multiple PBF part builds at once (i.e., enabling a total of 5 parts in 4 builds)

budget

- DOE+Cost Share

Organization	Year 1	Year 2	Year 3	Total
PSU	170,280	146,869	151,081	468,230
Baylor University	71,354	67,964	68,798	208,116
GE		37,197	37,197	74,394
Total	$241,634	$252,030	$257,076	750,740

	Year 1	Year 2	Year 3	Total
Cost share:	$11,900	$48,747	$90,093	$150,740

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

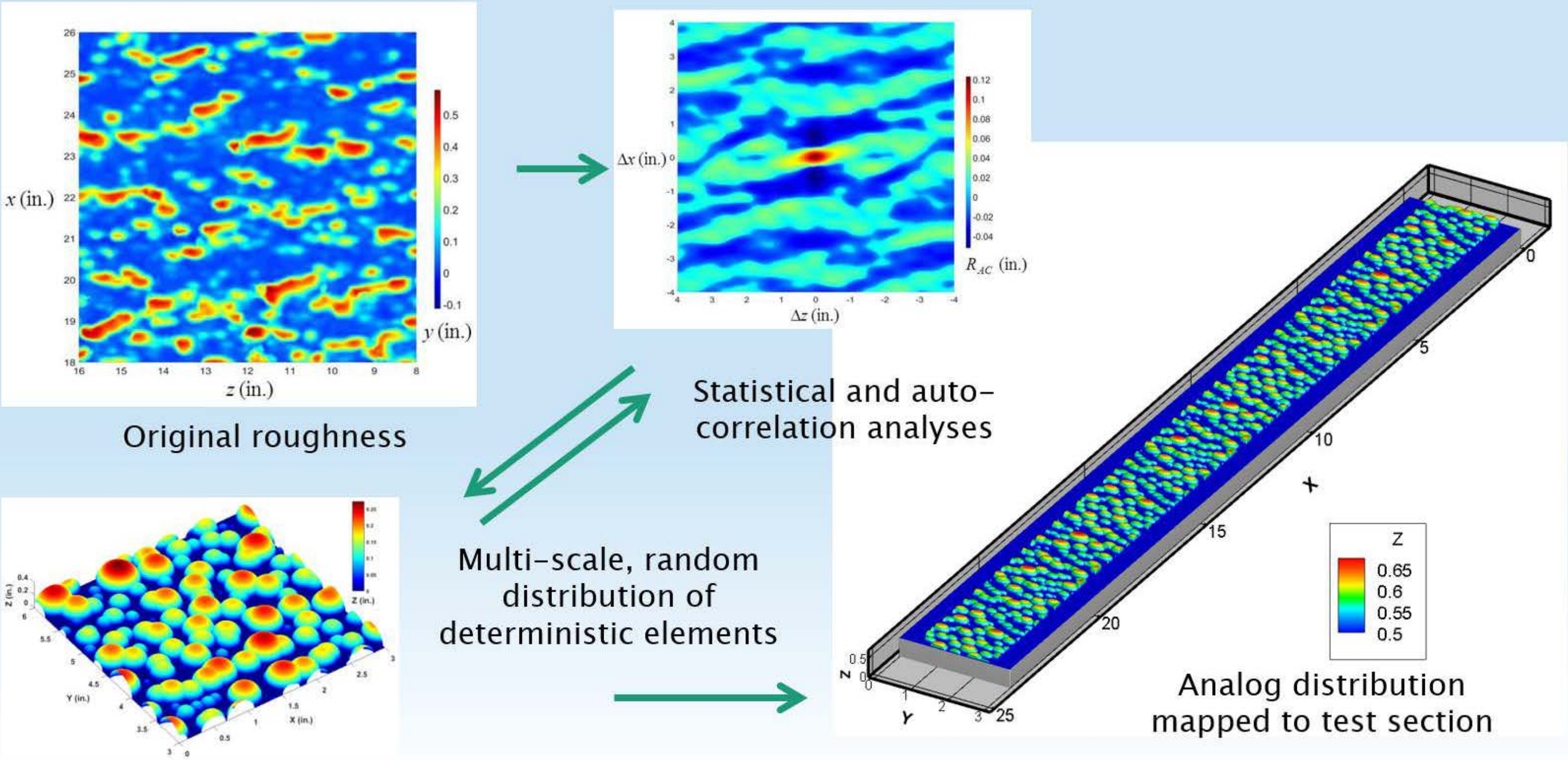
skewness, $Skw = \frac{1}{R_q^3}\left[\frac{1}{N_P}\sum_{i=1}^{N_P}(Y'^3)\right]$

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

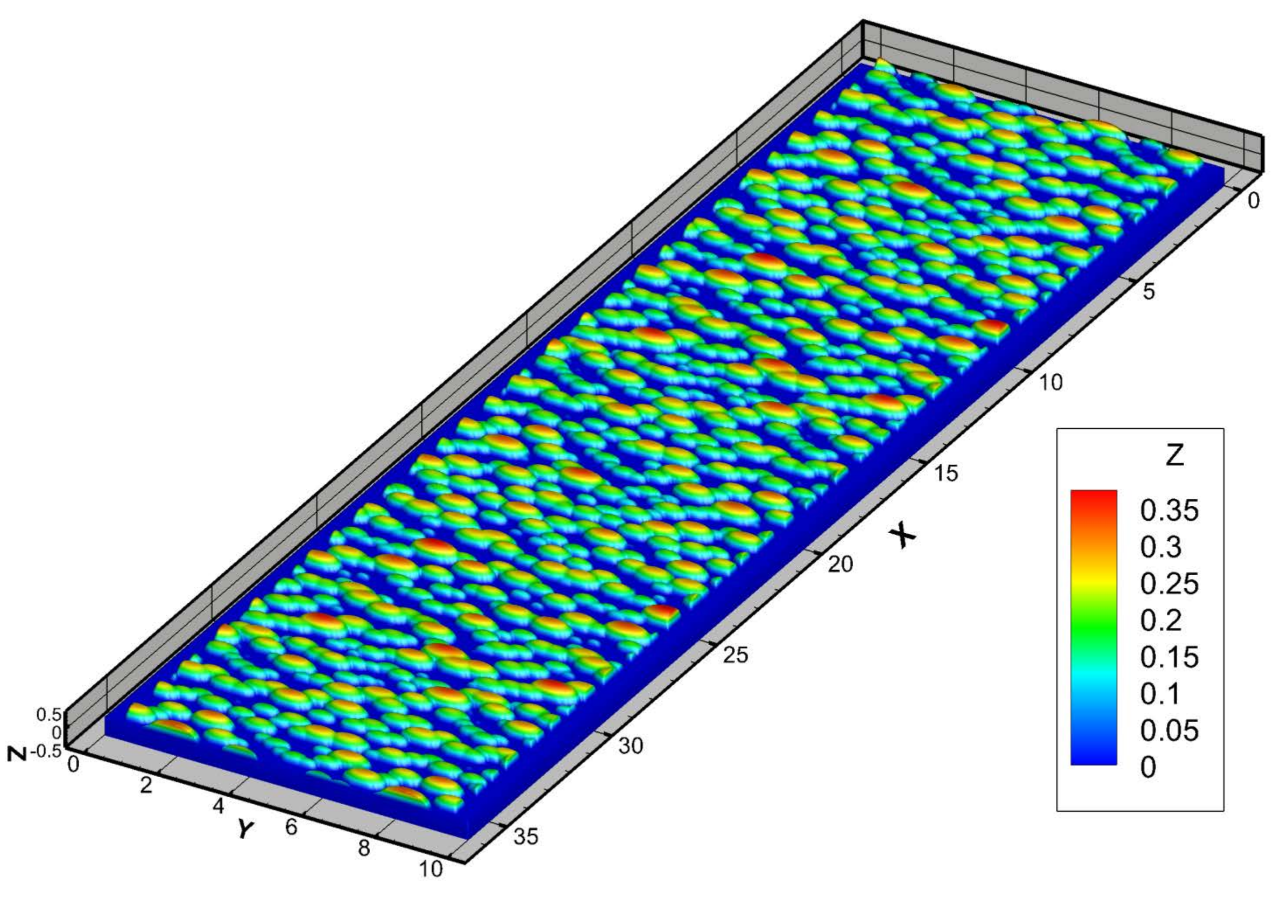
Surface Modeling

- Use CT or optical profilometry scans to generate unwrapped roughness
- Create surface panels with
  - Original real roughness mapped to wall
  - Analog/proxy surfaces using statistical and auto-correlation analyses

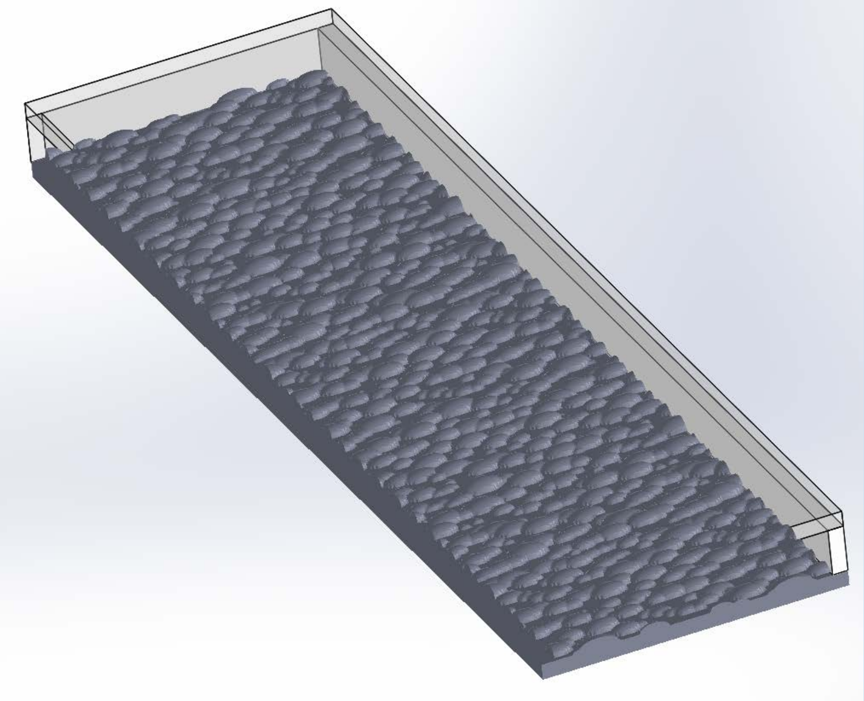


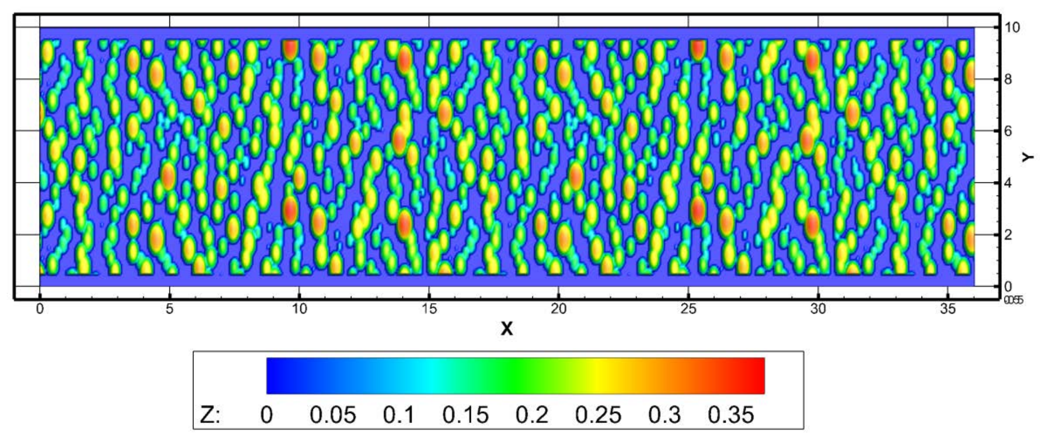
Roughness Scaling

- SLM R_a ~ 8-16μm from Snyder et al. (2015)
- R_q ~ 20μm based on R_a
- Peak-Valley (R_{PV}) on order of 5-6 times R_q
- Hydraulic diameters ranging from 0.38 mm to 3.18 mm
- R_{PV}/D_h ranging from 4% to 25%
- Mid-range in image to right (14%) using semi-deterministic distribution

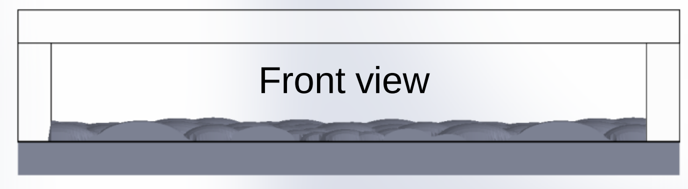


Perspective in Channel





(Dimensions in inches)



Baylor upscale activity: Channel HT and Fluid Diagnostics

- Flow diagnostics with V3V system from TSI
  - Particle tracking mode (5cm by 5cm by 2cm volume)
  - Hot-wire measurements will be a backup
  - Static pressure gradient measured (skin friction on rough wall measured using historical Schlichting (1936) approach as modified by Coleman et al. (1983)
- Heat transfer using infrared thermometry in steady state
  - FLIR SC4000 with 25-mm lens
  - Plate heated using gold thin-film heaters or Kapton heaters
- Roughness panels printed using Dimension 1200es FDM

GE specification of test hardware configurations

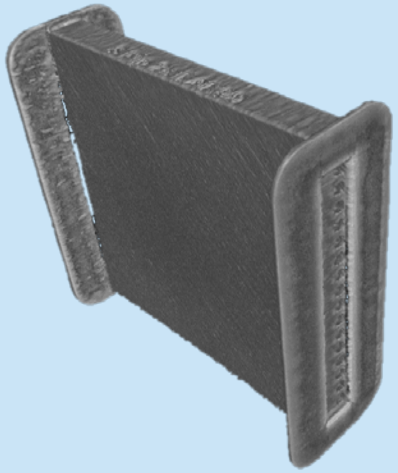
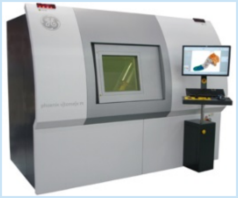
- GE Priorities:
  1. Straight channels
  2. Nominally circle, ellipse, square cross sections
  3. 15-130 mil nominal diameters ($\cong$ 0.4-3.0 mm)
  4. Re up to 30,000
  5. Build direction parameterization
  6. Powder choice parameterization

GE specification of test hardware configurations

- PSU team can handle this range:
  - PBF build
  - CT (including micro-CT [3um resolution])
  - OP
  - Maybe SEM (budget/calendar)
  - Definitely can handle all range in engine scale Δp, St rig
- Good news is that we have circular cross section data we can send to Baylor **<u>now</u>**

PSU inspection techniques to characterize dimensions and surface roughness

Industrial CT Scanning

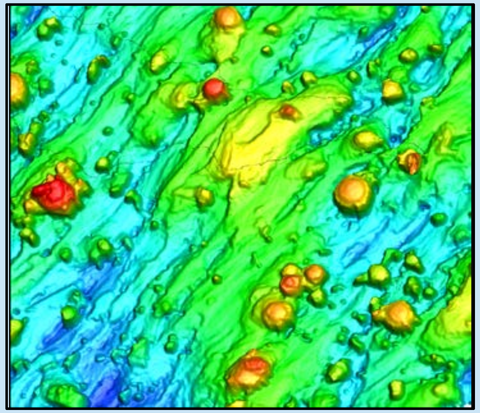



Full 3D reconstruction of part with ~ 35µm resolution

Non-destructive measurements of internal dimensions

Preliminary non-destructive internal surface roughness measurements

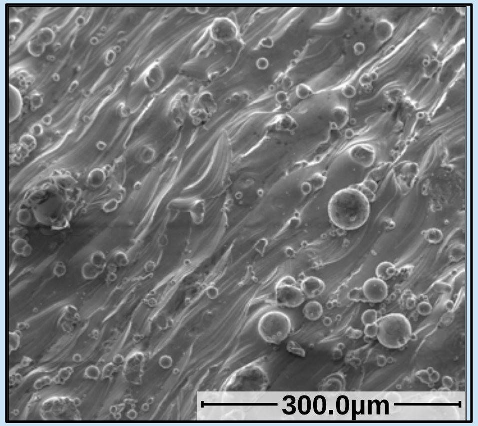
Optical Profilometer




Quantitative line of sight images with < 1 µm resolution

Destructive measurements of internal surface roughness

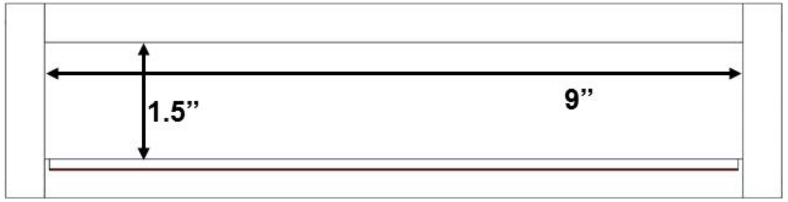
Scanning Electron Microscope



Semi-quantitative 3D images of surface with << 1 µm resolution

Detailed inspection of surface morphology

Year 1 Activities and Progress

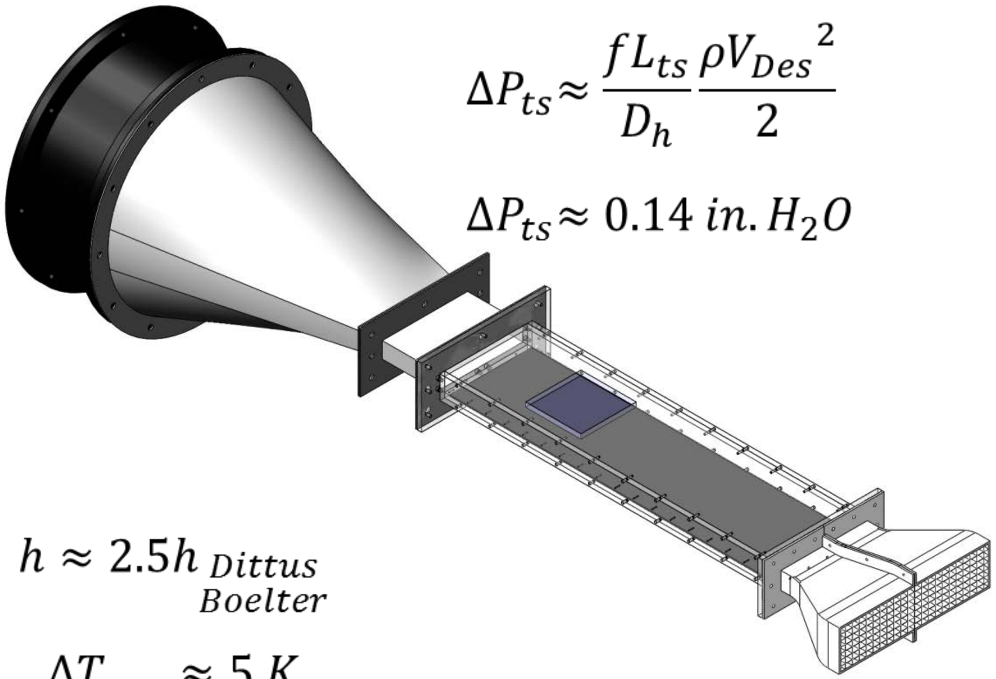


Channel Cross Section

$$Re_{D_h} = \frac{\rho D_h V_{Des}}{\mu} = 30{,}000$$

$$V_{Des} = 7.1\, m/s$$

$$Q_{Des} = 130\, cfm$$

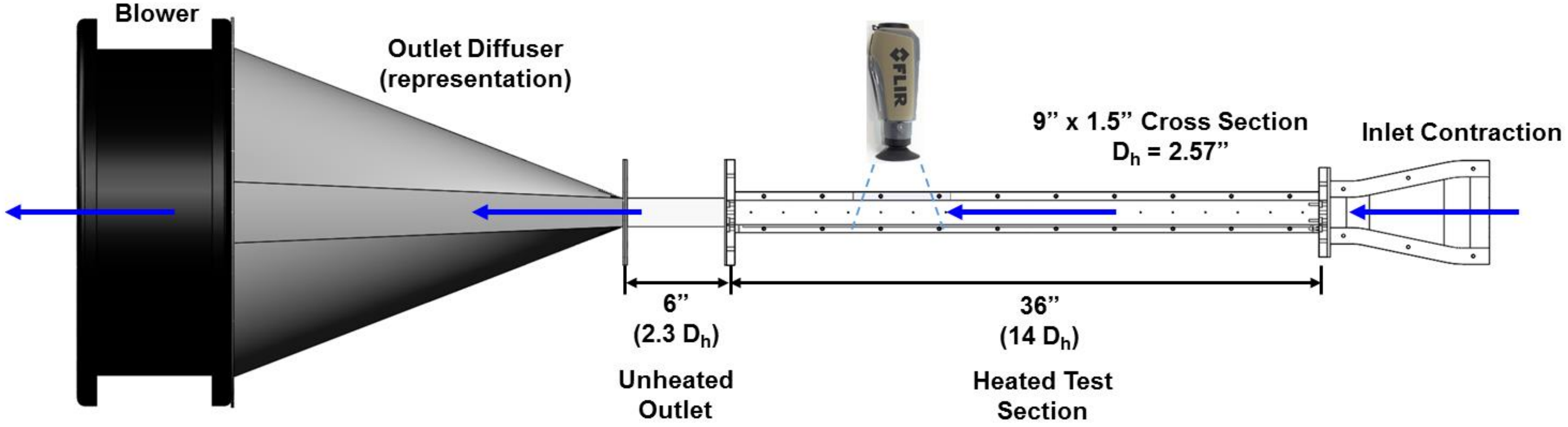


$$\Delta P_{ts} \approx \frac{f L_{ts}}{D_h} \frac{\rho V_{Des}^{\;2}}{2}$$

$$\Delta P_{ts} \approx 0.14\, in.\, H_2O$$

$$h \approx 2.5 h_{\substack{Dittus \\ Boelter}}$$

$$\Delta T_{s-a} \approx 5\, K$$

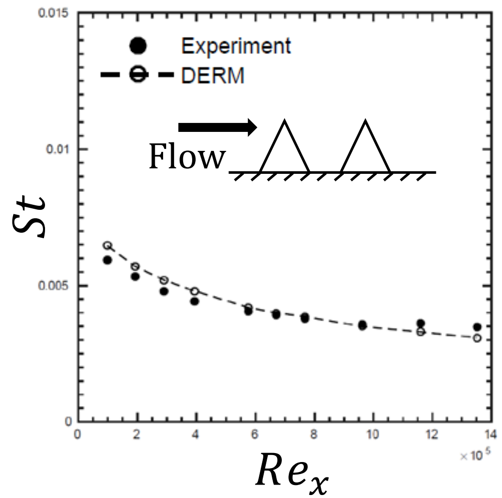


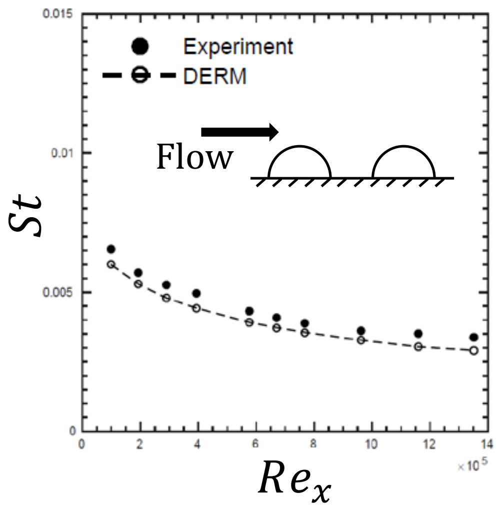
Year 1 Activities and Progress

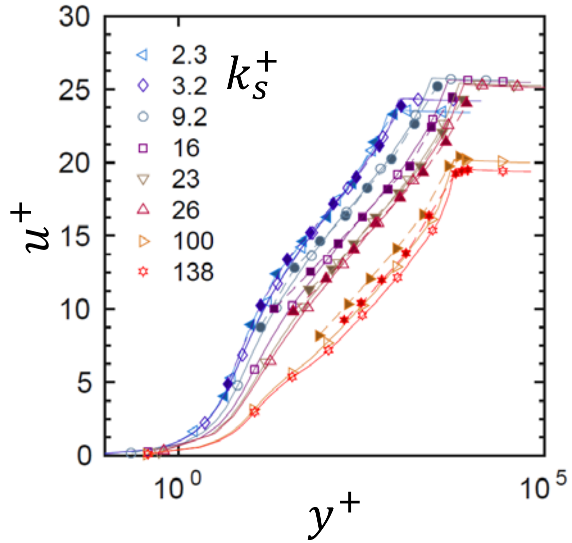
Up-Scale Experiments

- Upcoming facility upgrades for heat transfer measurements:
  - Impose steady state constant flux conditions using either gold thin film heaters or traditional Kapton resistive heaters. Flux meastrued by standard DC or AC electrical measurements and subtracting spanwise and sub-plate conduction losses. A FLIR infrared camera will be used for measuring average surface temperatures

Year 1 Activities and Progress
DERM model development







Experiment reported in Mart, McClain, and Wright, 2003; “Turbulent Convection from Deterministic Roughness Distributions with Varying Thermal Conductivities.” Journal of Turbomachinery