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Validation Study of the Multi-Fidelity Toolkit in SPARC

Compressible fluid dynamics at multiple physics fidelities

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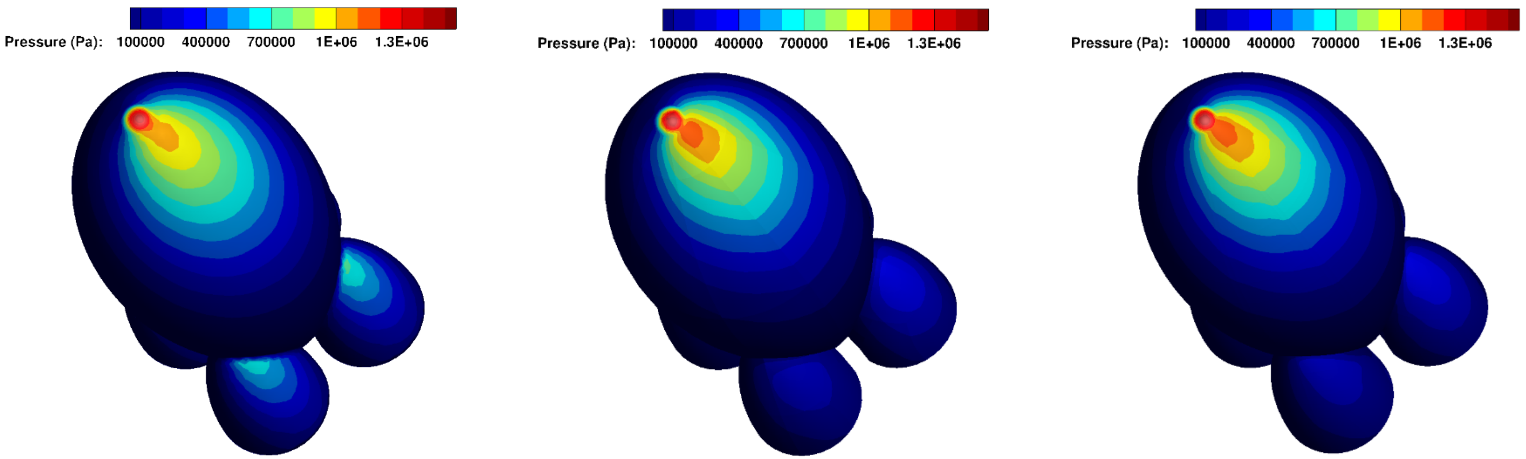
The Multi-Fidelity Toolkit (MFTK) is implemented in SPARC, developed by Sandia National Laboratories, to solve compressible fluid dynamics

- Developed as efficient aerodynamic table generator for hypersonic vehicle analysis
- Has three levels of physics fidelity
  - High: Reynolds-Averaged Navier—Stokes (RANS)
  - Medium: Euler + Momentum/Energy Integral Technique (Euler+MEIT)
  - Low: modified Newtonian aero + flat-plate boundary layer model (MNA+FPBL)

Rocket ship example at angle of attack of 16º, yaw of 8º, Mach 15, altitude 20 km



Modified Newtonian Aero	Euler	RANS
Runtime ~10 seconds, 1 core	Runtime ~10 minutes, 8 cores	Runtime ~100 minutes, 288 cores

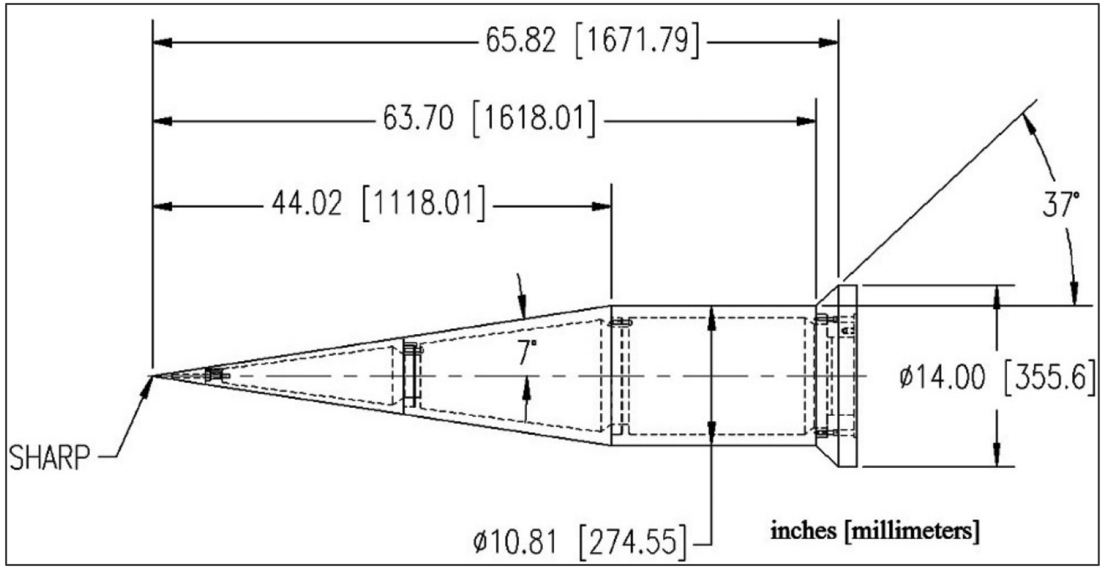
Wagnild, R. M., "Multi-fidelity Toolkit," Sandia Poster SAND2019-11991 C, Sandia National Laboratories, 2019.

Model validation is the process of determining the predictive accuracy of physics codes

- Validation: “The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model”
- Validation Error
  - $E = S - D$
  - S is a simulation result
  - D is experimental data
- Validation Uncertainty
  - $u_{\text{val}} = \sqrt{u_{\text{num}}^2 + u_{\text{input}}^2 + u_D^2}$
  - u_{num} is numerical uncertainty
  - u_{input} is input uncertainty propagated through model
  - u_D is the experimental data uncertainty

HIFiRE-1 wind tunnel tests provide high quality, hypersonic validation data on a complex vehicle

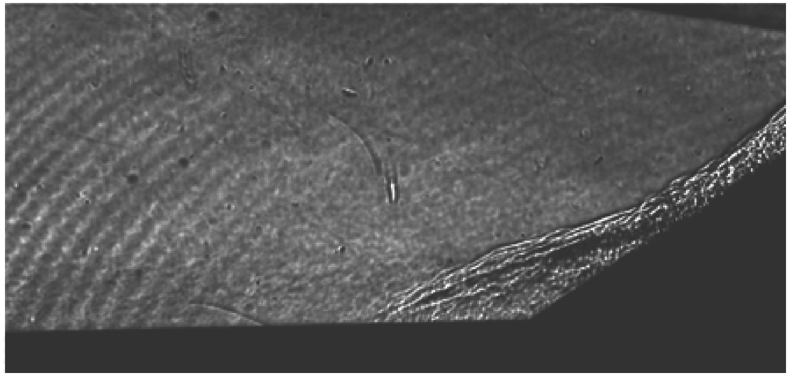
- Geometry has
  - Laminar cone
  - Turbulent cone
  - Cylinder
  - Flare
- High quality and spatial resolution pressure and heat flux measurements
- This study used Run 30
  - $\mathrm{M} = 7.19$
  - $\alpha = 0°$
- Validation studies of other runs with angles of attack and different Reynolds numbers are planned



The HIFiRE-1 wind tunnel test geometry that shows the fore-cone on the left, the cylindrical section in the center, and the flare on the right; from Wadhams 2008. The text states that the final nosetip was changed from sharp to a radius of 2.5 mm and the flare angle was changed from 37° to 33°.

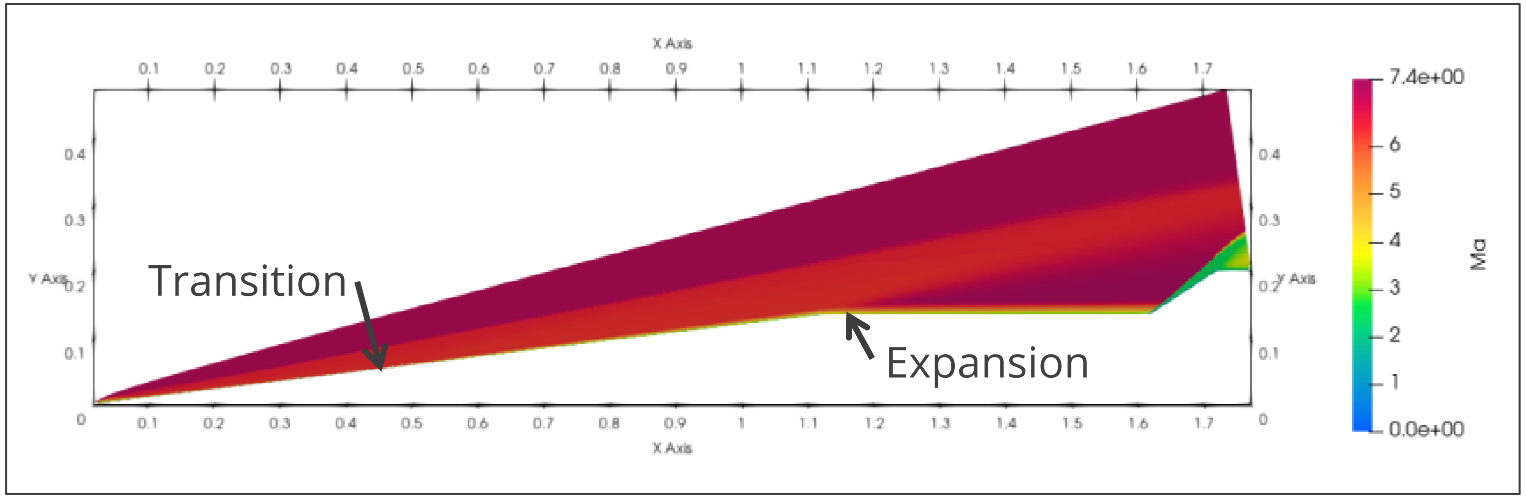
The flow includes a separation region near the cylinder-flare intersection that is a challenge

- Like the findings of HIFiRE-1 modelers (see MacLean 2008)
  - The SA prediction has negligible separation at the cylinder-flare intersection
  - The SST prediction has sizeable separation (larger than experiment)

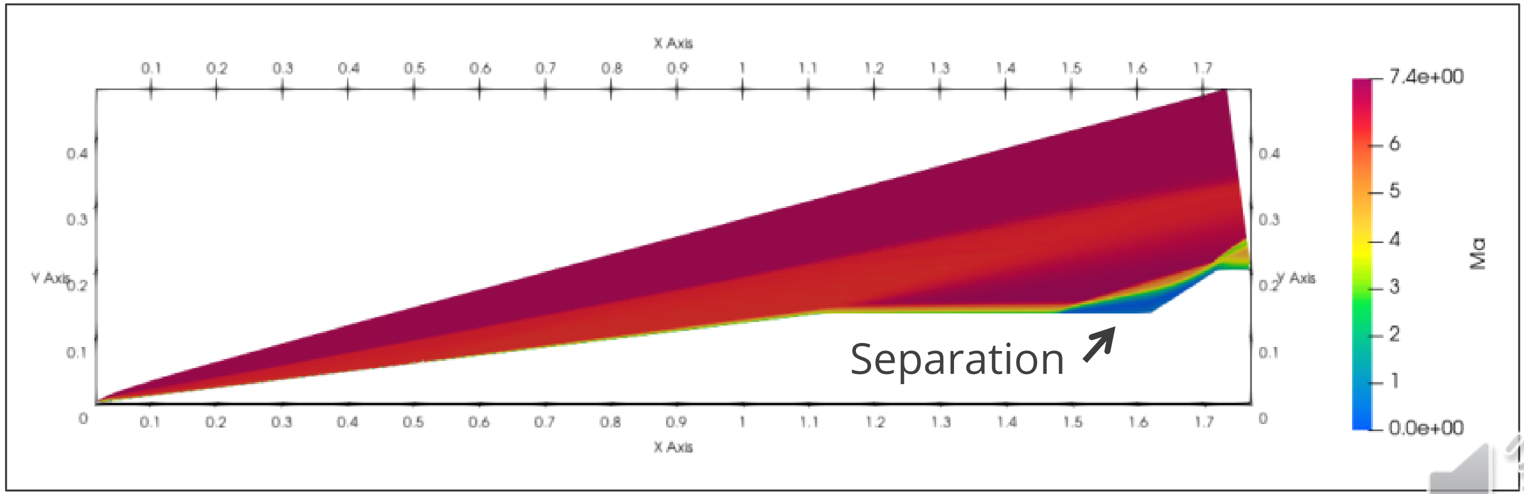


Measured separation from Schlieren imaging, from MacLean 2008

RANS Spalart—Allmaras (SA)



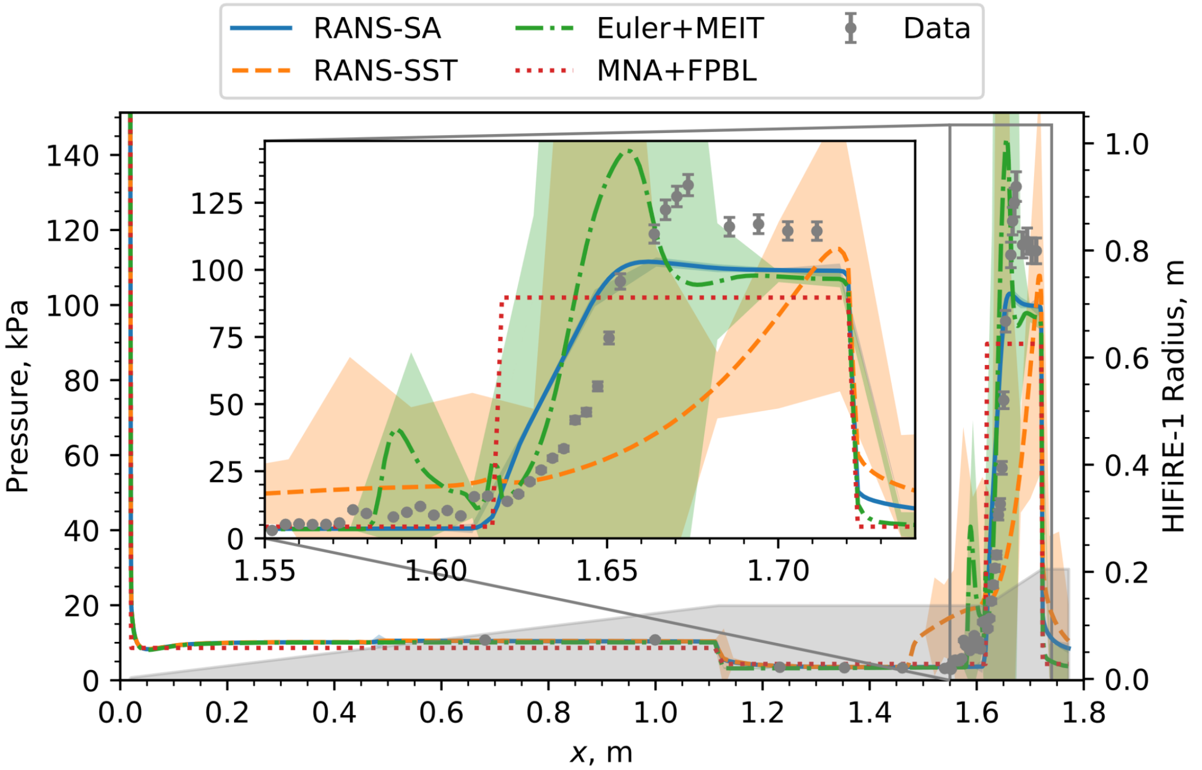
RANS Shear Stress Transport (SST)



Surface pressure validation comparisons along axis

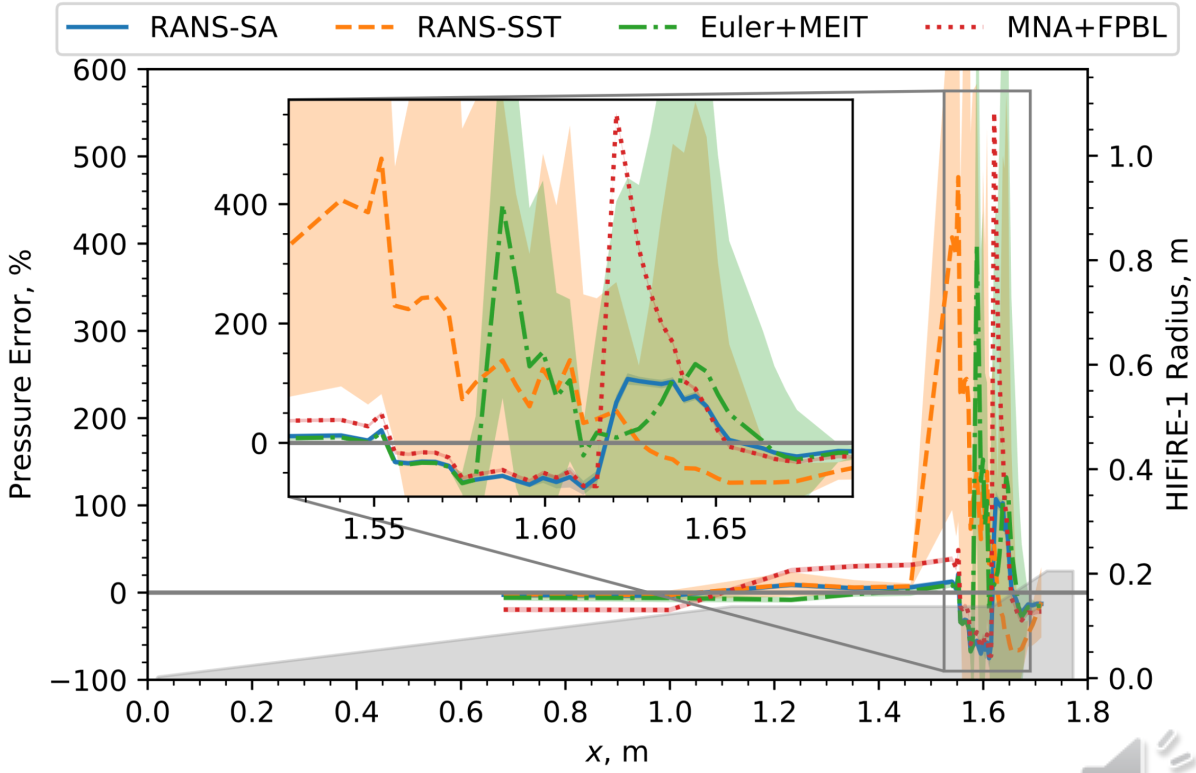
Nominal Results

- Four model predictions with numerical uncertainty
  - Uncertainty from grid convergence study, see Krueger MFTK verification 2022 SciTech paper
- Experimental data points with uncertainty



Error Results ($E = S - D$)

- Error is relative to measurements
- Each model has its own error curve
- Validation uncertainty u_{val} shown on error plots
  - u_{input} not calculated in this work



- HIFiRE-1 geometry is shaded gray

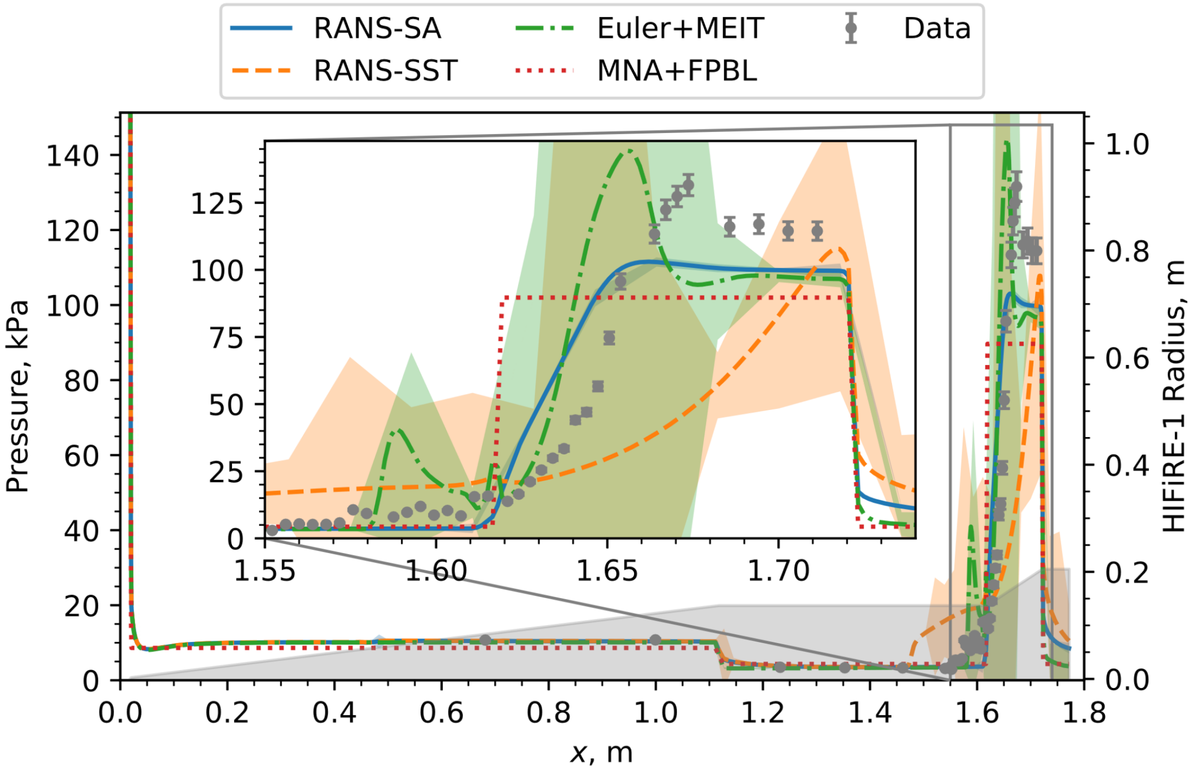
Surface pressure validation comparisons along axis

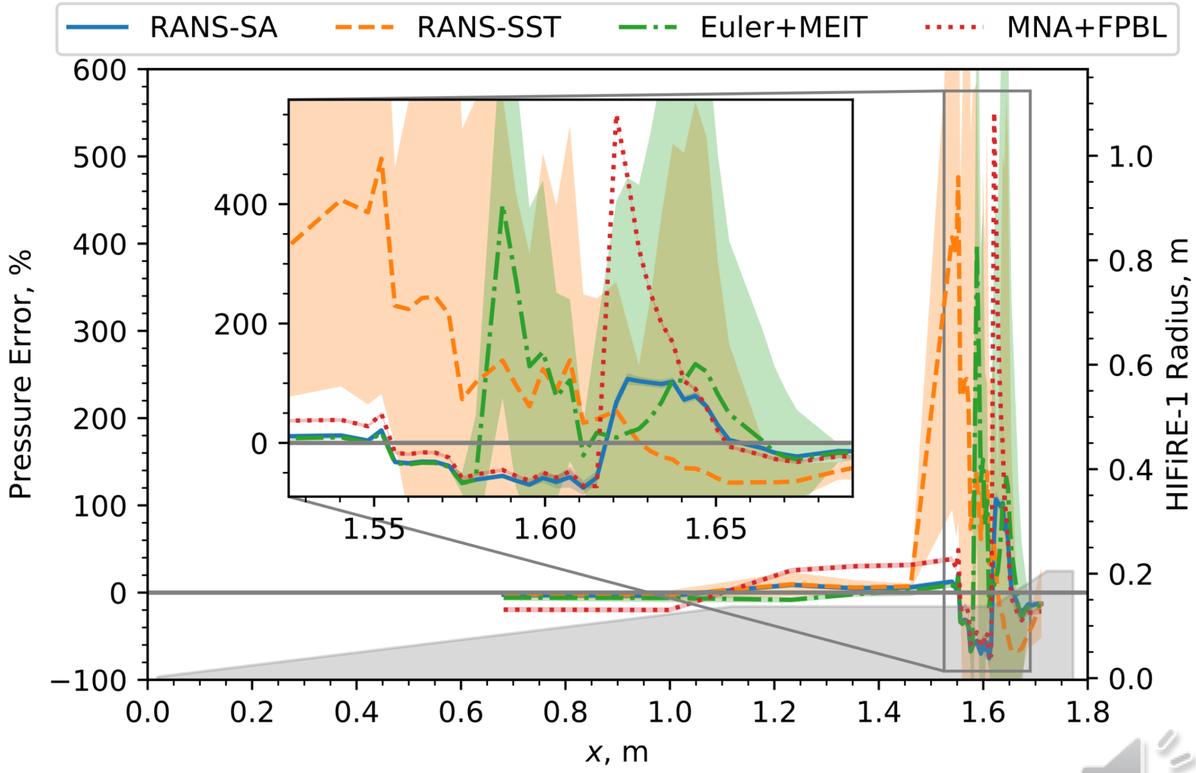
Nominal Results

- Agreement is very good in cone and cylinder sections
  - More challenging near separation
- RANS-SA and Euler+MEIT capture separation behavior best

Error Results

- Validation uncertainty is large for RANS-SST and Euler+MEIT
  - Driven by numerical uncertainty
- Error in cone and cylinder upstream of separation below 40%

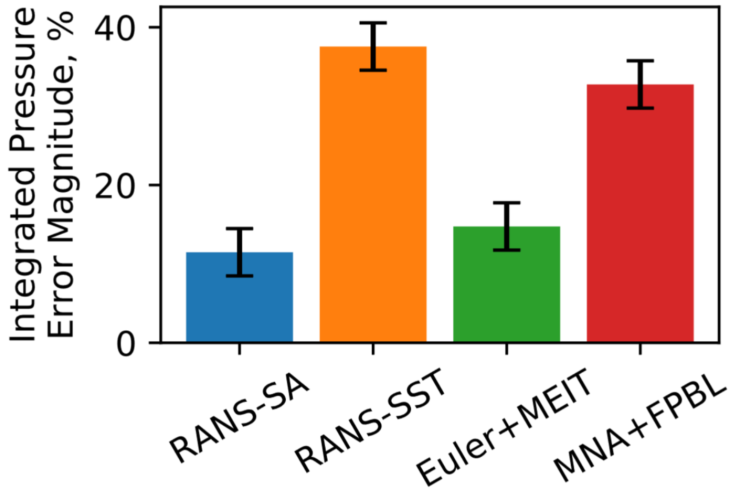




Surface pressure validation error integrated over space

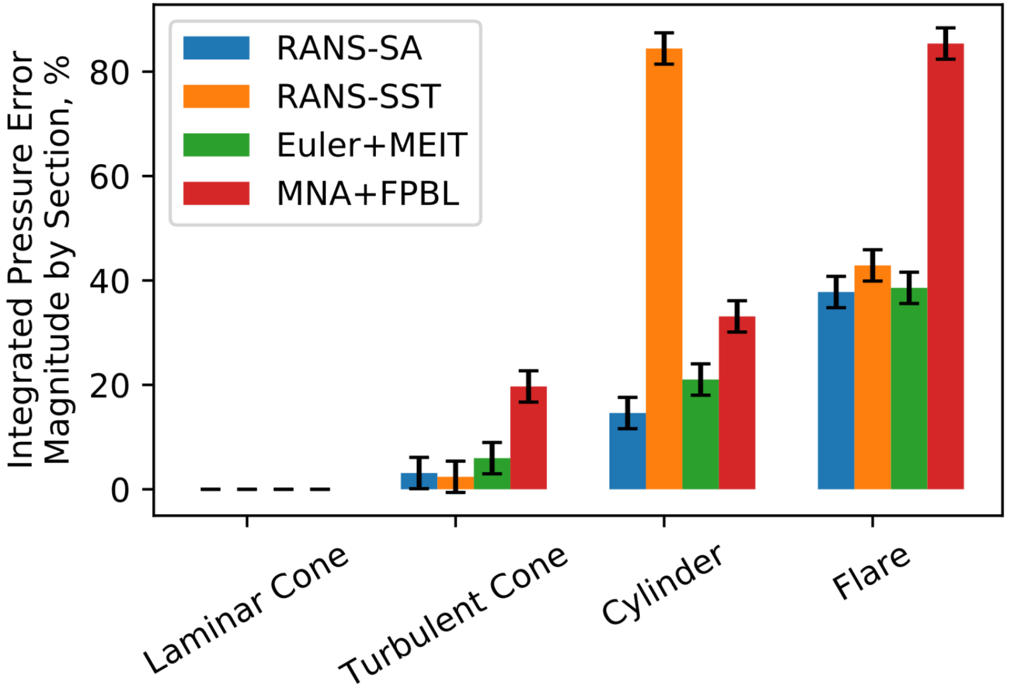
The validation error magnitude $|E|$ is normalized by experimental data and integrated over all space

- RANS-SA is most accurate, followed by Euler+MEIT
- RANS-SST predicts much larger separation region than measured
- Uncertainty bands (error bars) showing only experimental uncertainty (3%)



The validation error magnitude $|E|$ is normalized by experimental data and integrated within each section

- No pressure data for laminar cone section
- The three higher-fidelity models are much more accurate in the turbulent cone and flare sections
- The RANS-SST error is quite large in the cylindrical section



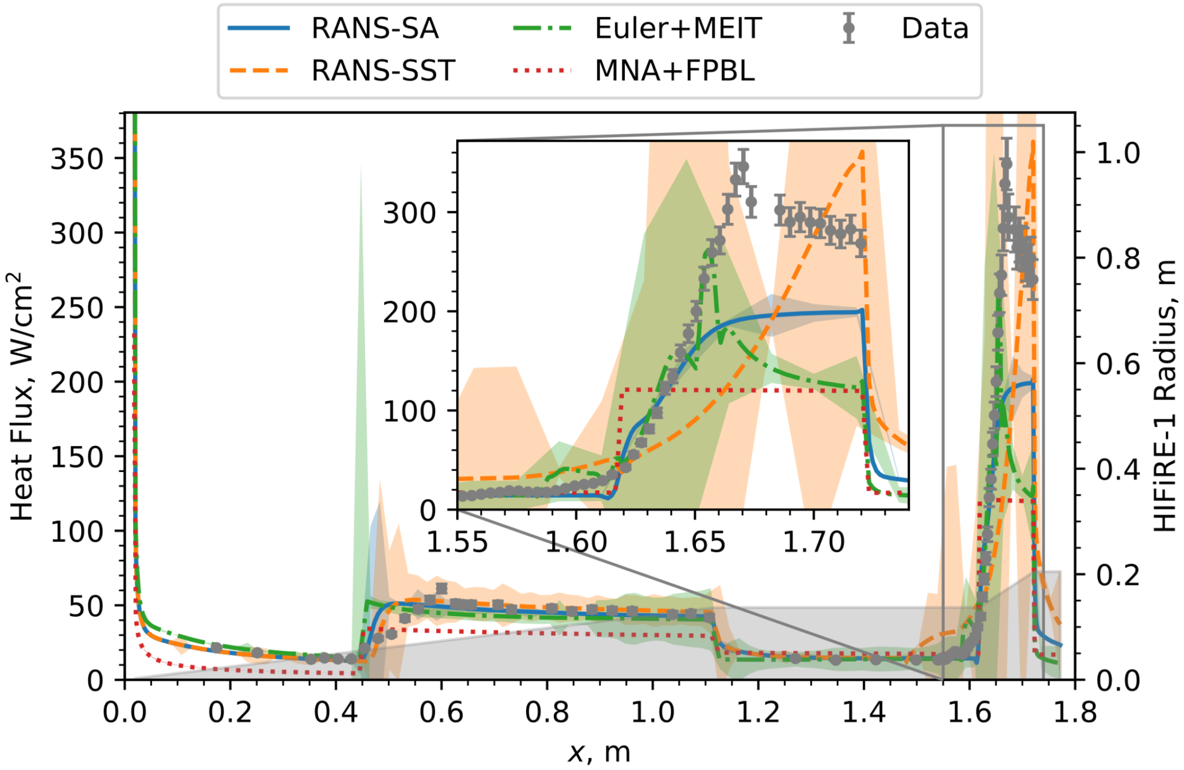
Surface heat flux validation comparisons along axis

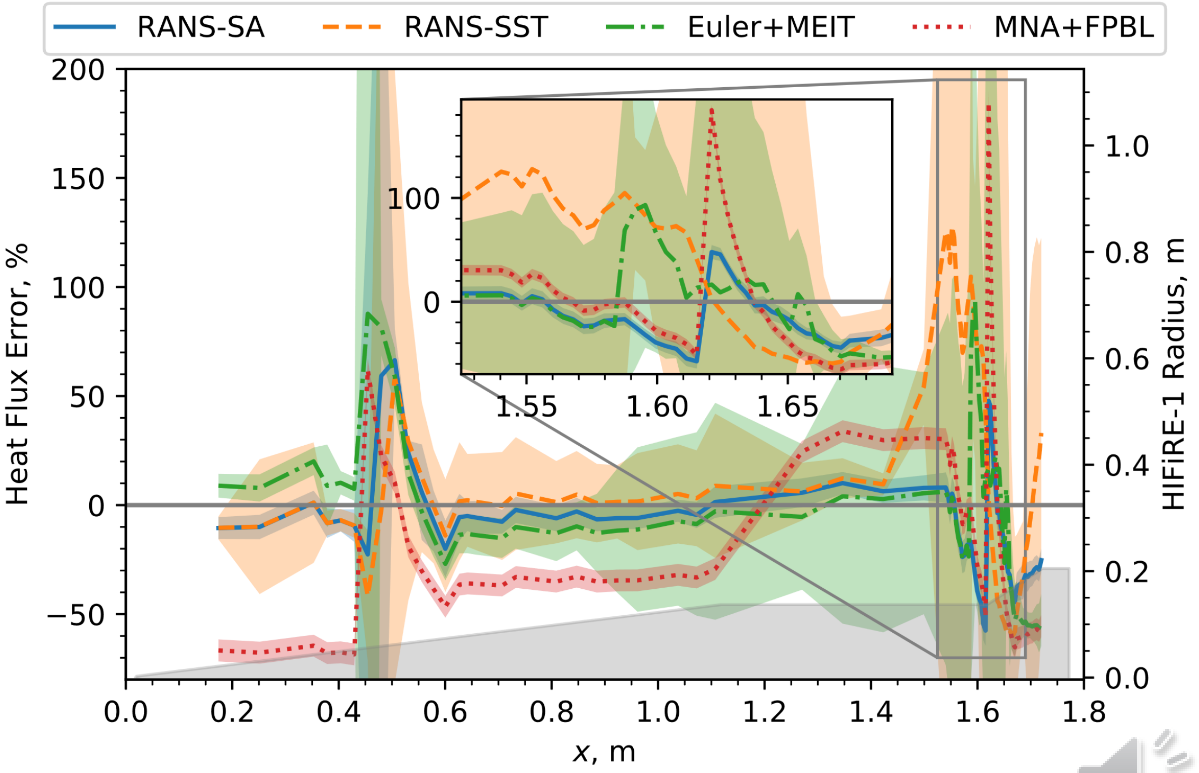
Nominal Results

- Agreement is very good in cone and cylinder sections
  - more challenging near separation and transition ($x \approx 0.45$ m)
- RANS-SA and Euler+MEIT capture separation behavior best

Error Results

- Validation uncertainty is large for RANS-SST and Euler+MEIT
  - Driven by numerical uncertainty
- Higher-fidelity models predict best upstream of separation

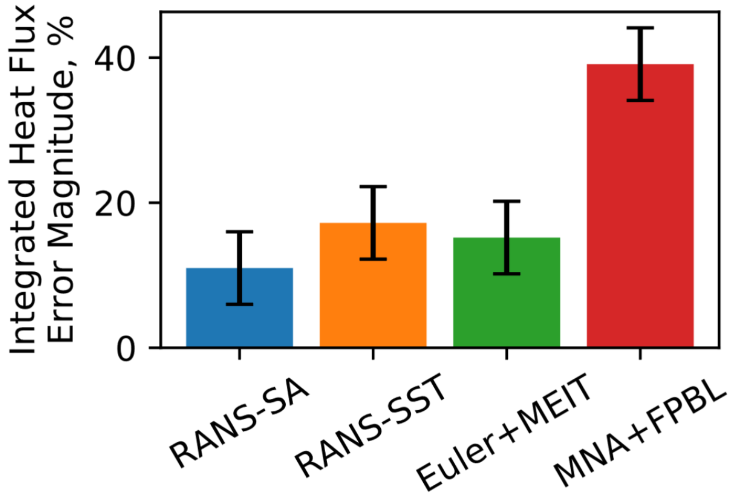




Surface heat flux validation error integrated over space

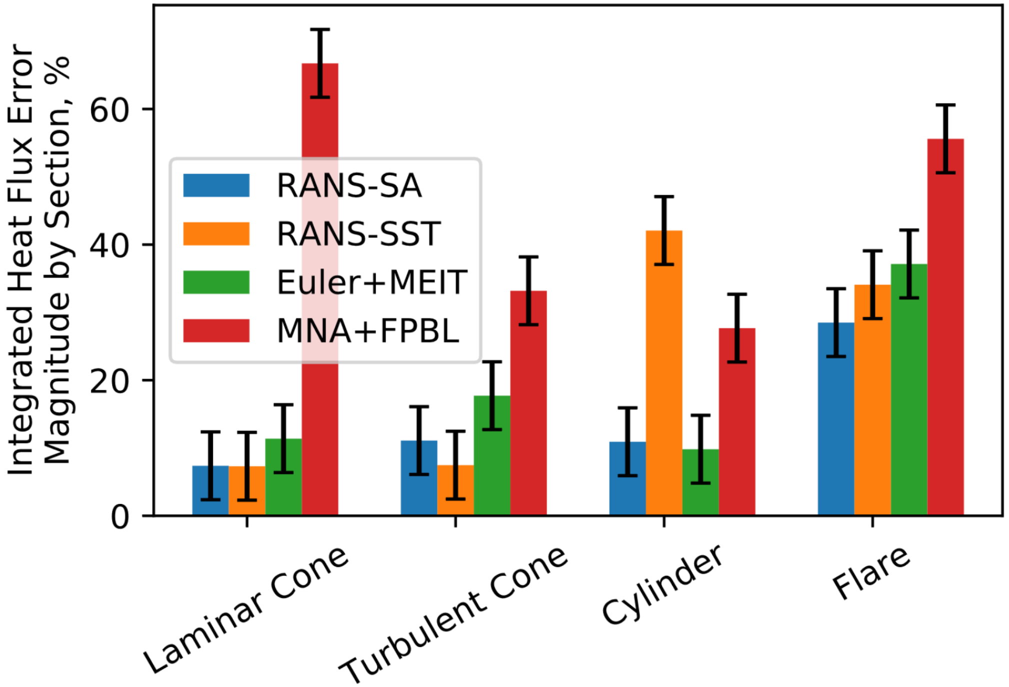
The validation error magnitude $|E|$ is normalized by experimental data and integrated over all space

- RANS-SA is most accurate, followed by Euler+MEIT (same as for pressure)
- RANS-SST predicts much larger separation region than measured
- Uncertainty bands (error bars) showing only experimental uncertainty (5%)



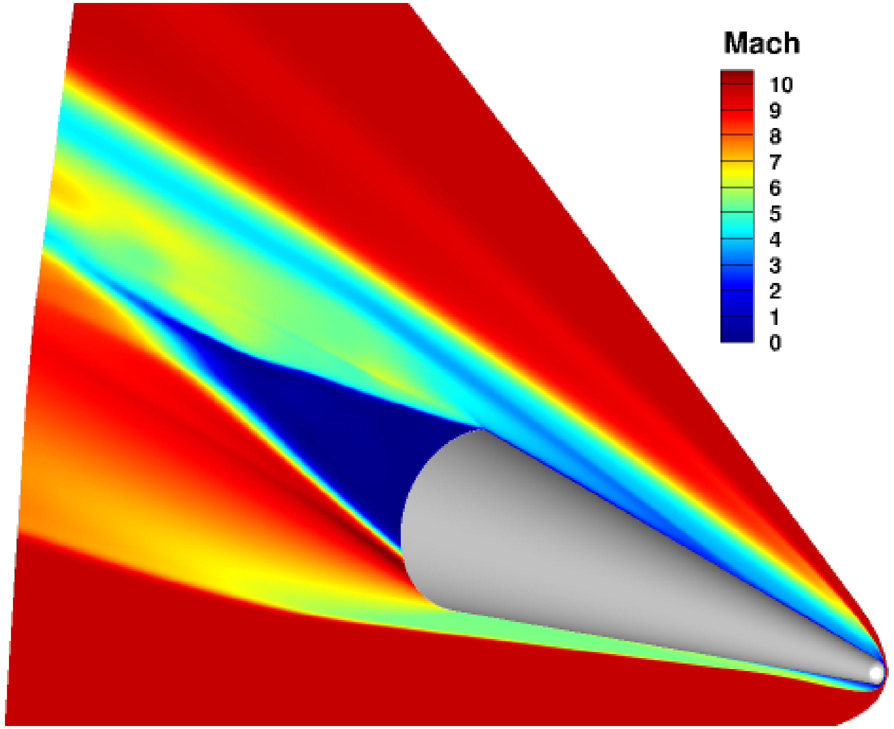
The validation error magnitude $|E|$ is normalized by experimental data and integrated within each section

- RANS-SST is most accurate on the cone
- The three higher-fidelity models are much more accurate in the cone and flare sections
- The RANS-SST error is large in the cylindrical section



Conclusions

- This is the first known validation study for different physics-fidelity models in SPARC (MFTK)
- HIFiRE-1 wind tunnel test data were used for validation
- The RANS models are most accurate for cones
- Most models struggled in the separated region
  - RANS-SA model is most accurate overall
- Lack of grid convergence for RANS-SST and Euler+MEIT should be investigated
- Though not quantified, the reduced fidelity models have sizeable speedup
  - ~100× for Euler+MEIT over RANS
  - ~100× for MNA+FPBL over Euler+MEIT



“Hypersonic Research at Sandia National Labs”, Aerosciences Org 1515