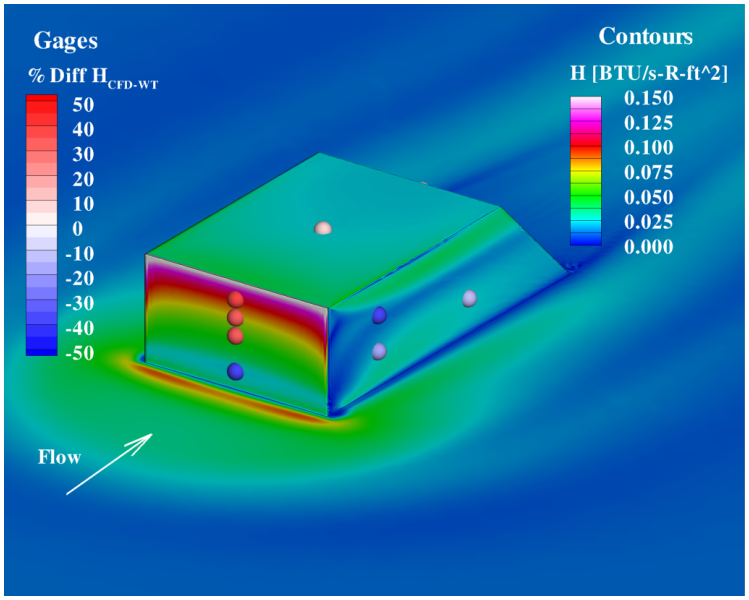
High Speed Turbulence Working Group

Lessons Learned from CFD Validation Study of Protuberance Heating



May 3, 2011

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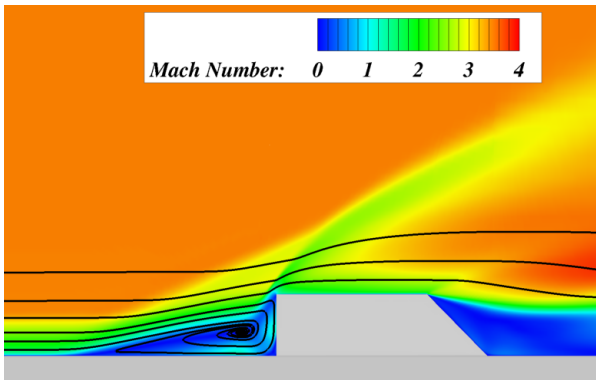
Presentation Objectives

- **Share lessons learned from a recent exercise in CFD validation of protuberance heating**
  - Impact of experimental data reduction assumptions and techniques on validation activity
  - Advanced data reduction techniques may provide useful data from non-typical test methods
  - Significance of the recovery factor for high-speed flows
- **Show typical results of the Lag turbulence model on protuberances**
- **Introduce and inform the listener of a protuberance heating dataset which will soon be available for comparison**

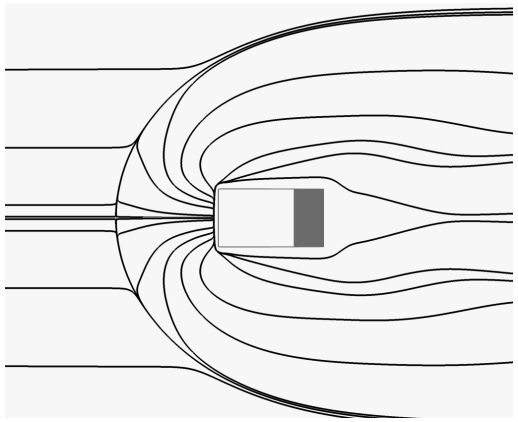
Case Description

- **Objective of present work is to assess the accuracy of heating solutions on 3D protuberance flows**
  - 3D protuberance geometry provides a stiffer test than simple unit problems, but are less complicated than flight-relevant cases
  - Recently acquired wind tunnel data is available to aid in the analysis
  - Front-face of protuberance perpendicular to flow, with the height being just above the height of the incoming boundary layer
- **CFD run with the OVERFLOW code using the Lag turbulence model**
  - Our previous work indicated that Lag performed the best at predicting separation in plan compression ramps

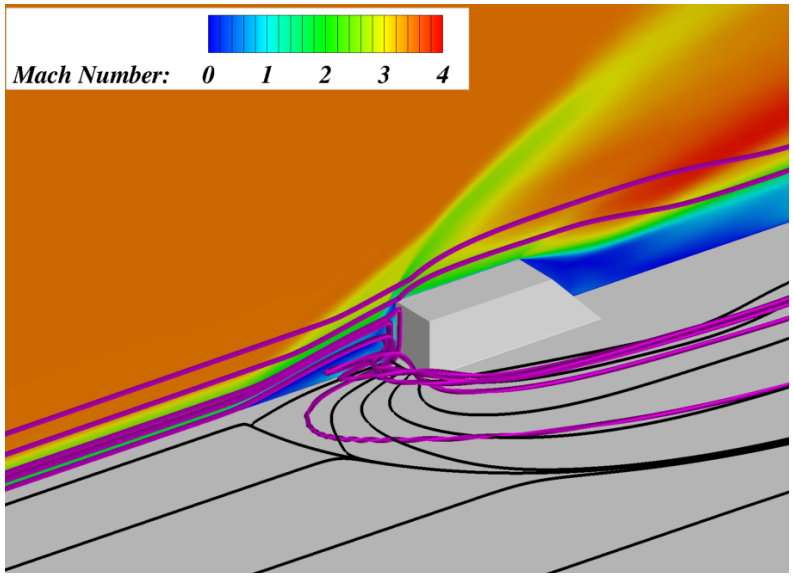
Mach 3.5 Freestream:



Side View

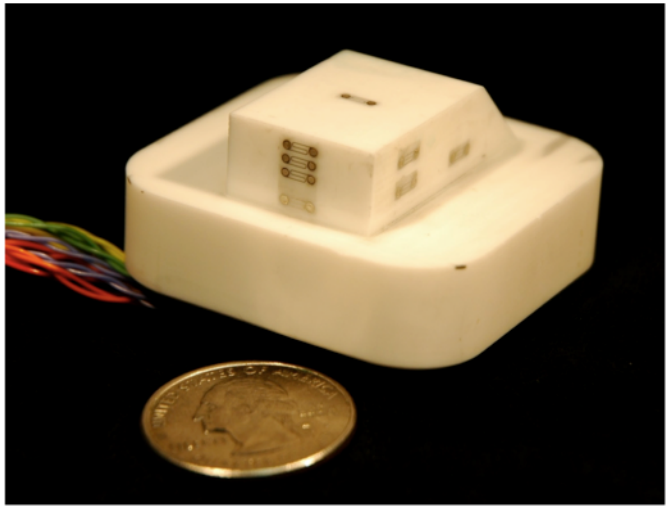


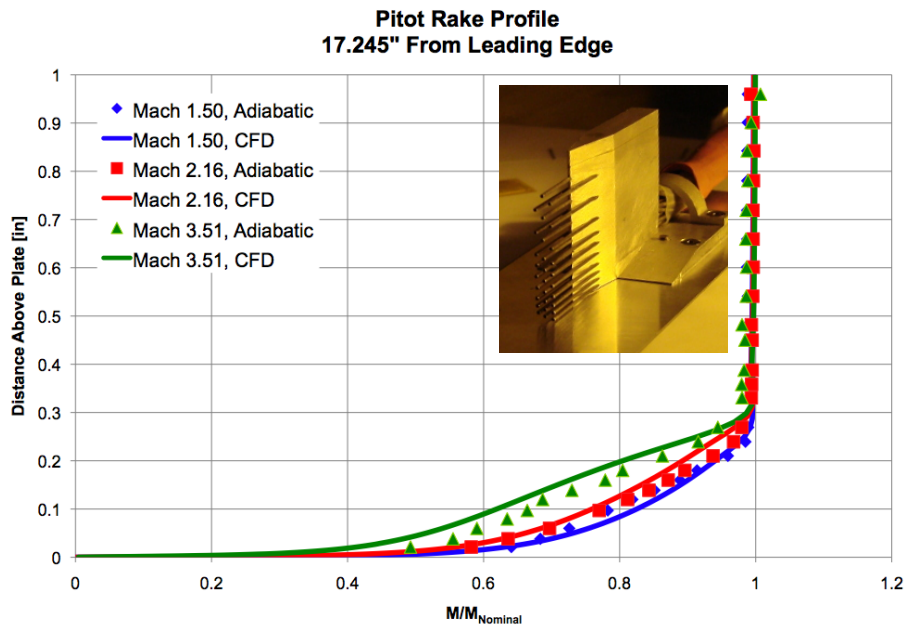
Top View



Shuttle/Ares Protuberance Heating Test

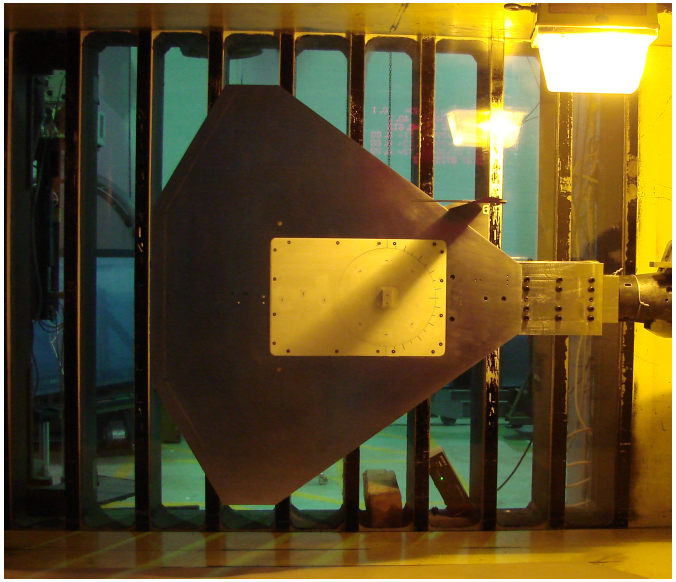
- **Test objectives:**
  - Duplicate and extend 60's era test which is used for ET protuberance environments
  - Obtain heating data useful for CFD model validation
- **Geometry and Conditions:**
  - 11 different Macor protuberances on a flat plate
  - Mach numbers of 1.5, 2.16, 3.51
  - Reynolds number ~5e6 ft^{-1}
  - Protuberances in turntable to permit crossflow variation
  - Boundary layer tripped at plate leading edge (grit)
- **Instrumentation:**
  - Thin-film gages
  - IR thermography
  - Limited surface pressure measurements
  - Boundary layer rake
  - Freestream measurements in test section near protuberance models

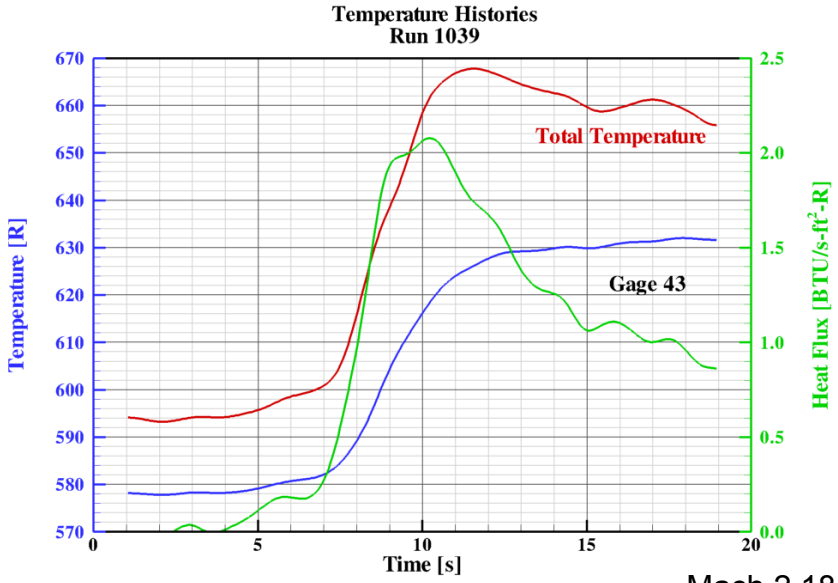




Shuttle/Ares Protuberance Heating Test

- **Run Technique:**
  - Closed-circuit tunnel w/o injection mechanism
  - Model exposed to flow at steady conditions to heat soak until in thermal equilibrium
  - A 'heat pulse' was initiated in the tunnel which increased the total temperature, driving heating which was measured by instrumentation over 15-30 seconds
  - Tunnel allowed to cool down and model soaked for next run
  - Post-test, the measured surface temperatures were reduced to time-histories of heat flux using the Cook-Felderman 1D reduction method
- **A considerable amount of effort has been directed at making sure this data is reduced correctly**
  - Planning, execution, and analysis of the data has extended >4 years
  - Although it is a very complicated dataset, a significant amount of effort has been put into reducing, understanding, and correcting the data.
  - It is nearly in a form that can be used for CFD validation.

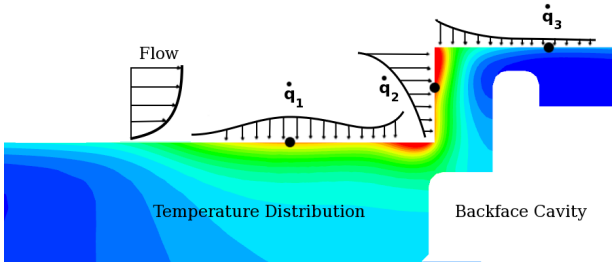


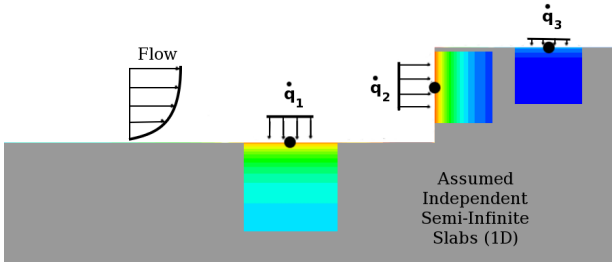


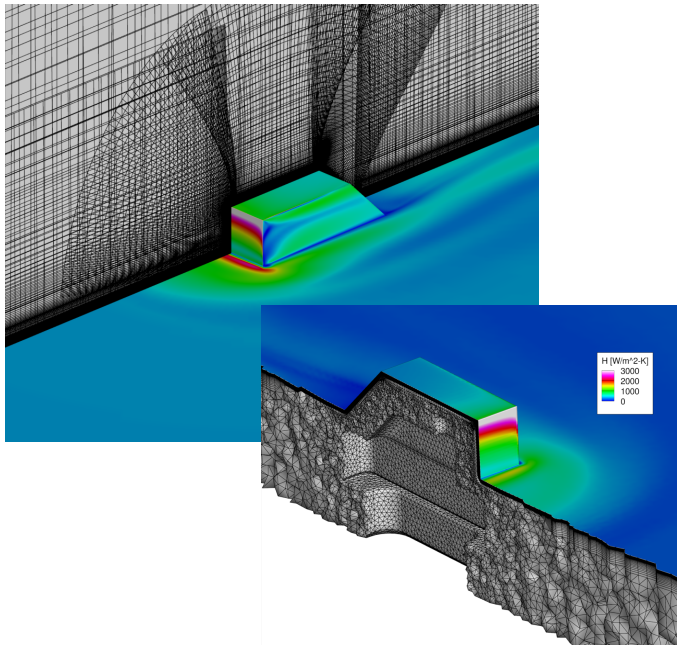
Mach 2.18

Known Issue With Protuberance Test

- **Long run times and small model sizes bring into doubt the 1D conduction assumption used to reduce thin-film temperatures to heat fluxes**
- **A thermal analysis technique was developed to introduce '3D conduction errors' into CFD predictions in order to compare to test data on similar terms**
  - CFD predictions of recovery factor and heat transfer coefficient are used to drive a thermal simulation of the wind tunnel run
  - The results of thermal analysis are reduced from temperature to heat flux just like the tunnel data, introducing the same errors
  - These numbers can be meaningfully compared
  - Method cannot be used to 'correct' the tunnel data, as it is dependent on an un-validated CFD result
- **Currently developing a simplified 3D inverse heat conduction capability to eliminate the need for the CFD computation of heating and recovery factor distributions**
  - Trends from this and other protuberance heating tests will define distribution shapes, and the inverse code will scale the distributions appropriately to match the test data







Recovery Factor

- **The recovery factor was found to be a particularly important parameter**
  - Non-uniform thermal conditions necessitates reducing data to heat transfer coefficient:

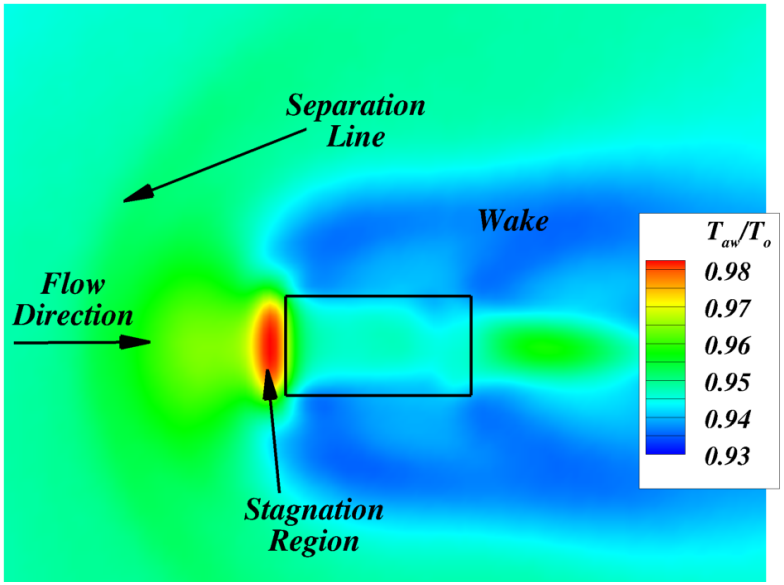
$$H = \frac{q''_w}{T_{rec} - T_w}$$

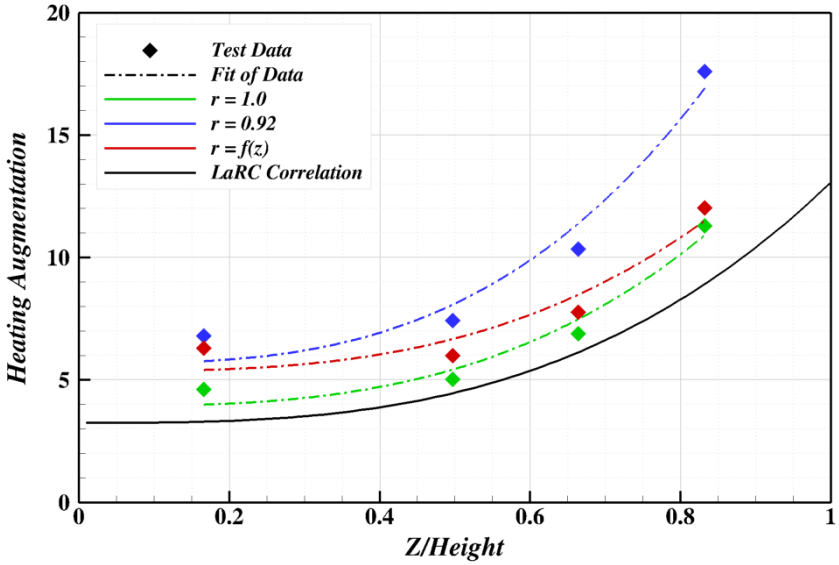
    - The recovery factor in the protuberance flowfield was observed to vary in space

$$r = \frac{T_{rec} - T_{edge}}{T_o - T_{edge}} \qquad r \approx \frac{T_{rec}}{T_o}$$

  - The low driving potential makes the resulting heat transfer coefficient particularly sensitive to the assumption of recovery factor used
    - The model begins the run with T_w very near T_{rec}
    - The heat pulse only increased T_o by ~10%
- **Given observation of varying recovery factor, data reduction from conventional tunnels becomes more difficult**
  - Heat flux is only half the story

Mach 2.16 Protuberance Recovery Factor



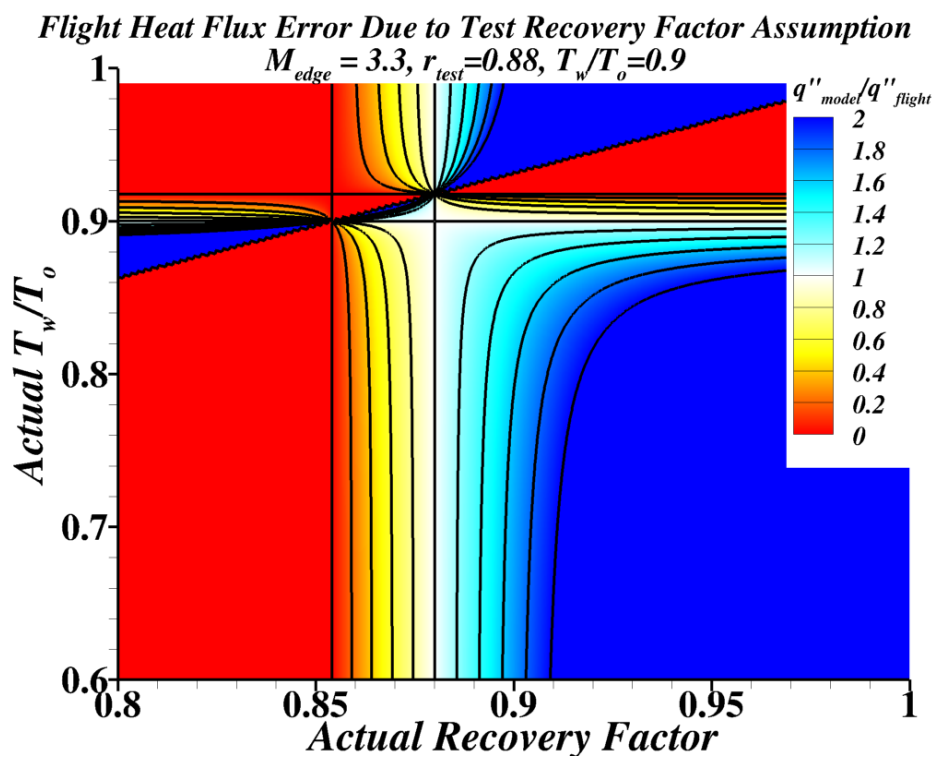


Recovery Factor

- **Subsequent work on launch vehicle ascent environments indicated that similar conditions actually exist in ascent flight environments**
  - Relatively low freestream enthalpy & high surface temperatures (due to effective TPS materials) yields flows with low driving potential
  - High edge Mach numbers yields flows with significant contributions to the total temperature from kinetic energy
  - When the kinetic contribution to the recovery enthalpy is of the same order as the driving potential, the recovery factor will be important for scaling to flight
  - Must make recovery factor assumption twice:
    - Reducing test data
    - Computing flight heat flux
- **In much of the work I've come across to date, it does not appear that this factor is regularly given much thought**

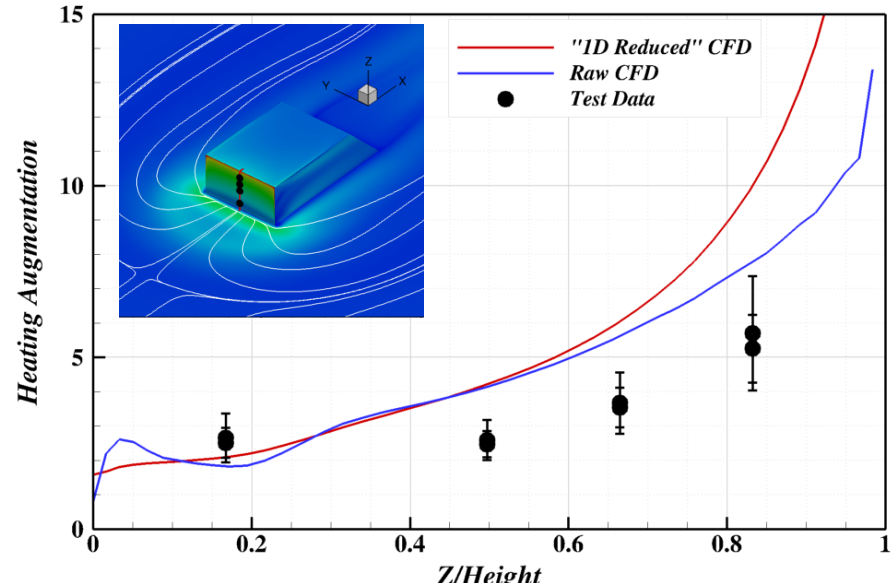
$$H = \frac{q''_w}{T_{rec} - T_w}$$

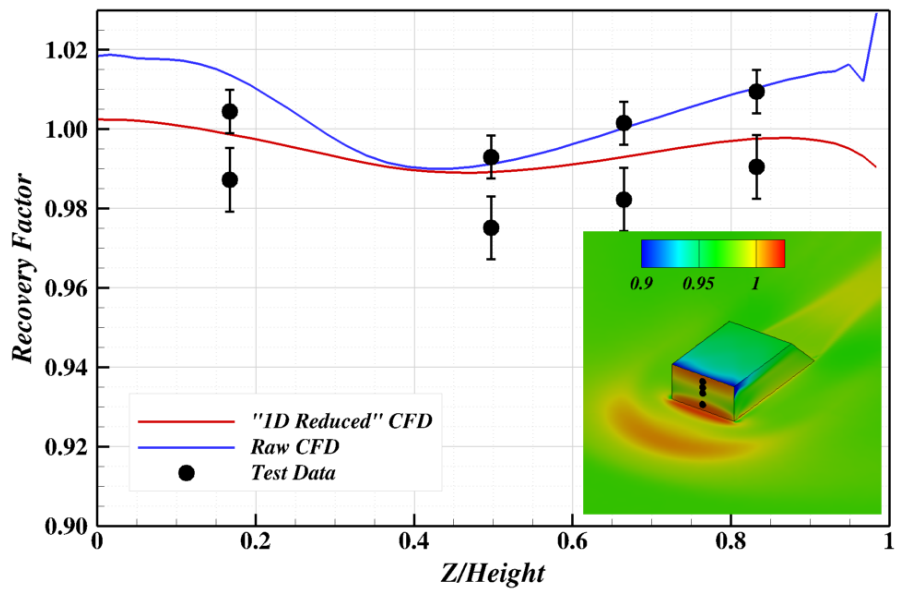
$$r = \frac{T_{rec} - T_{edge}}{T_o - T_{edge}}$$



Mach 1.50 CFD Results

- **CFD generally over-predicts heating**
  - Consistent trend across the Mach number range and protuberance geometries run
  - This observation is consistent with other work using the Lag turbulence model
- **CFD predicts recovery temperatures in excess of the freestream total temperature**
  - Adiabatic wall boundary conditions
  - Approximate recovery factor formulation
  - Trend is consistent with other work
- **Conduction errors have not been removed from the data yet**
  - Estimate of conduction error given by difference between 'Raw' and '1D Reduced' lines
- **Other analysis (not shown) indicates that we may be overestimating the conduction errors**





Summary

- **Even a simple protuberance on a flat plate presents a difficult challenge**
  - Unable to obtain solid grid convergence…grids became too large for numerical stability
  - Heating estimates for 'engineering predictions' were higher than observed, especially in the highly separated region
- **Test data and analysis indicates that the recovery factor needs more attention than I think it typically gets**
  - Definitely must address how to appropriately scale heat flux with wall temperature/enthalpy for design applications
  - The recovery factor could be a function of wall temperature (ie: heat-flux vs wall temperature may not be a linear relationship)
- **Shuttle/Ares Protuberance Heating test will soon have some data available for validation work**
  - Not necessarily of adequate quality for high-quality validation studies, but will be good for the studies between unit problems and real-world application
  - More advanced data reduction techniques being developed for this dataset could open the door for more heating tests in university level research facilities
- **Future work**
  - Make protuberance data available to others
  - Implement a couple algebraic turbulent heat flux models in OVERFLOW and assess performance