

# Mars Sample Return Earth Entry System Woven Roughness Mach 6 Aeroheating Test

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The Mars Sample Return Earth Entry System is the first entry vehicle designed for a NASA flagship mission to utilize a woven thermal protection system as well as a 52.5 degree sphere cone forebody geometry. As a result, no heritage aeroheating experimental data set exists to compare with computational predictions. In order to obtain a set of validation data for computational models, an extensive wind tunnel test campaign was funded by the Mars Sample Return Earth Entry System project. The first entry in the test campaign was completed in April of 2023, which was an investigation of turbulent heating augmentation due to woven thermal protection system roughness on the 52.5 degree Mars Sample Return - Earth Entry System vehicle forebody geometry. This test entry produced the first ever experimental aeroheating data on a 52.5 deg sphere-cone geometry as well as the first NASA experimental aeroheating data on a woven surface roughness pattern. Data obtained from this test campaign are being directly leveraged to support the NASA flight program, as experimental results are being utilized to validate the computational models that characterize the aeroheating environment that the vehicle experiences and predict turbulent surface heating levels and margins across the woven surface.

## Nomenclature

|                         |   |                                                                                 |
|-------------------------|---|---------------------------------------------------------------------------------|
| $C_H$                   | = | Film Coefficient, $\text{kg}/(\text{m}^2 \cdot \text{s})$                       |
| $C_{H,FR}$              | = | Fay-Riddell Reference Film Coefficient, $\text{kg}/(\text{m}^2 \cdot \text{s})$ |
| $H$                     | = | Enthalpy, $\text{J}/\text{kg}$                                                  |
| $H_0$                   | = | Freestream Total Enthalpy, $\text{J}/\text{kg}$                                 |
| $H_{300}$               | = | Wall Enthalpy at 300 K, $\text{J}/\text{kg}$                                    |
| $k$                     | = | Roughness Height, m                                                             |
| $k^+$                   | = | Roughness Reynolds Number                                                       |
| $M_\infty$              | = | Freestream Mach Number                                                          |
| $P$                     | = | Peak-to-Peak Distance, m                                                        |
| $Re_\infty$             | = | Freestream Unit Reynolds Number, $1/\text{ft}$                                  |
| $T_\infty$              | = | Freestream Temperature, K                                                       |
| $U_\infty$              | = | Freestream Velocity, $\text{m}/\text{s}$                                        |
| $\Delta H_{\text{tot}}$ | = | Enthalpy Difference, $\text{J}/\text{kg}$                                       |
| $\mu_w$                 | = | Wall Viscosity, $\text{kg}/(\text{m} \cdot \text{s})$                           |
| $\phi$                  | = | Model Roll Angle, deg                                                           |
| $\rho_w$                | = | Wall Density, $\text{kg}/\text{m}^3$                                            |
| $\rho_\infty$           | = | Freestream Density, $\text{kg}/\text{m}^3$                                      |
| $\tau_w$                | = | Wall Shear Stress, $\text{N}/\text{m}^2$                                        |

## I. Introduction

THE Mars Sample Return (MSR) project is a planned NASA flagship mission [1] in which a Sample Retrieval Lander (SRL) with a fetch rover will be flown to Mars to retrieve sample tubes on the surface obtained by the Mars 2020

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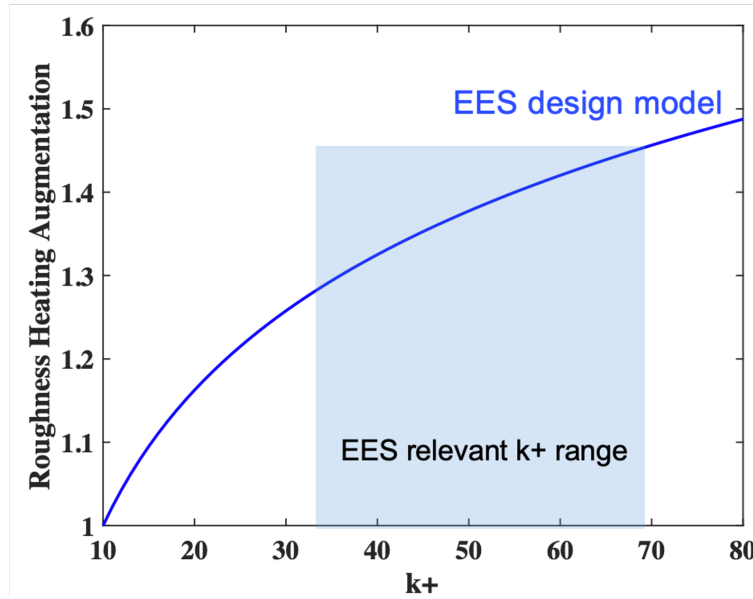
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rover [2]. The rover will load the samples onto the Mars Ascent Vehicle (MAV), which will then ascend to Martian orbit. The samples will be put onboard the Earth Entry System (EES) and, upon return to Earth, will descend through the Earth's atmosphere, landing in the Utah Test and Training Range (UTTR). The EES vehicle is planned to be a 52.5 degree sphere cone capsule geometry and utilize a 3-D woven Mid-Density Carbon Phenolic (3DMCP) Thermal Protection System (TPS), which is a derivative of the Heatshield for Extreme Entry Environment Technology (HEEET) [3]. Due to strict planetary protection requirements on landing ellipse size, the EES will not contain a parachute system and will have an extremely steep entry flight path angle. Because of this, the EES would experience unprecedented levels of turbulent heating and, due to its woven TPS, unparalleled levels of roughness augmentation of the surface convective heating. The EES vehicle would be both the first NASA capsule to be a 52.5 degree sphere cone as well as the first NASA capsule to have a woven TPS.

From a mission design perspective, it is currently considered prohibitively expensive computationally to perform computational fluid dynamics (CFD) analysis on full-vehicle grids that accurately resolve surface roughness elements due to extremely large grid cell count requirements. As a result, current computational modeling of surface roughness effects on aeroheating use correlative models based on roughness Reynolds number,  $k^+$ , defined in Eq 1:

$$k^+ = \left( \frac{\tau_w}{\rho_w} \right)^{1/2} \frac{\rho_w}{\tau_w} k \quad (1)$$

For EES vehicle design, the Dahm roughness model [4] is applied as a post-processing step to computational results to obtain surface convective heating augmentation as a result of surface roughness, where the nominal roughness height is obtained from post arc-jet samples of the 3DMCP TPS in the Interactive Heating Facility (IHF) [5] at the NASA Ames Research Center. The roughness model used for EES design can be seen in Figure 1.



**Fig. 1 Dahm roughness model used for EES design. The EES-relevant  $k^+$  range is shaded in blue.**

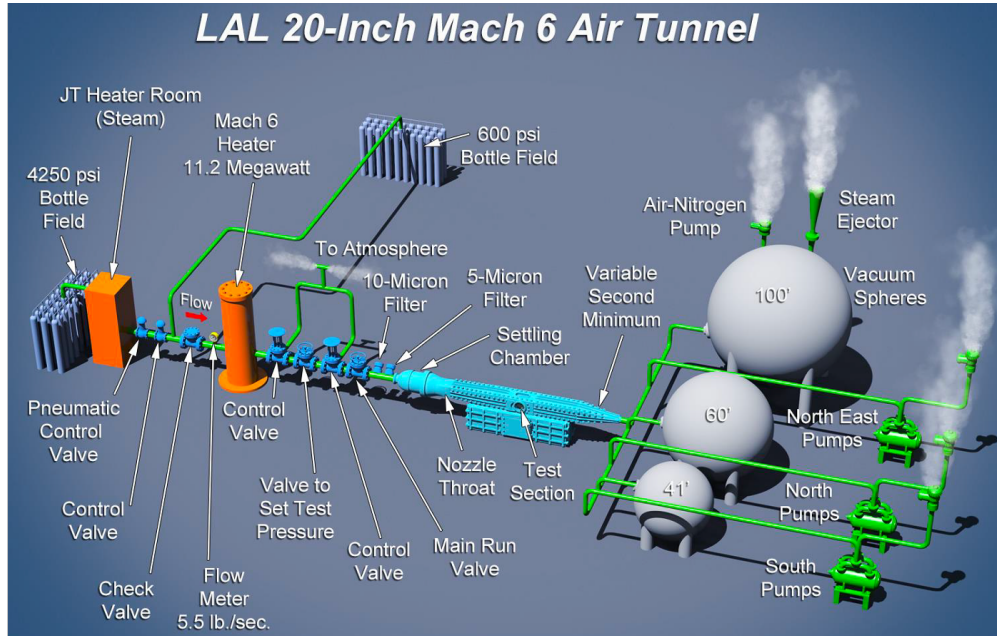
In addition to the lack of flight heritage of the capsule forebody geometry and surface roughness pattern, no experimental aeroheating data sets exist to validate current computational models. As current computational models do not directly model the woven surface roughness, correlative models of roughness augmentation effects are used. These models are typically applied to small-scale distributed roughness patterns, such as hexcomb [6] and sandgrain roughness [7], both of which have been studied extensively. However, for the EES vehicle, due to its size and its TPS, the scale of surface roughness elements relative to the boundary layer is significantly larger than previously studied surface roughnesses; and existing experimental data sets do not sufficiently validate computation roughness augmentation models for surface roughness of this scale nor a woven roughness pattern. As a result of this lack of flight heritage and experimental validation data sets, there is a significant amount of added uncertainty to computational aeroheating predictions.

Three specific areas of interest related to aerothermodynamics were identified of which there are no experimental data sets to validate models against. These are 1) surface heating on a 52.5 deg sphere cone geometry, 2) surface heating on a 3-D woven roughness pattern, and 3) surface heating on a 3-D woven roughness pattern with supersonic flow near the roughness elements. In an effort to address this lack of experimental data and sufficiently validate the CFD models used to obtain TPS surface heating predictions and reduce uncertainties in computational results, a wind tunnel test campaign at the Langley Aerothermodynamics Laboratory (LAL) 20-inch Mach 6 air tunnel [8] was funded by the MSR-EES project. The first test entry, containing various 52.5 degree sphere cone models, was performed in April of 2023 and sought to address the first two phenomena outlined prior. This paper will primarily compare and analyze experimental results obtained from this MSR-EES Mach 6 test entry to computational predictions, as well as discuss the experiment itself, data reduction techniques, and computational models used for comparison.

## II. Experimental and Computational Methods

### A. Experimental Test Facility and Operating Conditions

The LAL Mach 6 wind-tunnel is a low enthalpy blowdown facility with air as its test gas. The test section is  $20.5 \times 20.0$  inches; and the wind tunnel model is mounted on a sting and injected into the test section in less than 0.5 seconds. The facility is capable of running for up to 15 minutes for a given run; however, for this test campaign, and, more broadly, for aeroheating studies in this tunnel, run times of only a few seconds are required. Nominally, this facility produces perfect-gas freestream flows at Mach numbers of 5.8 to 6.1 and unit Reynolds numbers of  $0.5 \times 10^6$  to  $8.3 \times 10^6$  /ft. A schematic of the LAL Mach 6 facility can be seen in Figure 2 and more details of this facility can be found in Refs. [8],[9].



**Fig. 2 Schematic of the LAL Mach 6 Hypersonic Facility.**

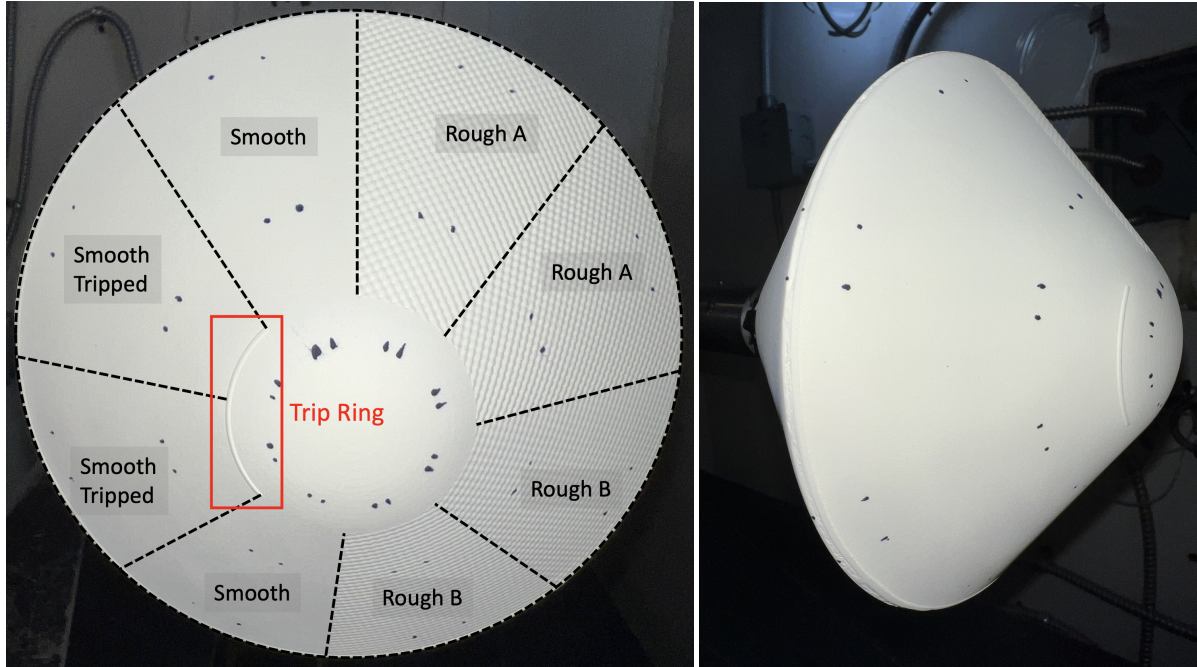
For this test entry, 144 runs were performed over twelve unit Reynolds numbers ranging from  $Re_{inf} = 1.06 \times 10^6$  to  $8.17 \times 10^6$  /ft. Aside from two runs, the sphere-cone models were tested at  $\alpha = 0$  deg throughout this entry. Values for each unit Reynolds number condition of  $M_\infty$ ,  $U_\infty$ ,  $\rho_\infty$ , and  $T_\infty$  are listed in Table 1. The enthalpy difference  $\Delta H_{tot}$ , defined as the difference  $H_0 - H_{300K}$  between the total enthalpy of the freestream and the wall enthalpy at 300 K, or cold-wall conditions, is also tabulated. Additionally, the reference film coefficient value  $C_{H,FR}$  is included in the table, and is defined as the stagnation film coefficient value from Fay–Riddell theory [10] for a hemispherical radius at cold-wall conditions, with radius equal to the nose radius of the wind-tunnel model which, in this case, is the sphere-cone geometry.

**Table 1 Run conditions for the 20-Inch Mach 6 MSR-EES sphere-cone roughness test.**

| $Re_\infty$ , 1/ft | $M_\infty$ | $T_\infty$ , K | $\rho_\infty$ , kg/m <sup>3</sup> | $U_\infty$ , m/s | $\Delta H_{tot}$ , J/kg | $C_{H,FR}$ , kg/(m <sup>2</sup> ·s) |
|--------------------|------------|----------------|-----------------------------------|------------------|-------------------------|-------------------------------------|
| 1.06E+06           | 5.90       | 61.84          | 1.66E-02                          | 930.53           | 1.94E+05                | 1.81E-01                            |
| 2.06E+06           | 5.97       | 62.38          | 3.19E-02                          | 945.15           | 2.08E+05                | 2.56E-01                            |
| 2.45E+06           | 5.99       | 62.19          | 3.79E-02                          | 945.45           | 2.08E+05                | 2.79E-01                            |
| 3.03E+06           | 6.00       | 62.64          | 4.70E-02                          | 951.15           | 2.14E+05                | 3.13E-01                            |
| 3.57E+06           | 6.01       | 61.82          | 5.49E-02                          | 945.52           | 2.08E+05                | 3.36E-01                            |
| 4.05E+06           | 6.02       | 61.79          | 6.22E-02                          | 946.04           | 2.09E+05                | 3.58E-01                            |
| 5.01E+06           | 6.03       | 63.29          | 7.78E-02                          | 960.02           | 2.23E+05                | 4.07E-01                            |
| 5.77E+06           | 6.04       | 63.17          | 8.94E-02                          | 959.75           | 2.23E+05                | 4.36E-01                            |
| 6.85E+06           | 6.04       | 61.44          | 1.05E-01                          | 945.41           | 2.08E+05                | 4.64E-01                            |
| 7.22E+06           | 6.04       | 61.41          | 1.10E-01                          | 945.29           | 2.07E+05                | 4.76E-01                            |
| 7.63E+06           | 6.05       | 61.30          | 1.17E-01                          | 944.46           | 2.06E+05                | 4.88E-01                            |
| 8.17E+06           | 6.04       | 58.96          | 1.23E-01                          | 923.36           | 1.84E+05                | 4.87E-01                            |

**B. Model Overview**

For this test campaign, six separate wind tunnel models were used. The outer mold line (OML) geometry was identical for each, that being a 52.5 degree sphere cone forebody with a generic aeroshell aftbody. Models were fabricated through ceramic casting on-site at NASA Langley. The forebody of each sphere cone was segmented into eight distinct panels. An image of one of the wind tunnel models with each panel outlined and labeled can be seen in Figure 3 as well as an oblique angle of the smooth half of the wind tunnel model.



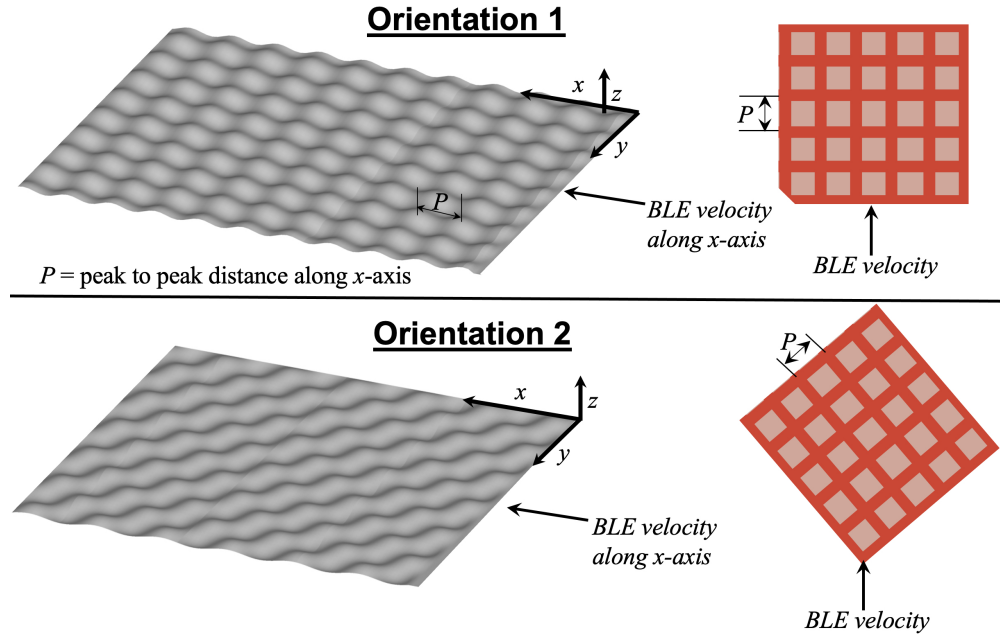
(a) Sphere-cone model with each panel outlined and labeled      (b) Smooth half of one of the sphere-cone models

**Fig. 3 Images of the wind tunnel models used in the MSR-EES sphere-cone roughness test entry.**

Four of the forebody panels had a woven roughness pattern cast directly onto their surface to emulate the surface topology of 3MDCP. The roughness parameters specified for these patterns were the roughness height, defined as the

peak-to-valley distance, the roughness spacing, defined as the peak-to-peak distance, and the roughness orientation, defined as orientation of the peak-to-peak direction with respect to the flow direction down the flank of the sphere cone. Model 1 was chosen as the baseline wind tunnel model and the woven roughness height and spacing on the model were scaled accordingly to match the boundary layer conditions that would be seen in flight, with nominal flight surface roughness parameters determined by post arc-jet samples of the 3MDCP TPS. Subsequent wind tunnel models were made with variations to either the woven pattern height, spacing, or orientation in order to study the convective heating augmentation effects of variations those parameters.

Models 2 and 3 varied the roughness height of the weave pattern, and models 4 and 5 varied the roughness spacing. The two primary orientations studied were 0 deg and 45 deg, indicated as orientation 1 and 2, respectively; however, model 6 was made to study the effects of weave orientation and its roughness panels were oriented 22.5 deg with respect to the flow direction. A diagram illustrating these orientations can be seen Figure 4.



**Fig. 4 Schematic outlining the two primary weave orientations studied in this test entry.**

These roughness panels were divided into two groups, one on the top of the model as oriented in Figure 3 (denoted with A), and one on the bottom of the model (denoted with B). For a given model, these two groups differed from each other in one specific roughness parameter. Due to only one half of the model being visible for data collection for a given run, this asymmetry in roughness parameters enabled two distinct data sets to be collected from a single model by rolling the model 180 degrees. The roll angle for a particular model is specified as  $\phi$ . This in conjunction with the segmented model approach significantly reduced model fabrication costs and lead times for the test entry. An outline of the parameters of the woven roughness patterns for each model can be seen in Table 2.

The other half of the forebody panels retained a smooth OML, and a trip ring was directly cast onto the model surface at the nose-flank junction for two of the smooth panels, indicated in Figure 3 in red. The purpose of the trip ring was to incur turbulence to enable the collection of turbulent, smooth-wall aeroheating data. For a given run, smooth-wall tripped and untripped heating data as well as rough-wall heating data were all obtained and can be seen in Figure 5. This simultaneous data collection enables direct comparison to computational data for each distinct region of aeroheating and allows for direct validation of the magnitude of convective heating augmentation as a result of turbulence and surface roughness.

### C. Data Acquisition and Reduction Techniques

Experimental aeroheating data were obtained using the two-color, relative-intensity, global phosphor thermography method [11] and reduced using the Imaging for Hypersonic Experimental Aeroheating Testing (IHEAT) code [12]. For this method, a model is illuminated by ultraviolet (UV) lights during a wind tunnel run that induce temperature

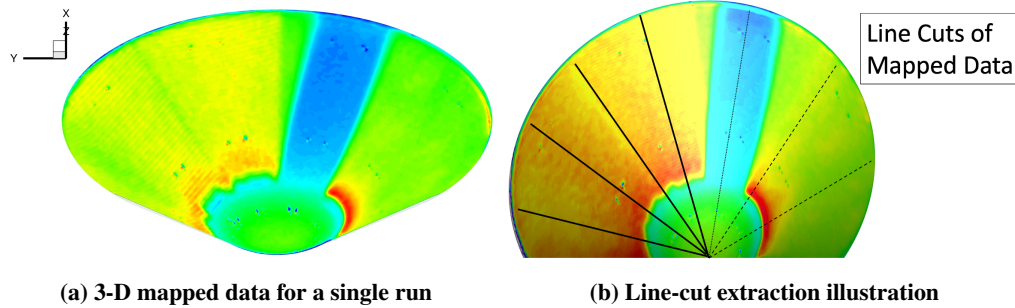
**Table 2 Model roughness parameters. Roughness height is normalized with respect to model 1.**

| Model Information<br>Number   Variation Type | Peak-to-Valley Height, $k$<br>Top   Bottom | Peak-to-Peak Spacing, $P/k$<br>Top   Bottom | Alignment, Deg<br>Top   Bottom |
|----------------------------------------------|--------------------------------------------|---------------------------------------------|--------------------------------|
| 1   Baseline                                 | 1.00   1.00                                | 4.50   4.50                                 | 0   45                         |
| 2   Height                                   | 1.50   1.50                                | 4.50   4.50                                 | 0   45                         |
| 3   Height                                   | 0.50   0.50                                | 4.50   4.50                                 | 0   45                         |
| 4   Spacing                                  | 1.00   1.00                                | 7.00   7.00                                 | 0   45                         |
| 5   Spacing                                  | 1.00   1.00                                | 3.00   3.00                                 | 0   45                         |
| 6   Orientation                              | 1.00   1.00                                | 4.50   7.00                                 | 22.5   22.5                    |

dependent fluorescence of the phosphor coating that is applied to the surface of each model prior to testing. Intensity images of the model are taken in the tunnel prior to the run, referred to as the prerun image, and then are taken during the run at a rate of 30 frames per second. Images are captured using a three-color, charge-coupled device camera. The intensity data are converted to temperature using calibrations of the phosphor system prior to testing. The temperature data are processed to determine global surface heat transfer rates. Global  $C_H$  values are determined by assuming a step function in the film coefficient from the prerun temperature to the run temperature. The heating data are typically presented in terms of ccc, where  $C_H$  is defined in Equation 2.

$$C_H = q/(H_{AW} - H_w) \simeq q/(H_0 - H_w) \quad (2)$$

For calculating the heat transfer film coefficient, it is assumed that, for a blunt wind tunnel model, the adiabatic wall enthalpy  $H_{AW}$  is equal to the tunnel freestream total enthalpy,  $H_0$ . This definition provides a theoretically near-constant value of  $C_H$  over the course of a run. The two-dimensional (2-D) heating data from IHEAT [12] were transformed to account for optical effects and then mapped onto a three-dimensional (3-D) CAD geometry representative of the wind tunnel model; in this case, a 52.5 sphere-cone forebody with a smooth OML. After mapping, four streamline cuts were extracted from each mapped forebody panel as representative data sets to directly compare to computational predictions for smooth-wall laminar, smooth-wall turbulent, and rough-wall heating. A simplified graphic illustrating the process of line cut extraction can be seen in Figure 5.

**Fig. 5 Examples of experimental image data from IHEAT after being 3-D mapped.**

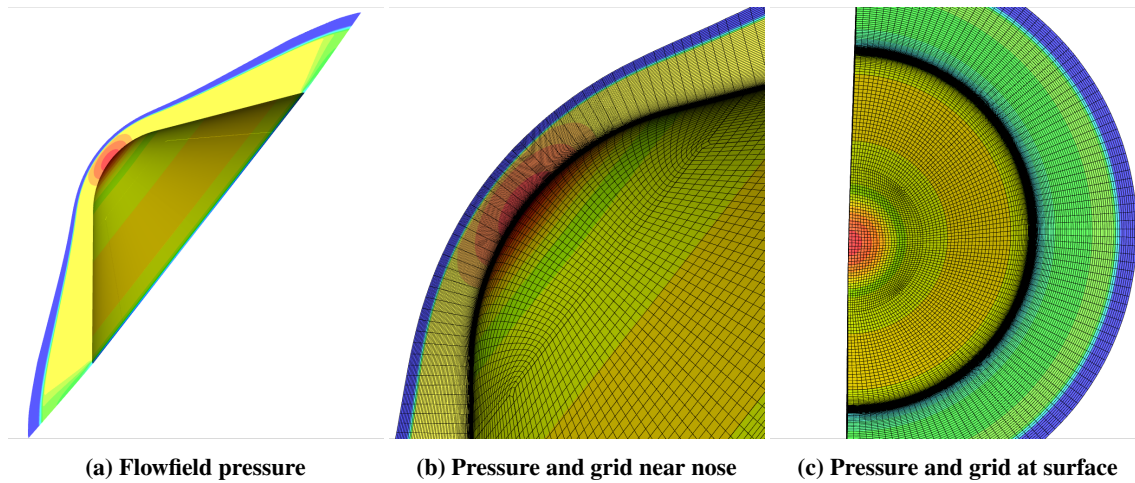
#### D. Experimental Uncertainty

The experimental uncertainty for convective heat transfer measurements on a smooth, blunt-body geometry model in the 20-Inch Mach 6 Air Tunnel is quantified as a function of net uncertainties resulting from the data acquisition method (10%); flow quality and test-condition repeatability (5%), and the accuracy of the 3-D mapping process (10%), which results in an overall root-sum-squared value of 15%. The woven surface roughness patterns are assumed to introduce additional uncertainties due to 1) the thin walls of the weave elements resulting in multidimensional conduction, which is not modeled by the reduction technique in IHEAT [12], 2) insufficient spatial resolution of weave peaks and valleys due

to fixed resolution of the data acquisition system, and 3) lack of illumination of weave pattern valleys for image regions in which the surface of the model is not normal to the camera system. These rough-wall uncertainties are estimated to be in the 10–20% range, which, when combined with the smooth-wall uncertainty, results in a total experimental uncertainty in convective heat transfer measurements for woven surface roughness patterns on a blunt-body geometry to be in the 18–25% range, which is in-family with previous surface roughness tests conducted in the LAL 20-Inch Mach 6 facility [6].

### E. Computational Tools and Methods

Flowfield solutions were generated using the Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA) code [13]. LAURA is a three-dimensional, structured-grid, finite-volume solver that includes perfect-gas and non-equilibrium chemistry options, a variety of turbulence models, ablation, and radiative transport capabilities. LAURA solutions are used to characterize the aerothermal environment that the EES vehicle would see during reentry. The heating data from this test entry along extracted streamlines were directly compared to LAURA solutions in order to assess the conservatism of the computational modeling of the woven surface roughness as well as update the convective heating margins used to size the TPS of the EES vehicle. LAURA comparison solutions were computed on a single-block, 3-D, forebody grid of the 52.5 sphere cone model geometry with a smooth OML. Freestream conditions for CFD comparison solutions were set to the nominal wind-tunnel conditions for each run, which are outlined in Table 1. The perfect-gas air option was used to generate solutions. Solutions consisted of laminar, turbulent, and turbulent with roughness augmentation in order to directly compare to data collected from each panel type on the wind tunnel model. The Cebeci–Smith algebraic turbulence model [14] with fully turbulent flow over the entire geometry was used to obtain turbulent heating solutions, and the Dahm roughness model [4], as shown in Figure 1, was used to obtain rough-wall turbulent heating results. An example LAURA comparison solution and grid for a 52.5 deg sphere-cone geometry can be seen in Figure 6.



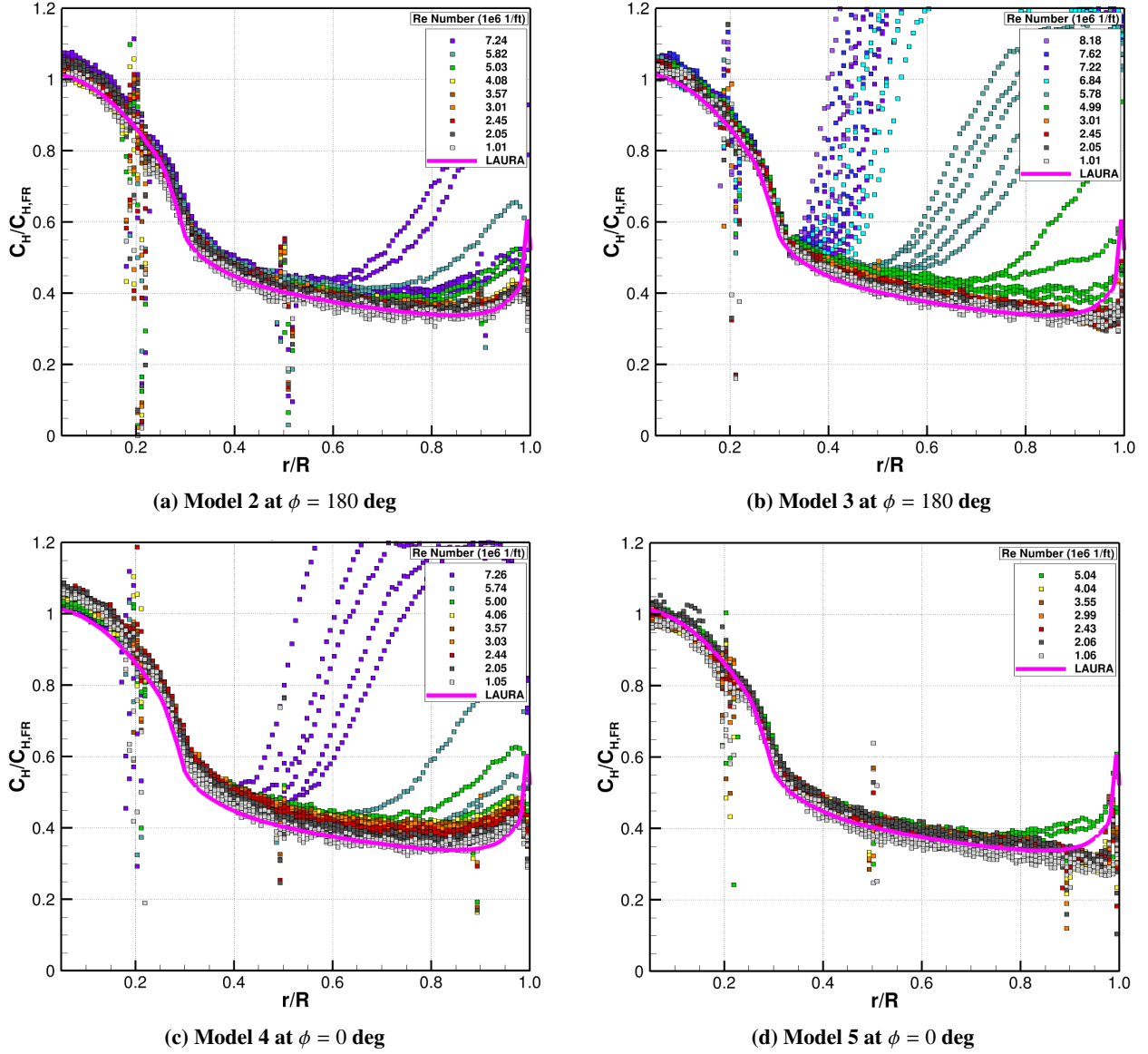
**Fig. 6 3-D LAURA flowfield solution and grid for a 52.5 sphere-cone forebody.**

## III. Experimental Results

### A. Reynolds Number Sweep

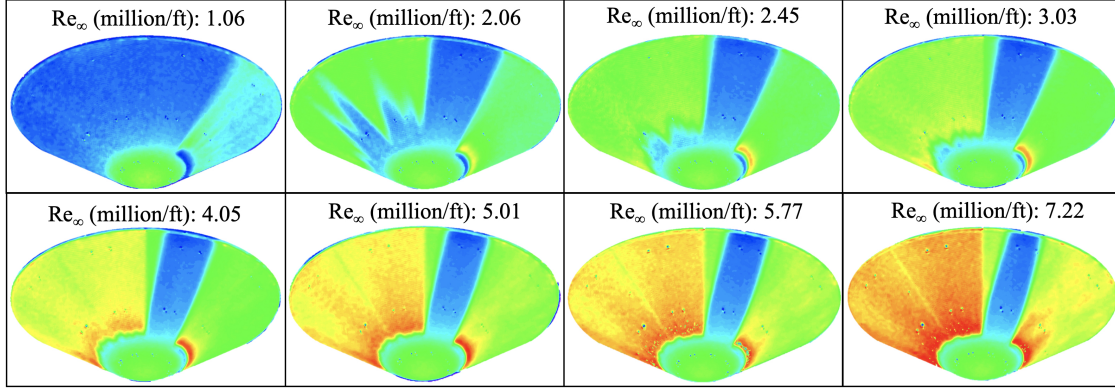
In order to assess the performance of the phosphor system and provide a baseline validation comparison to CFD results, a Reynolds number sweep analysis is performed on the line cut extractions for the smooth, untripped panel heating. Assuming that the flow remains laminar,  $C_H/C_{H,FR}$  across the entire Reynolds number range should be expected to be close to invariant. The Reynolds number sweep results for Models 2 and 3 at  $\phi = 180$  deg and Models 4 and 5 at  $\phi = 0$  deg can be seen in Figure 7. In these plots, experimental data are represented by symbols and LAURA laminar comparison solutions are represented by the solid pink lines.

Overall, the experimental data appear to be relatively invariant to Reynolds number and agree well with LAURA



**Fig. 7 Reynolds number sweep comparison between experiment and CFD for various wind tunnel models.**

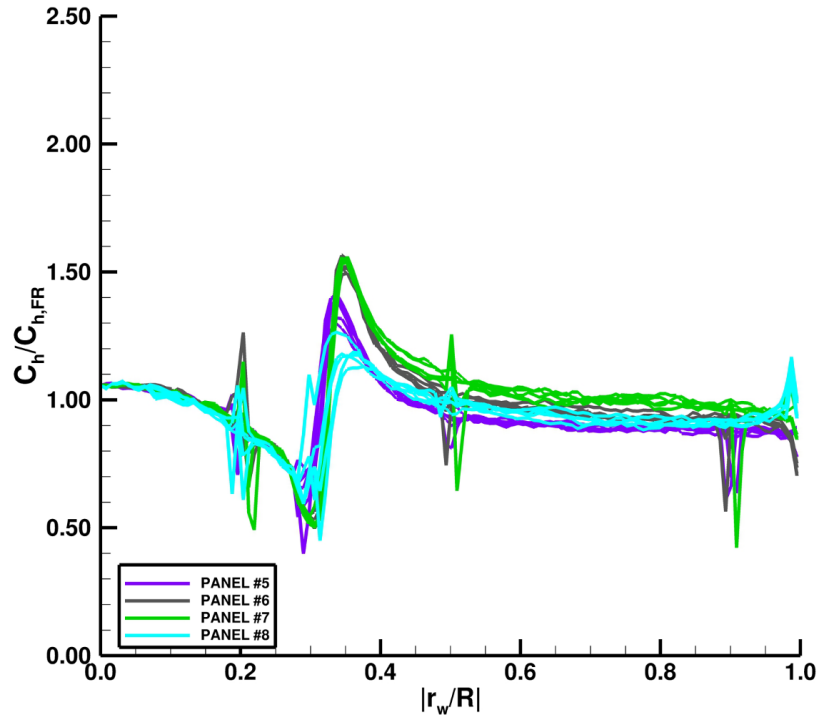
laminar predictions. At higher Reynolds numbers, turbulent flow from neighboring panels fans out and bleeds into the smooth, untripped panel, as can be seen by the illusory transition to turbulent flow seen in multiple plots. These data are considered to not be clean flow representative of turbulent data and are not considered for model validation. EES-relevant  $k^+$  values for the majority of models were obtained at low Reynolds numbers, which did not experience this turbulent flow bleeding phenomenon. Model 5 was only tested at unit Reynolds numbers of 5 million/ft or less, and showed very good collapse and agreement with CFD for these conditions, which are most relevant to EES flight conditions. Figure 8 contains heating images of the baseline model at various Re numbers, increasing from left to right and top to bottom. As Reynolds number increases, which in turn increases  $k^+$ , the rough-wall panels transition to fully turbulent flow and the heating increases present in Figure 7 from flow fanning out from neighboring panels can be seen in the higher Reynolds number images in Figure 8.



**Fig. 8** Mapped experiment results of a Reynolds number sweep for Model 1.

### B. Trip Ring Effects

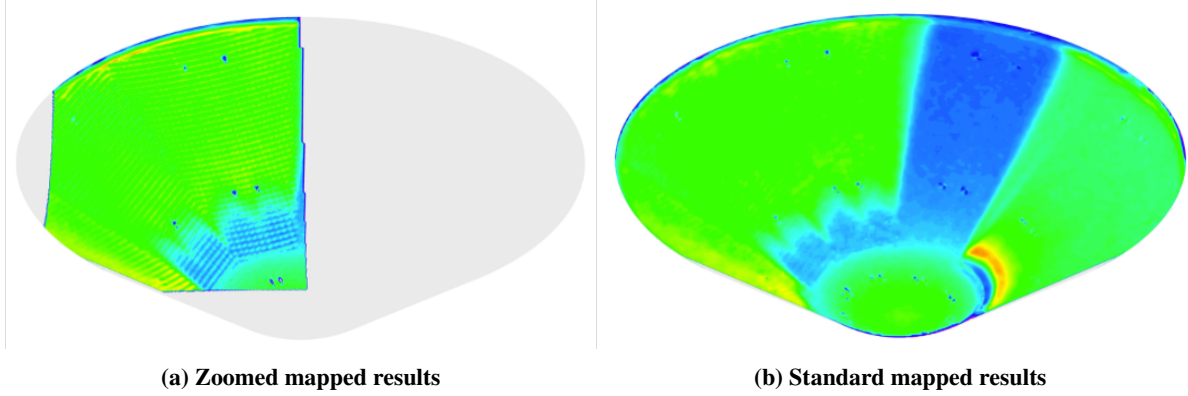
In an effort to assess the extent to which the presence of the trip ring disturbs the flow and whether or not the flow adequately recovers from this surface feature, several runs were performed in which trip tape was applied to the untripped, smooth panels of the forebody of Model 1 and the wind tunnel model was subsequently run at  $\phi = 90$  deg. Line cut results from one of the runs from this study can be seen in 9, and the panels containing the trip ring are the green and grey lines, labeled as panels 6 and 7. As can be seen, the trip ring appears to induce a separation region upstream of the feature, and has a significant impact on surface heating directly downstream as well. The flow appears to recover and asymptote to a similar heating value to the panels containing trip tape further downstream. While the presence of the trip ring was found to have an impact on surface heating immediately downstream, at locations further down the flank of the sphere cone, the discrepancies in heating between the panels with the trip ring versus panels with the trip tape was found to be overall relatively minimal and well within experimental uncertainty.



**Fig. 9** Line cut comparison between trip-ring and trip tape induced turbulent heating data.

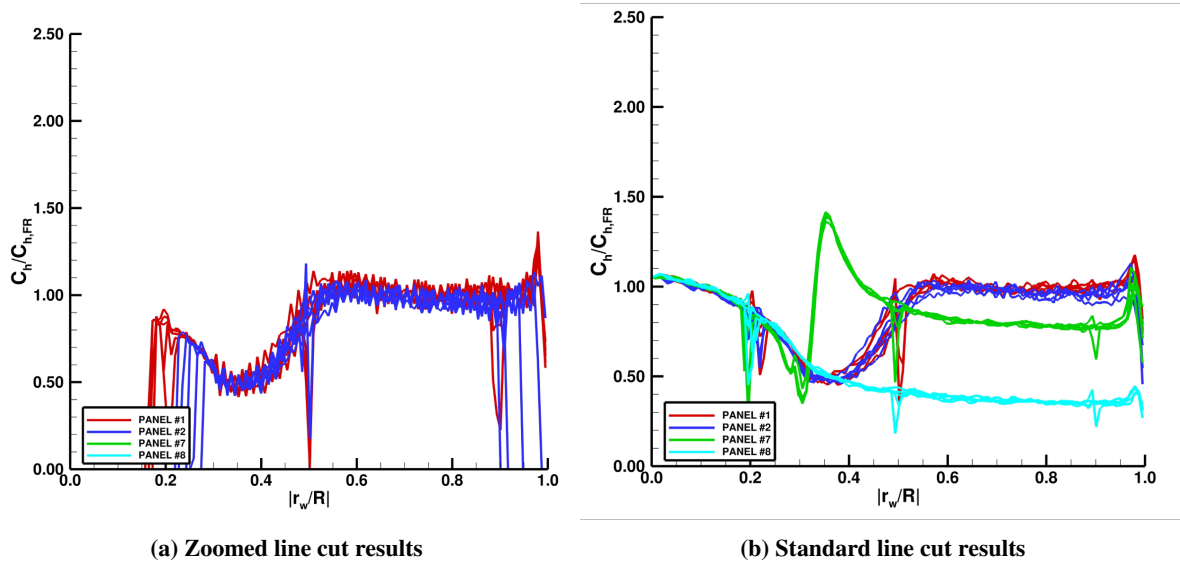
### C. Camera Zoom Study

A study involving zooming the camera system was also undergone in an attempt to better spatially resolve the peaks and valleys of the woven surface pattern. These zoomed runs were performed at Reynolds numbers most relevant to EES and were done on a number of different models to obtain higher resolution image data on various woven roughness patterns. Figure 10 shows a side-by-side comparison of mapped data for a zoomed run, shown left, versus a standard run, shown right, for Model 2, which has the largest roughness height, at the same Reynolds number. As can be seen, the weave is much more clear in the zoomed run image, enabling spatial resolution of weave elements.



**Fig. 10** Mapped experimental results for a zoomed and standard run of Model 2 at the same Reynolds number.

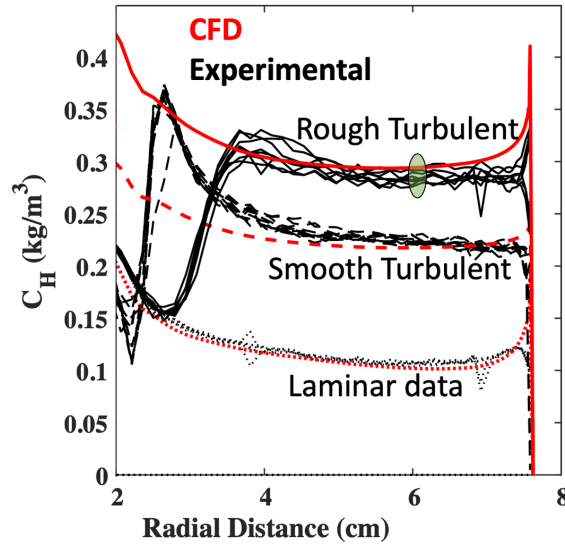
Line cut extractions for each mapped image shown can be seen in Figure 11, with the left plot corresponding to the zoomed image and the right plot corresponding to the standard image. The zoomed line cuts contain higher magnitude fluctuations in surface heating, which appear to correspond to weave peaks and valleys. From initial analysis, this zoomed study shows promising results and seems to have been extremely successful in being able to provide much higher resolution data than standard runs, providing an addition set of validation data. Although these data have not yet been more closely analyzed and compared to, this unique data set would enable direct comparison and validation for future computational studies and solutions in which the physical peaks and valleys of the weave are directly modeled and gridded.



**Fig. 11**  $C_H$  line cut results for a zoomed and standard run of Model 2 at the same Reynolds number.

#### D. Line Cut Extraction and Comparison

The primary objective of this test entry, as mentioned above, was to obtain experimental surface aeroheating data on both a 52.5 deg sphere cone geometry as well as a woven surface roughness pattern. Across all runs for this test entry, line cuts were extracted and compared with LAURA predictions. A line cut comparison between experimental and computational results for run 34 of the test campaign can be seen in Figure 12, where the black curves in the plot are the experimental data and the red curves are the computational predictions.



**Fig. 12** Line cut comparison between experimental data and computational predictions for smooth-wall laminar, smooth-wall turbulent, and rough-wall turbulent heating for run 34.

Heating results for smooth-wall laminar, smooth-wall turbulent, and rough-wall turbulent flow are all plotted together in Figure 12 and all show good agreement with computational predictions, which provides confidence in modeling capabilities across various flow behavior for a 52.5 deg sphere-cone. In addition to providing three separate sets of validation aeroheating data on a 52.5 deg sphere-cone geometry, these data also quantify the convective heating augmentation due to turbulence and surface roughness across a wide range of Reynolds numbers, enabling validation of the physics-based, correlative roughness models used in computational modeling and prediction of the convective surface heating that EES would see.

#### E. Aggregate Solutions

Aggregate comparisons were made at a downstream flank location on the model indicated in Figure 12 by the green circle. The comparisons were made far enough downstream to mitigate any impact that the smooth nose or trip ring would have on turbulent heating data. These aggregate comparisons are key to evaluating the conservatism of current computational models, as they provide validation across a wide range of  $k^+$  values, allowing margins built in to computational predictions to be more thoroughly reassessed. Figure 13 shows an aggregate comparison of over 50 runs for a wide range of  $k^+$  values, fully encompassing all EES-relevant conditions.

In this plot, experimental results are normalized by computational predictions in order to quantify the percent difference between the two  $C_H$  values obtained. The vast majority of experimental data obtained fell within 15% of computational predictions, with the largest underprediction of CFD being only 4%. This comparison shows very good agreement between experimental and computational results, providing confidence in computational correlative modeling capabilities of woven surface roughness.

Figure 14 is an aggregate comparison of over 30 runs outlining the impact that weave orientation with respect to the flow appears to have on convective heating augmentation. The two weave orientations studied were those outlined in Figure 4, and it was found that the convective heating augmentation of the 0 deg weave orientation was up to 8% larger than the augmentation of the 45 deg weave orientation.

Finally, an aggregate comparison of several runs was performed to measure the impact on heating augmentation as a

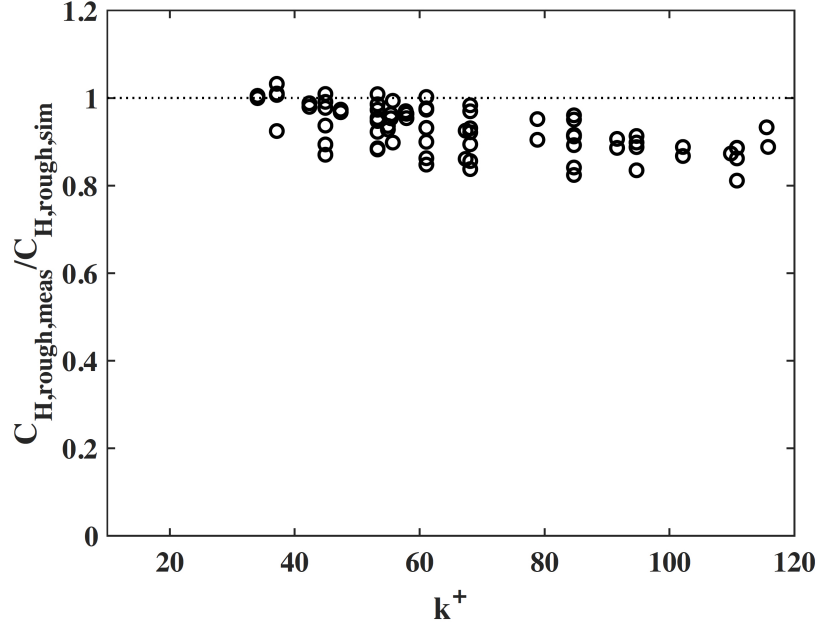


Fig. 13 Aggregate comparison between experimental data and computational predictions for over 50 runs over a wide range of  $k^+$  values.

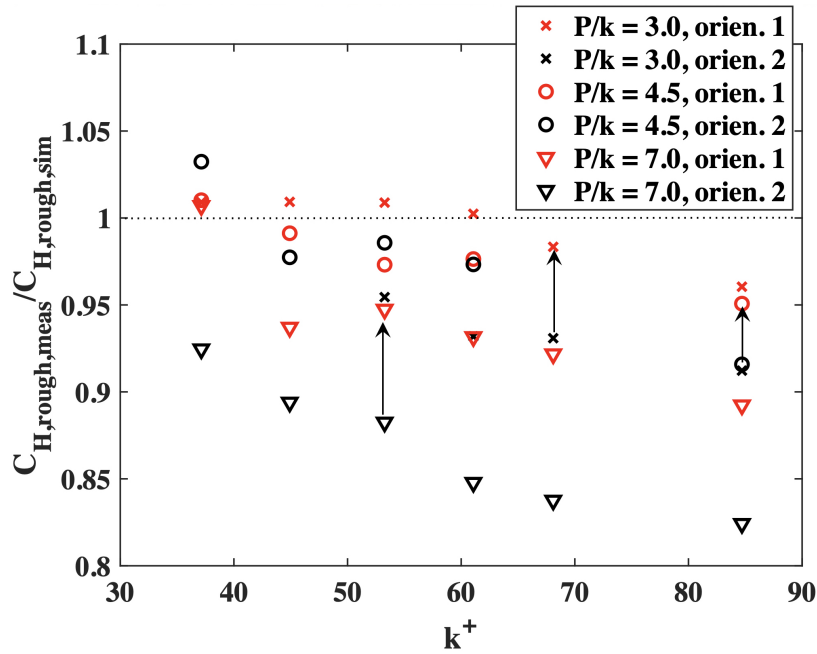


Fig. 14 Aggregate comparison between experimental data and computational predictions highlighting to effects of weave orientation on heating augmentation.

result of variations in weave spacing, as shown in Figure 15. An illustration of the change in weave cross-section as a result of changing  $P/k$  can also be found in Figure 15. It was found that as  $P/k$  decreased, heating augmentation increased, up to a 10% increase in augmentation for the weave parameters studied in this test entry.

Overall, the aggregate comparisons done thus far on the experimental data obtained during the April 2023 MSR-EES Mach 6 test entry have shown very good agreement between computational predictions and experimental

aeroheating results, providing confidence in the physics-based computational models used in CFD to characterize the aerothermodynamic environments that the EES vehicle would see. This test entry was able to provide validation aeroheating data for a 52.5 deg sphere cone geometry as well as for a woven surface roughness pattern, neither for which there were any existing experimental data sets to validate computational tools and models against.

#### IV. Concluding Remarks

The first wind tunnel test entry of the MSR-EES Mach 6 test campaign was performed in April of 2023. This test entry produced the first ever experimental aeroheating data set for a 52.5 deg sphere cone geometry as well as the first ever NASA experimental aeroheating data set for woven surface roughness patterns akin to HEEET and 3MDCP. As the MSR program has strict planetary protection requirements and a one-in-a-million reliability requirement, this data collection was crucial in reducing risk and uncertainties of the aeroheating environment that the EES vehicle would see during Earth EDL. The data obtained from this test are extremely valuable for the MSR mission, as they are being used to validate CFD physics-based models and assess whether the EES design models for turbulence and roughness augmentation are conservative. The ongoing validation effort and comparisons to this data set are being used to update the convective heating margin used for EES design, which directly feeds into the MSR mission design as a whole.

In addition to directly supporting a NASA flight program, the data obtained from this test entry are extremely valuable for the planetary community as a whole. There are many candidate planetary destinations in which a 3-D woven TPS is considered to be an enabling technology, such as Venus or Neptune, and this data set offers some of the first validation data sets and comparisons between correlative, physics-based computational models and experimental aeroheating results over a woven surface roughness pattern. The data from this test are unique in both geometry and surface features, and are extremely beneficial not only for validation of computational models, but also as a reference data set for future design of vehicles with a 52.5 degree sphere cone geometry or designs utilizing a woven TPS.

The largest remaining uncertainty in computational modeling of the aerothermodynamic environment of the EES vehicle is the presence of supersonic flow near surface roughness elements. While this specific test entry did not address this physical phenomenon, there is a planned MSR-EES test entry in the Mach 6 facility in late Fall of 2023 to test sphere-cone models in excess of  $\alpha = 20$  deg in order to obtain aeroheating data at relevant EES conditions over woven patterned surface roughness with supersonic flow near surface roughness elements. This test entry, in addition to a planned flat-plate test entry in Spring of 2024, would provide the first ever NASA experimental aeroheating data set of this phenomenon and would be instrumental in mitigating uncertainties in computational models with respect to heating augmentation as a result of near-surface supersonic flow.

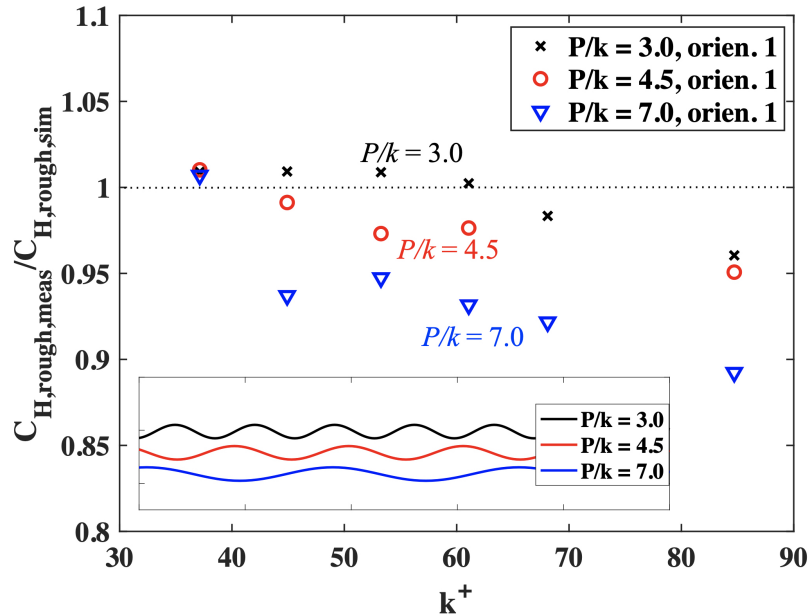


Fig. 15 Aggregate comparison between experimental data and computational predictions highlighting the effects of weave spacing on heating augmentation.

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