Aeroheating Testing of the Mars Sample Return Earth Entry System with Surface Roughness

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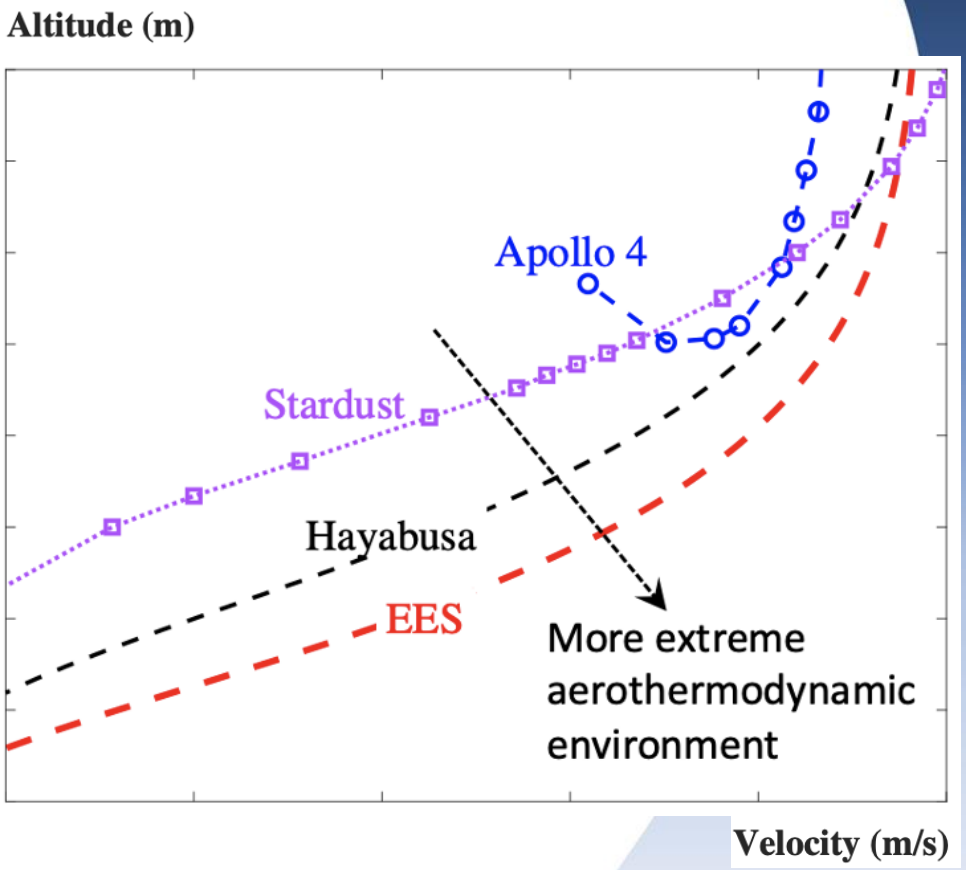
Motivation and Background

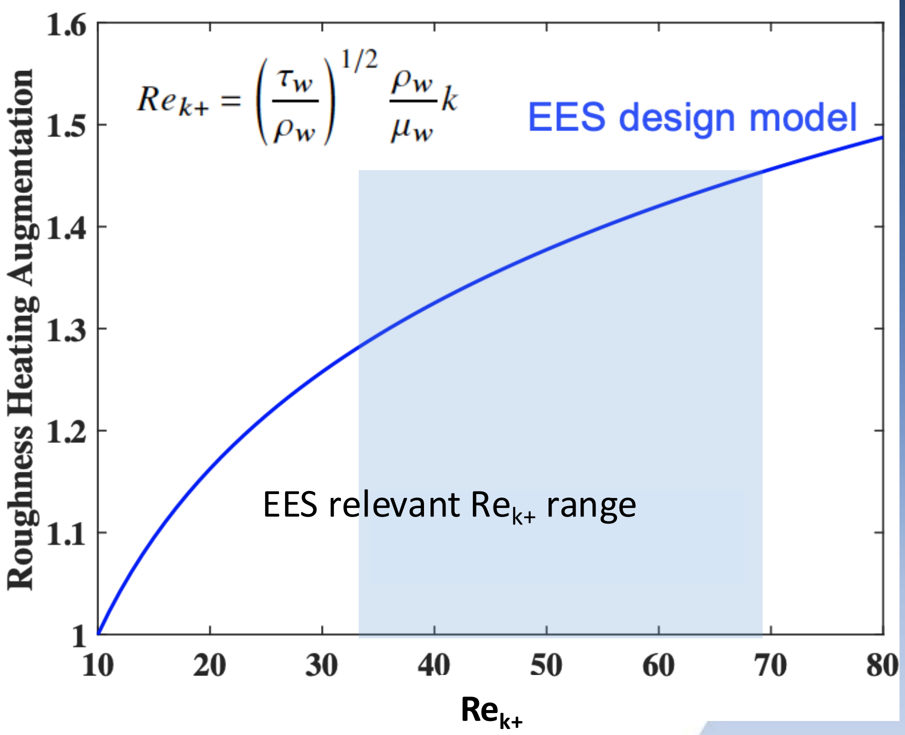
Unprecedented Aerothermal Challenges

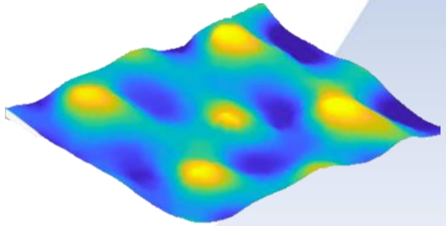
- The Earth Entry System (EES) vehicle concept is a 1.3-m diameter 52.5-deg sphere cone forebody with a woven 3-D Mid-Density Carbon Phenolic (3MDCP) Thermal Protection System (TPS)
  - NASA has never flown a 52.5-deg sphere cone forebody nor a woven TPS before
- Its steep entry flight path angle and large size would result in a much more extreme aerothermal environment than past NASA Earth missions



MSR-EES Computational Modeling Overview

- Computational solutions are obtained with NASA CFD solvers LAURA and DPLR
  - Cebeci-Smith turbulence model is used for attached flow regions
  - Only LAURA solutions were used for comparisons to wind tunnel measurements
- Dahm roughness model is used to obtain convective heating augmentation factor
  - Correlation based on Re_{k+} (roughness Re)
  - Applied as a post-processing step to turbulent CFD convective heating predictions
  - Post arc-jet 3MDCP samples from turbulent tests scanned to obtain simulation roughness height

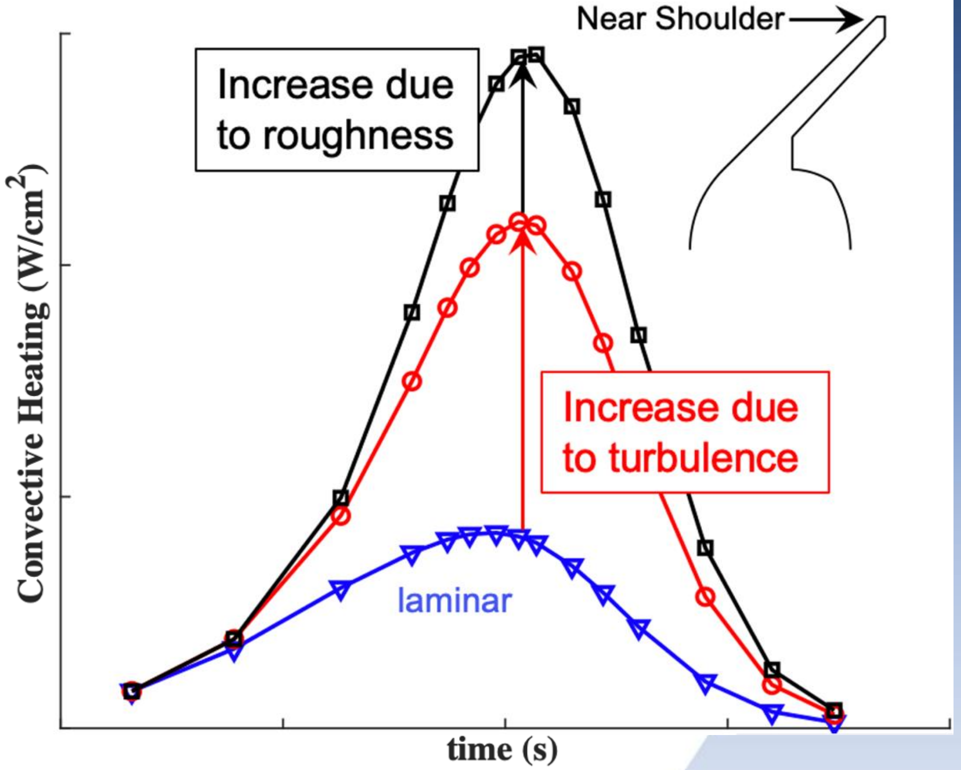




Post arc-jet scan of 3MDCP sample

NASA Langley Mach 6 Test Campaign

- Sufficient EES relevant experimental convective heating measurements did not exist:
  - On a 52.5-deg sphere cone geometry
  - For woven patterned surface roughness
  - With supersonic flow present near roughness elements
- Test campaign was performed at NASA Langley 20-inch Mach 6 air tunnel to reduce uncertainties
  - Goal: obtain turbulent convective heating data on a 52.5-deg sphere cone geometry on a representative woven roughness pattern and **at EES relevant Re_{k+} values**
- Data were obtained using phosphor thermography, mapped, and compared to simulation

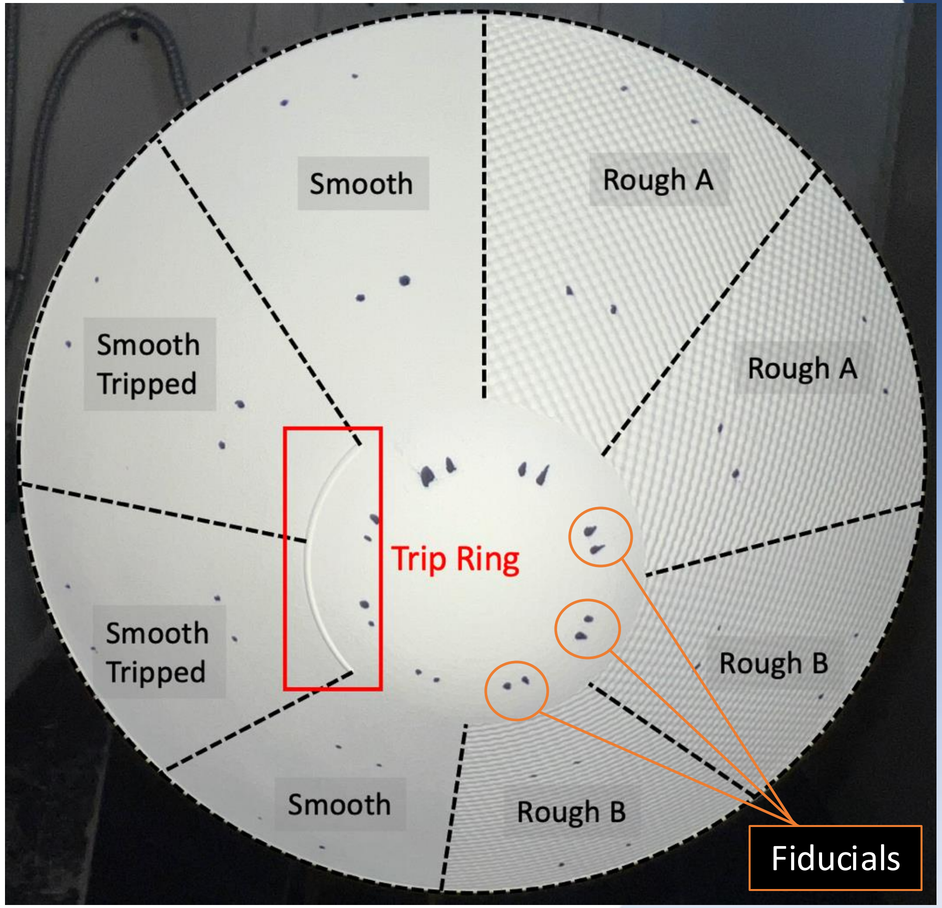


Near shoulder convective heating predictions

Data Acquisition and Reduction

MSR-EES Model Overview

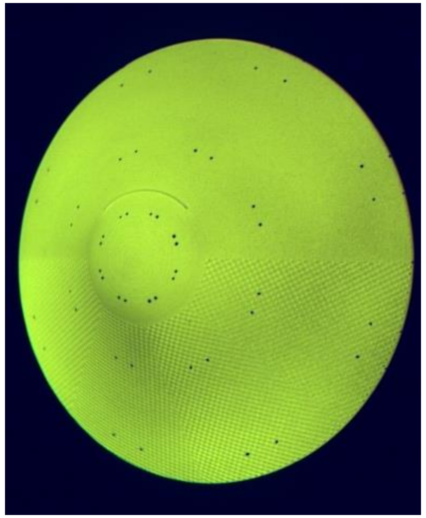
- Models were cast with a segmented forebody, which had distinct panels
  - Enabled simultaneous measurement of smooth-wall laminar, turbulent, and rough-wall convective heating data
- For first test entry, six models with varying roughness parameters were run at $\alpha = 0°$
  - Top and bottom rough panels differed in weave orientation
  - Fiducials are used for mapping image data on to geometry of model surface



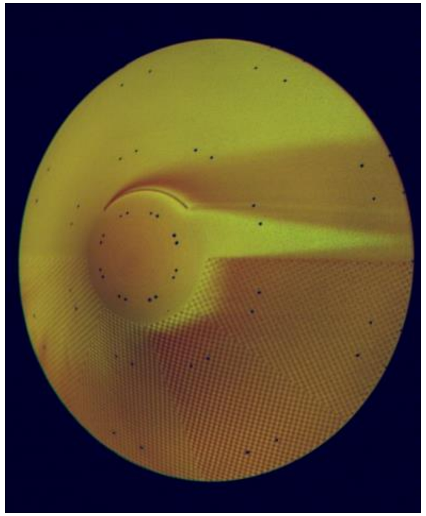
52.5-degree sphere cone model with panels denoted

Legacy Step Method Workflow [Analytical]

Prerun

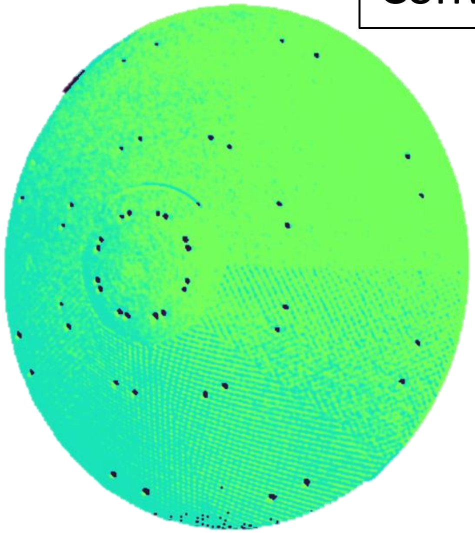


Single Run Frame



Phosphor Intensity Images

Converted to Temperature



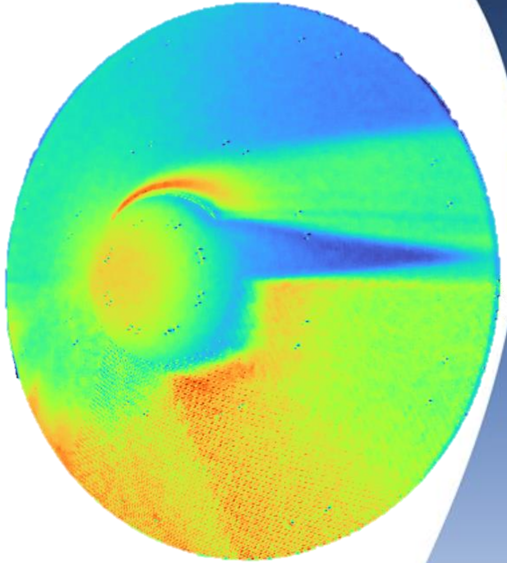
Δt

Obtain C_H assuming:

Semi-infinite model

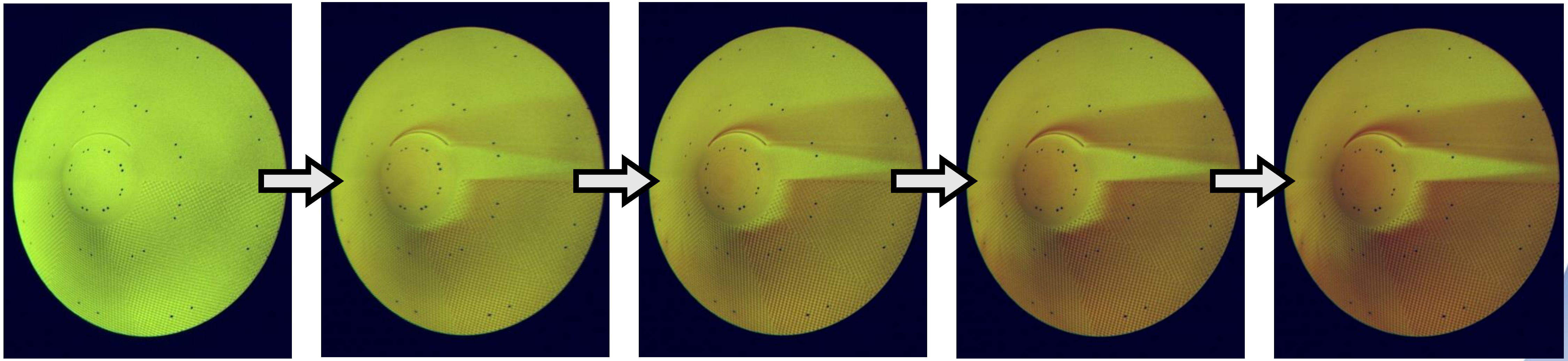
Constant material properties

C_H is a step function



Patch Integral Method (PIM) Workflow [Numerical]

Convert All Phosphor Intensity Image Frames to Temperature



Injection data gap is "patched" and 1-D heat conduction equation is solved at each pixel

- Prerun image is used as initial condition
- Phosphor measurements used as boundary condition (backside is treated as adiabatic)

$$\rho C_p\left(\frac{\partial T}{\partial t}\right) = \frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right)$$

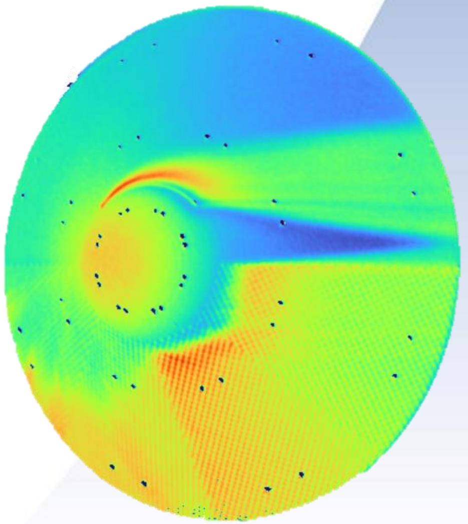
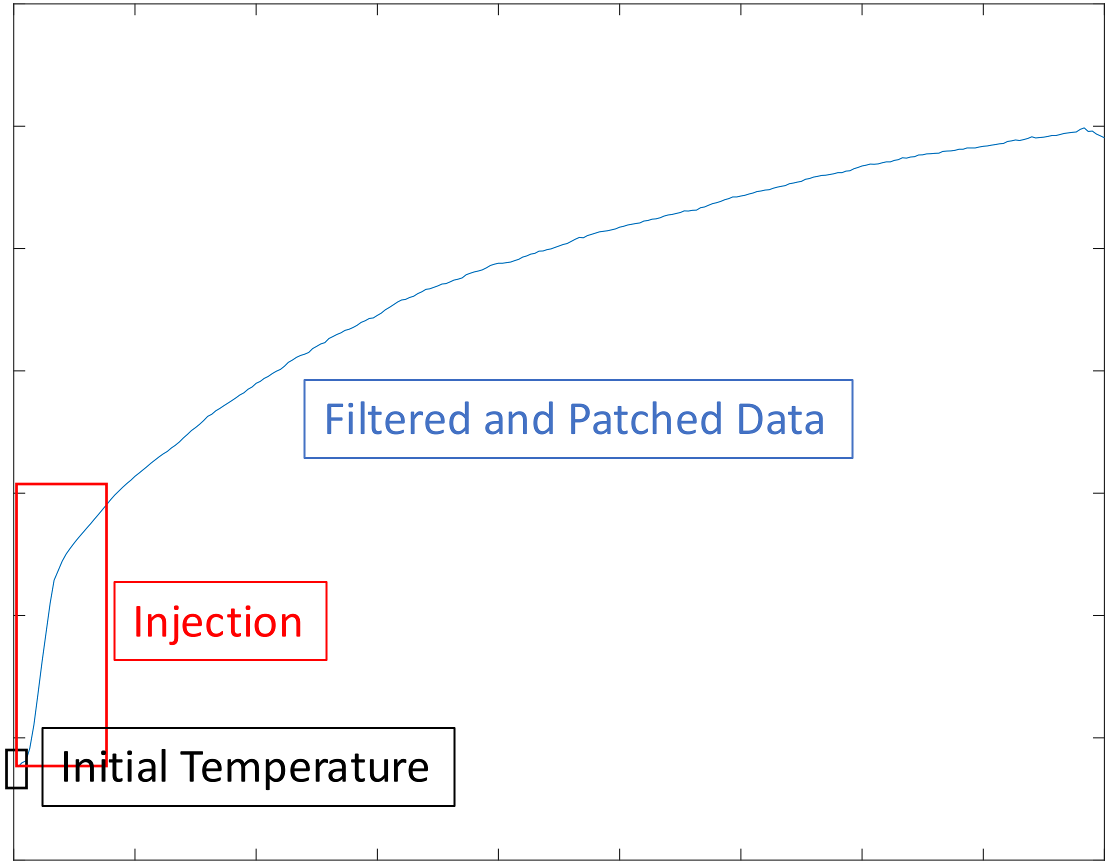
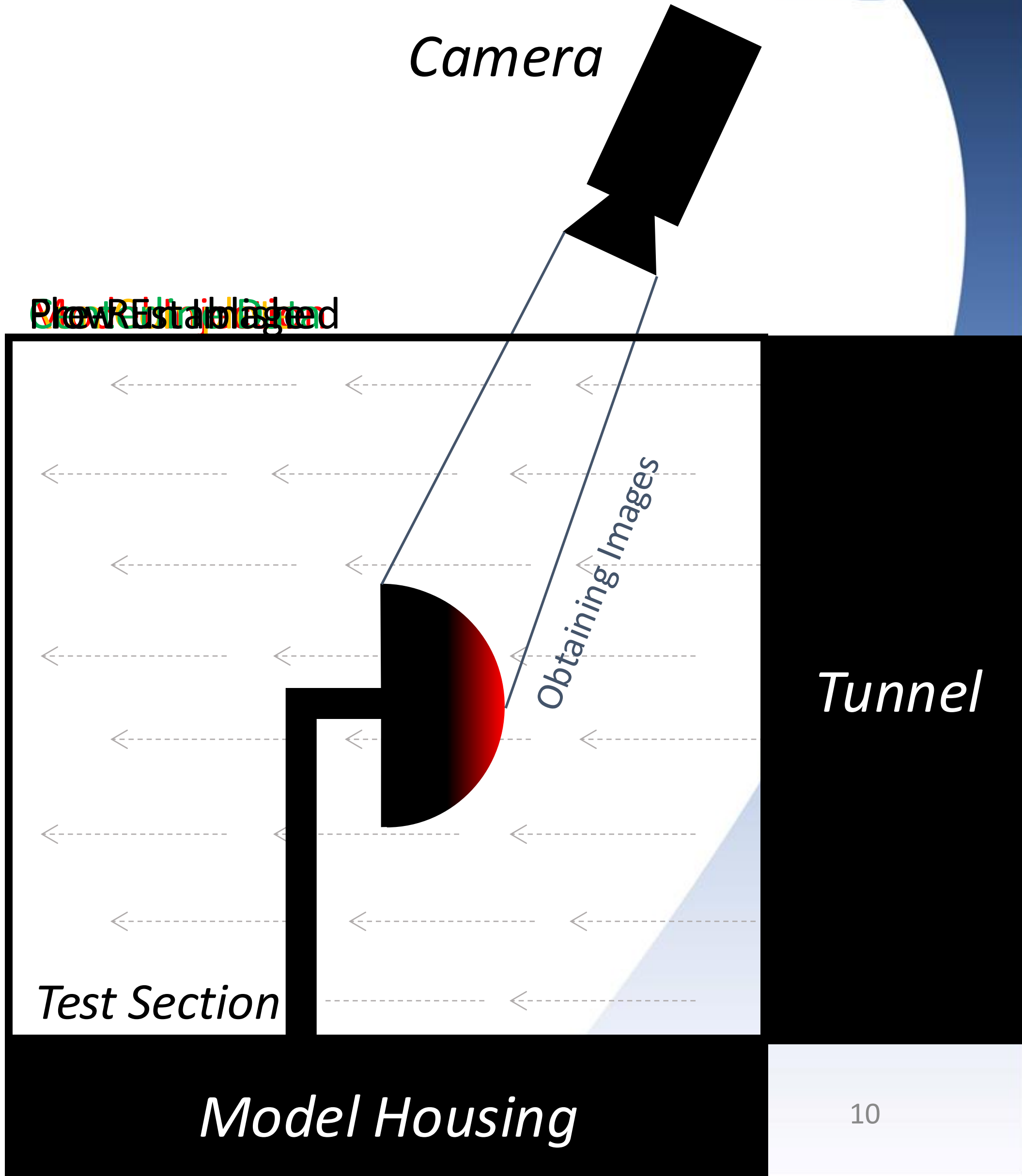


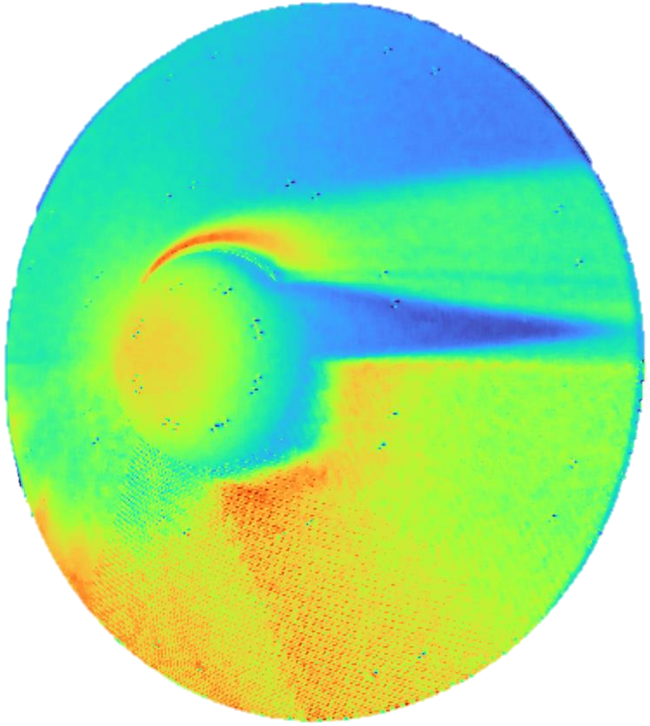
Illustration of Injection and Patching



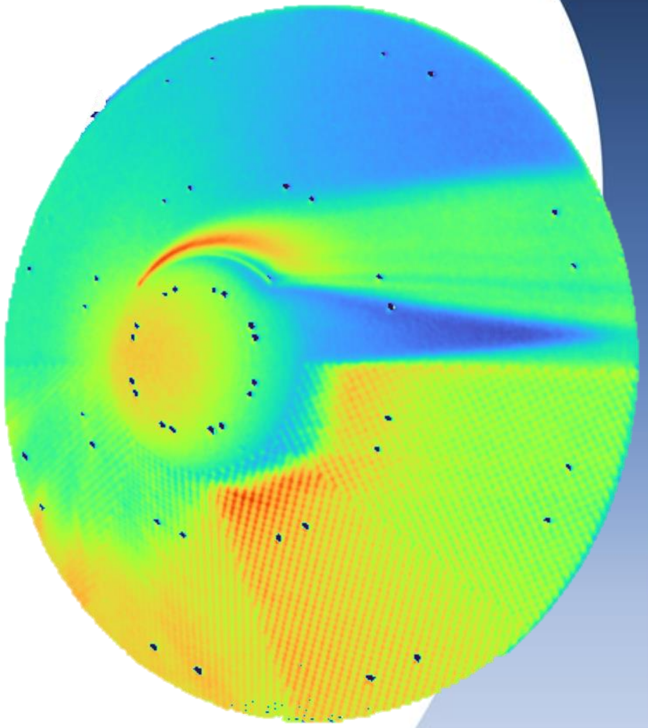


PIM Key Improvements

- PIM offers many benefits over the step method:
  - No approximation of CH
  - No semi-infinite assumption
  - Directly models variation in material properties
  - More resilient to uncertainties in data acquisition
  - Improved filtering and integral heat transfer solver better resolves surface features



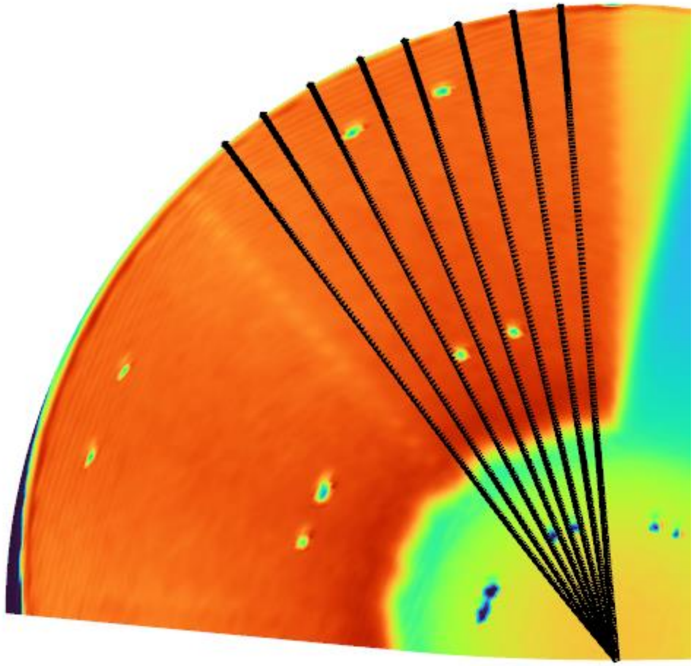
Step Method Heating

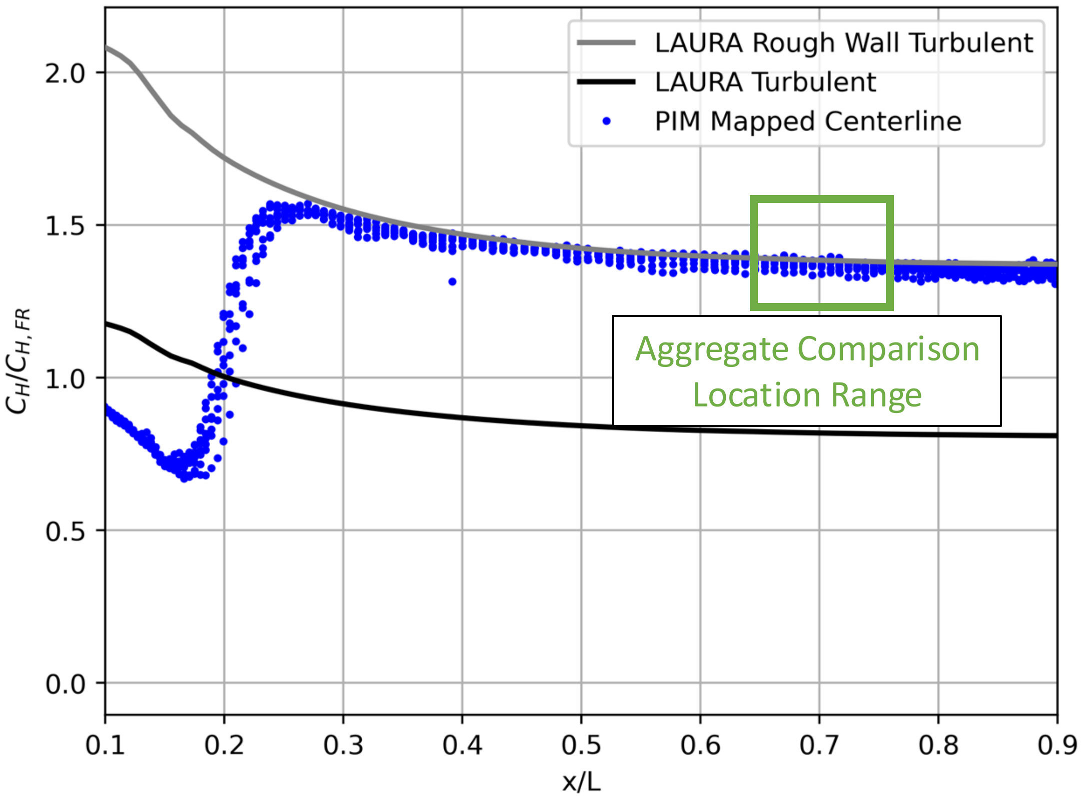


PIM Heating

PIM Mapping And Comparisons to Simulation

- PIM heating data are mapped to model surface using an affine transformation
  - Line cuts of mapped data are directly compared to simulation
  - For aggregate comparison plots, experimental data are averaged from x/L = 0.65 to x/L = 0.75

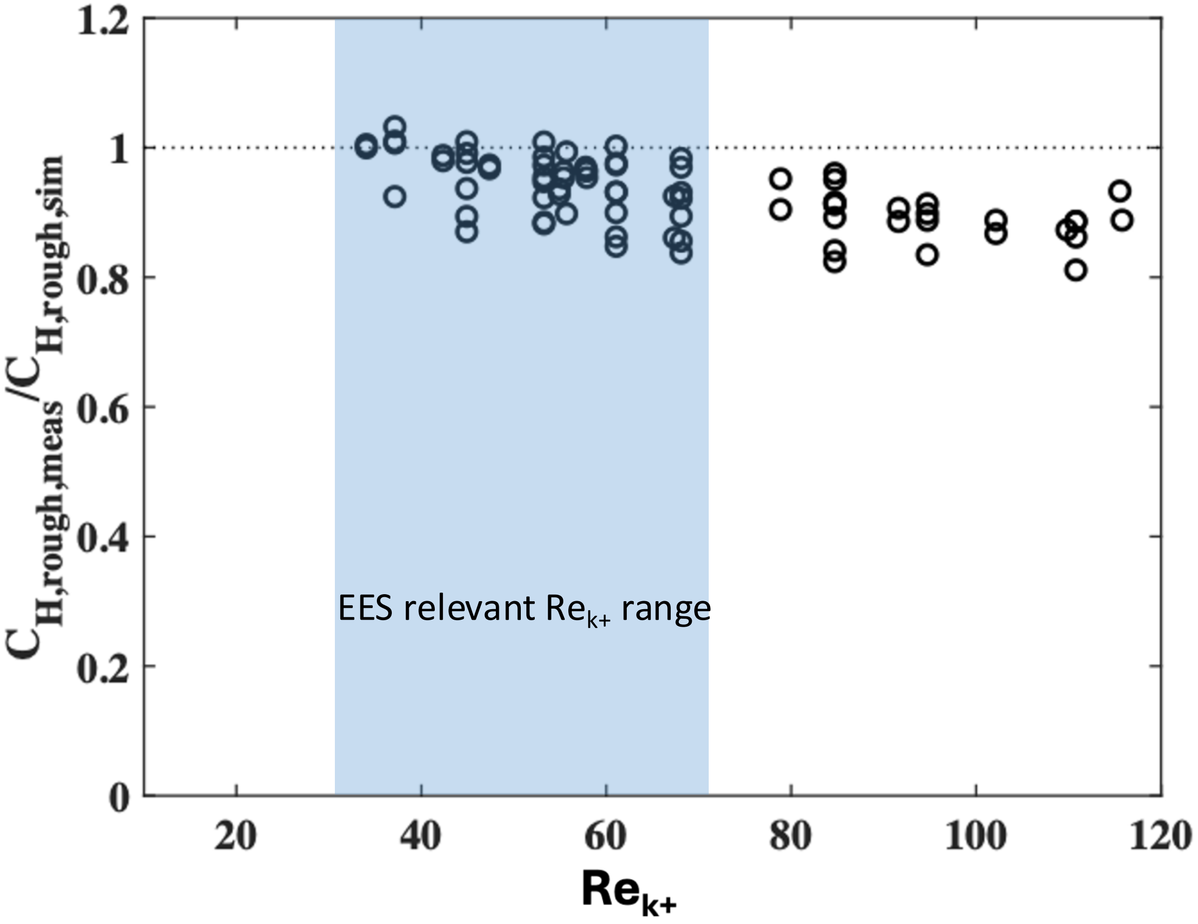




First Test Entry

Aggregate Roughness Heating Comparison

- Experimental measurements and simulation agreed within 20%
  - Provided confidence that Dahm roughness model is sufficient upper bound for convective heating augmentation for woven roughness
- Models were run at $\alpha = 0°$
  - Did not result in supersonic flow extending down to near roughness elements at Mach 6 conditions
- **Largest Remaining Uncertainty:** Impact of supersonic flow near roughness elements on heating

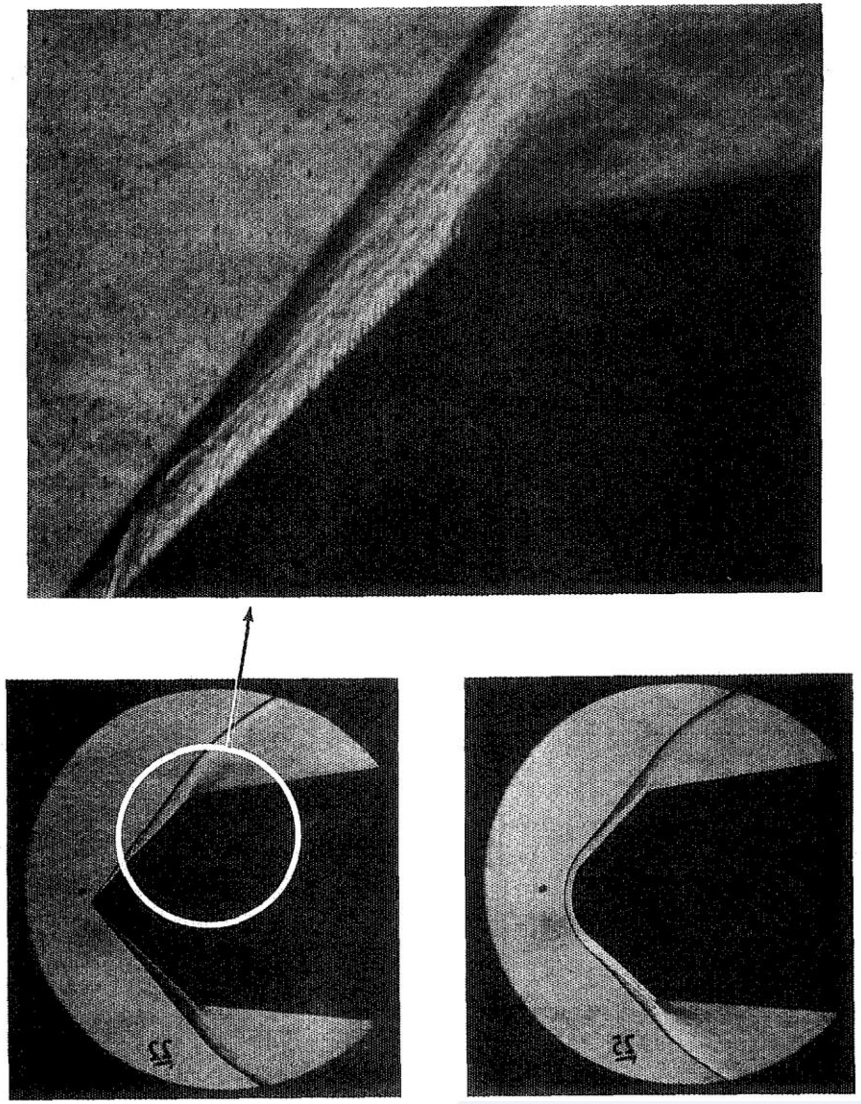


Comparison between experimental and simulation for 50+ runs

Motivation for Second Test Entry

Concerns Based on Existing Data

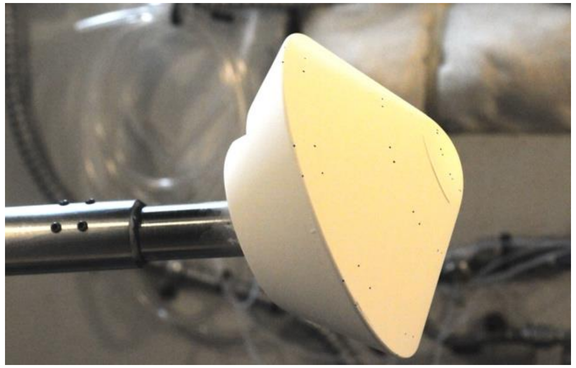
- 1984 experimental data obtained by Holden [1] showed shocks forming on individual roughness elements
- Re_{k+} values from this test were much higher than what is relevant to EES
  - However, supersonic flow was present near roughness elements, which EES would encounter
- Major concern and uncertainty in what the impact of supersonic flow near roughness elements would be at EES relevant Re_{k+} values
  - This uncertainty necessitated a follow-on wind tunnel test entry capturing this phenomenon



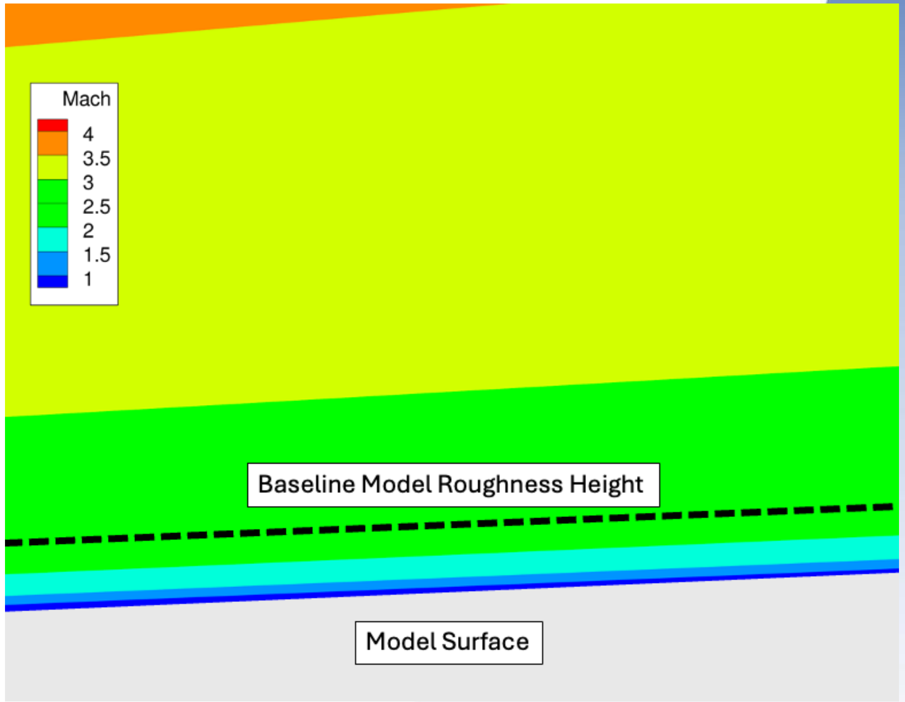
[1] Holden, M. "Experimental studies of surface roughness shape and spacing effects on heat transfer and skin friction in supersonic and hypersonic flows." *22nd Aerospace Sciences Meeting*. 1984.

Test 7087 Model Information

- Analysis found that supersonic flow could be attained near roughness elements at Mach 6 if models from the first test entry were run at α = 21°
  - To minimize turnaround, two models from the first test entry were recast
    - These models were not made to be run at angle-of-attack, only rough wall heating results were of interest
    - Angle-of-attack was chosen to attain supersonic flow at Mach 6 conditions, not to match EES (nominally α = 0°)
  - “Baseline” and largest weave height roughness models were chosen
- Smooth 52.5-deg sphere-cone model was run at α = 0° to support EES cone-angle trade study
  - Obtained smooth wall laminar and turbulent heating data



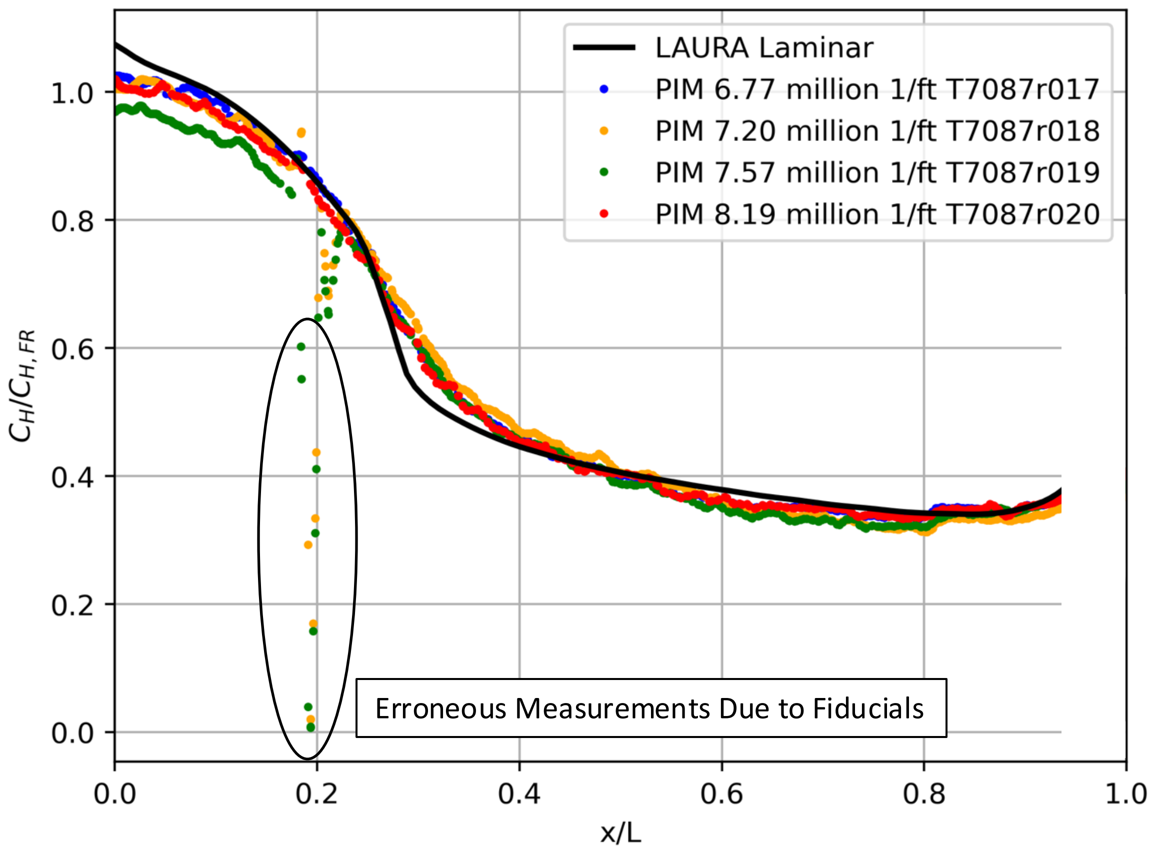
52.5-deg sphere-cone model at α = 21°



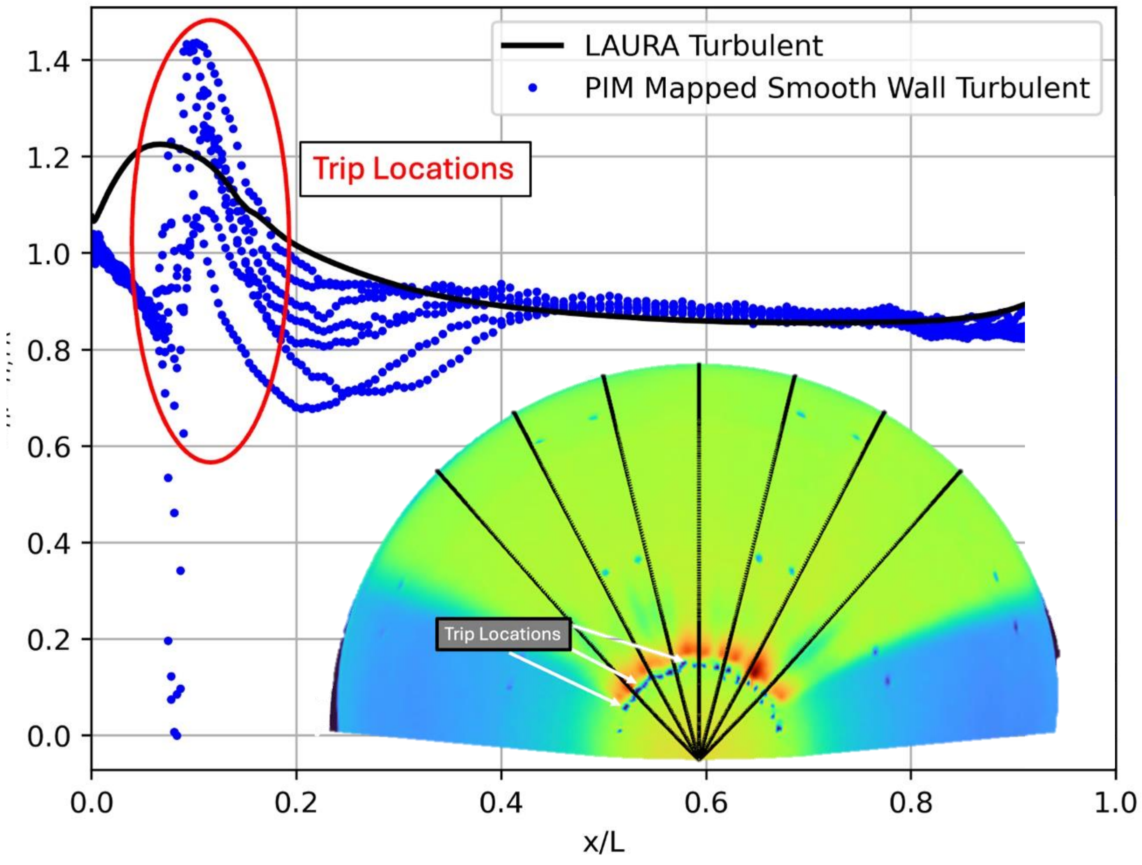
Near-surface Mach for a wind tunnel model at α = 21°

Second Test Entry Results

Smooth Wall Model Heating Results, α = 0°

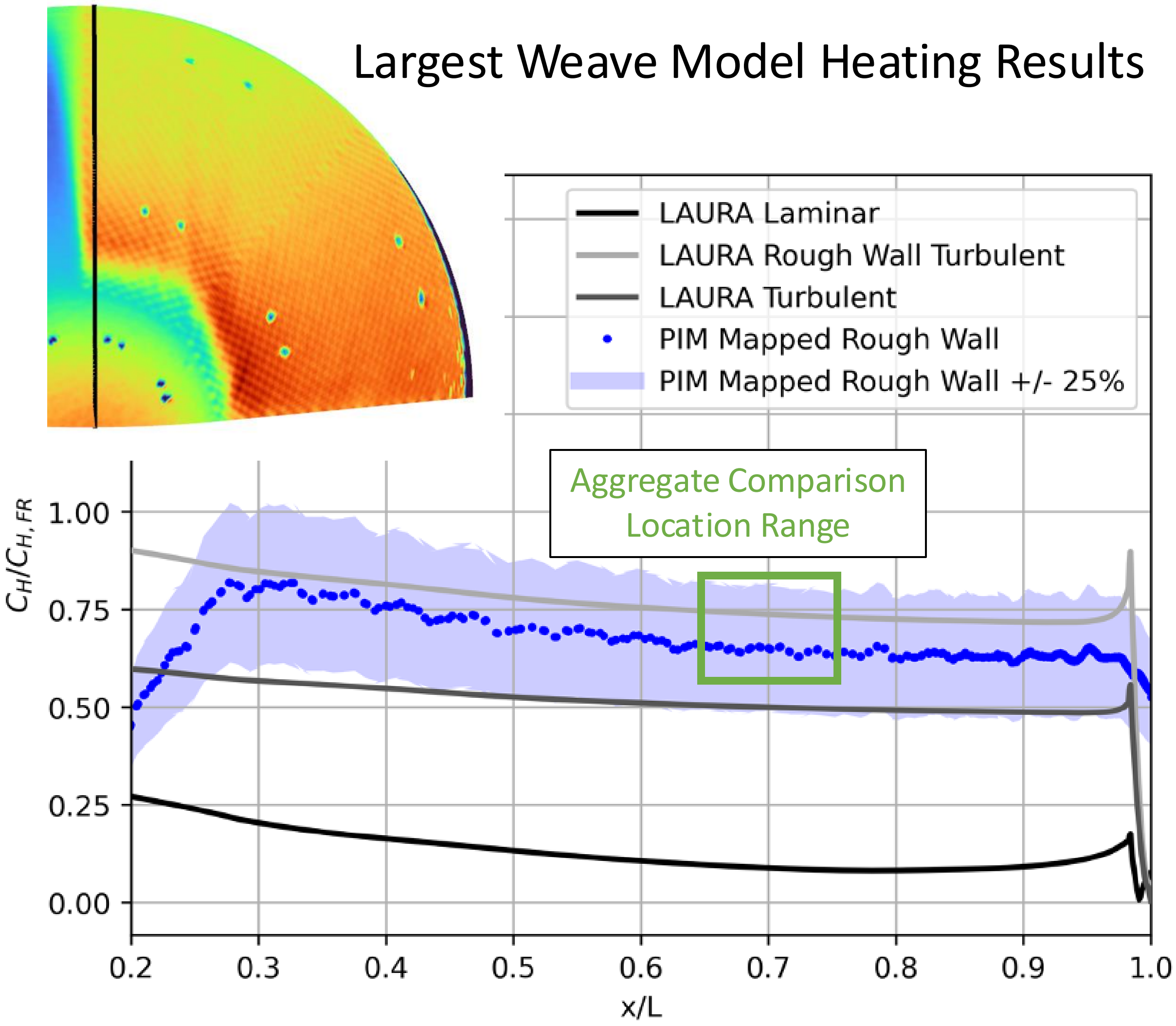


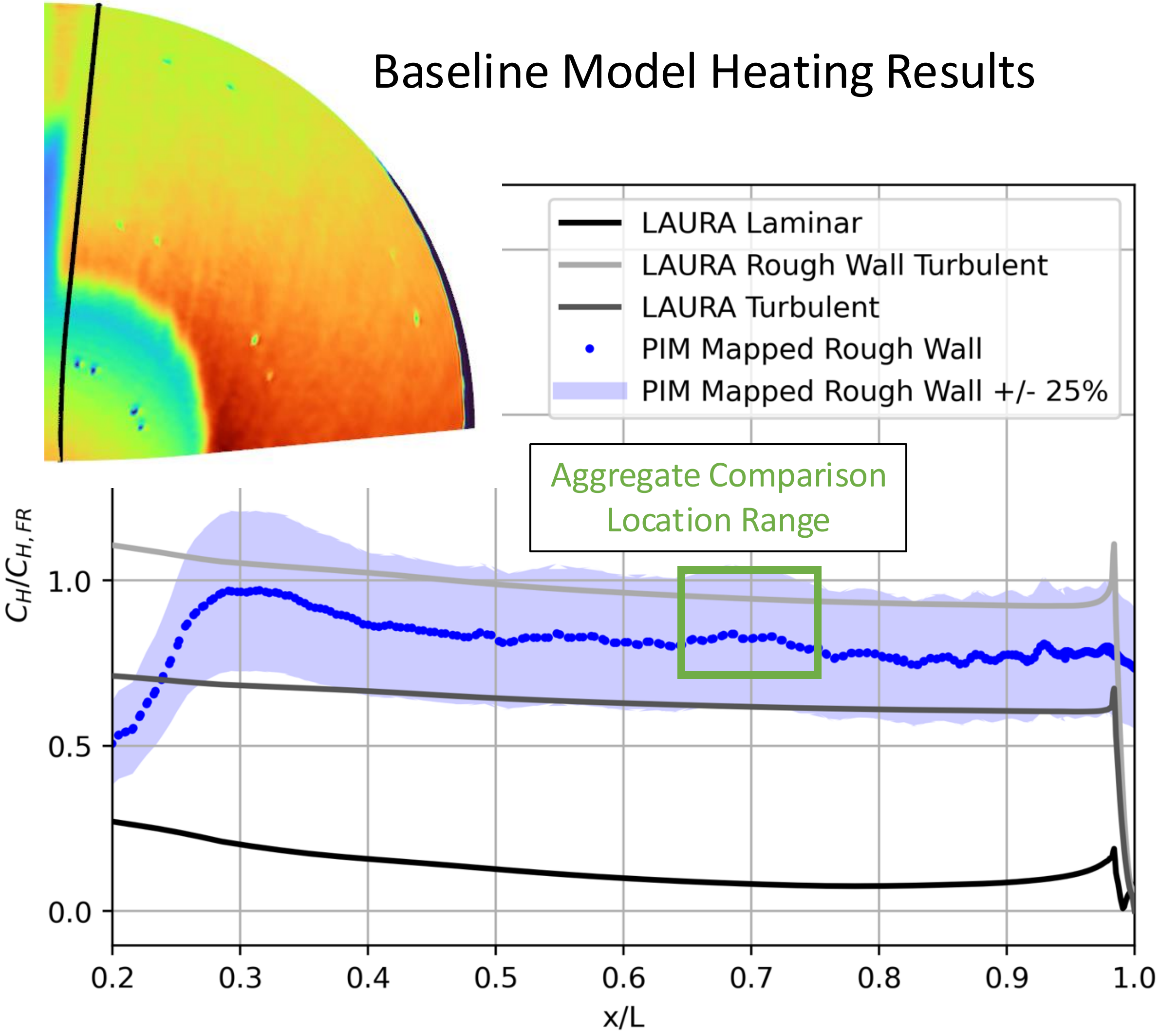
Re Sweep of Smooth Wall Centerline Heating



Smooth Wall Turbulent Heating Line Cuts

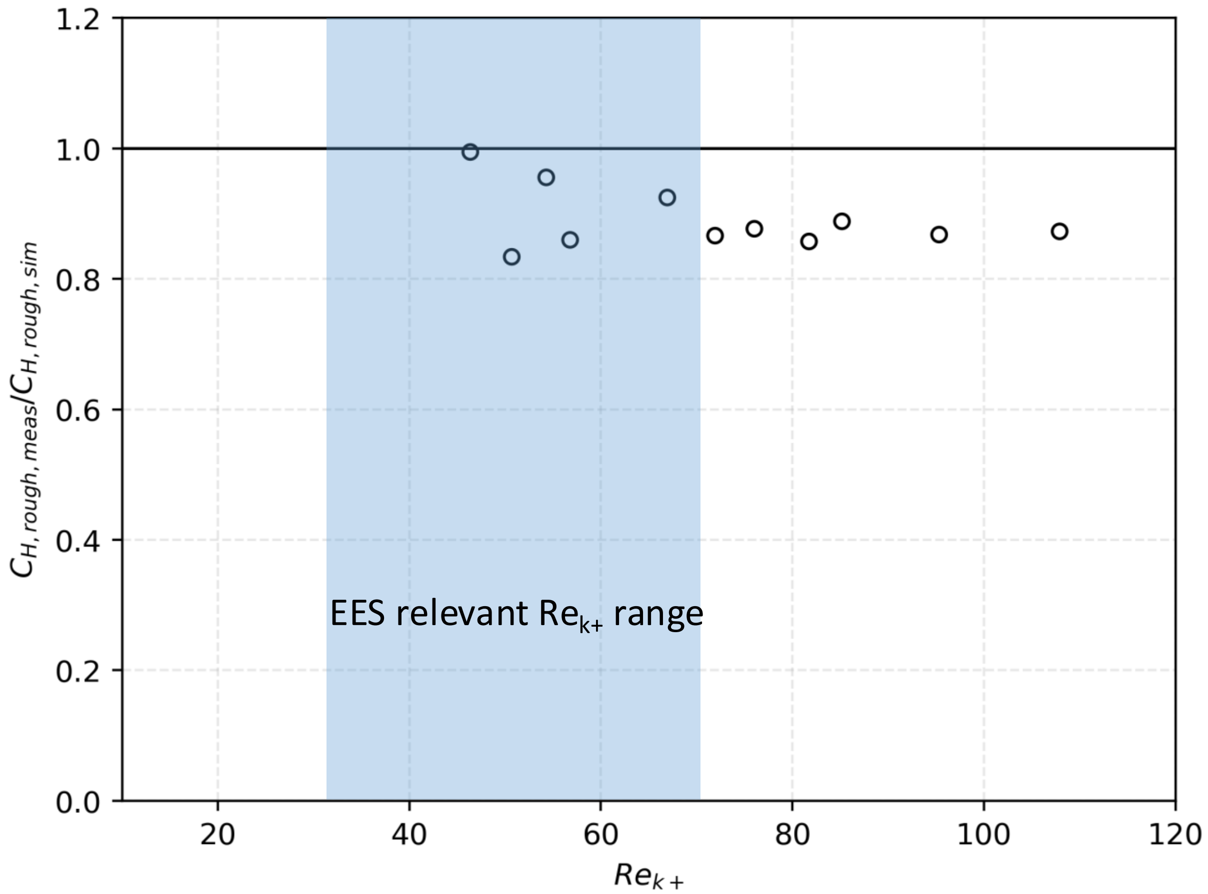
Test 7087 Segmented Model Line Cuts





Aggregate Rough Wall Heating Comparison

- Results are consistent with those obtained from first test entry
  - Simulation agreed with experimental data within 20%
  - The Dahm model was found to be conservative
- **No apparent impact** from supersonic flow present near roughness elements



Comparison between experimental and simulation for 13 runs

Conclusion

Conclusions and Impact

- Second test entry successfully obtained convective aeroheating data on a representative woven roughness surface with supersonic flow present near surface roughness elements
  - Considered to be the largest remaining uncertainty in aerothermal design of the EES vehicle
- Data obtained were consistent with results obtained from first test entry
  - Presence of supersonic flow did not have a noticeable impact on convective heating augmentation
  - The Dahm model was found to be sufficiently applicable to woven roughness patterns
- Smooth-wall heating data were also obtained on a 52.5-deg sphere-cone at $\alpha = 0°$
  - Both laminar and turbulent heating results were in agreement with LAURA predictions
- In addition to supporting MSR-EES, the data obtained from test 7087 are generally valuable for research and development toward validating CFD models, as experimental aeroheating measurements on a surface that simulates rough woven TPS are relatively sparse
  - Rocket Lab Venus Probe (RLVP) currently planning on using 3MDCP TPS as well