National Aeronautics and Space Administration

Challenges in Modeling Hollow Objects in the Transition Flow Regime

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Introduction

- The Object Reentry Survival Analysis Tool (**ORSAT**) is the primary NASA computer code for predicting the reentry survivability of satellite and launch vehicles
- ORSAT assumes primitive shapes to compute drag and heating coefficients for orbital debris re-entry analysis
  - Most re-entry analysis includes hollow bodies
  - ORSAT does not currently account for flow through hollow bodies

Initial Objective:

- Use high fidelity computational tools to determine drag and heating coefficients for hollow bodies
- Determine a “hollowness” criterion that can be used in engineering model

Background

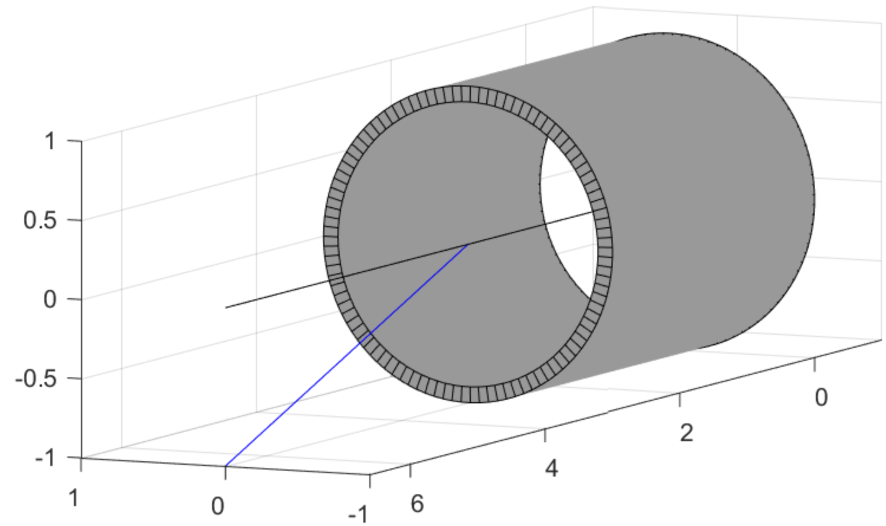
- **Drag and aeroheating coefficients in the transition flow regime are extremely difficult to verify and validate**
  - Wind tunnel time is expensive and may not accurately capture all desired flow characteristics
  - CFD inaccurate for 'high' Kn; TPMC inaccurate for collisional flows
  - DSMC is also expensive (wall clock and CPU cycles)
  - We typically use transition functions
    - **Sigmoid, log-sine, others common**

- **If solid objects are difficult enough to model, how do we deal with hollow objects?**

- **And what does "hollow" mean?**

Background

- **We frequently deal with hollow objects in reentry simulations (pipes, telescopes, etc)**
  - Typically model these using same “solid” shape primitive, just with less surface area for drag and heating
- **But!**
  - Blockage due to leading edge shocks can increase drag on hollow objects
  - Heating on inner surface needs to be accounted for



Approach (Phase I)

- Use NASA JSC Direct Simulation Monte Carlo (DSMC) Analysis Code (DAC) to simulate hollow-bodied cylinders and prisms in rarefied flow
  - Determine drag and heating coefficients from results
  - Establish a “hollowness” criterion:

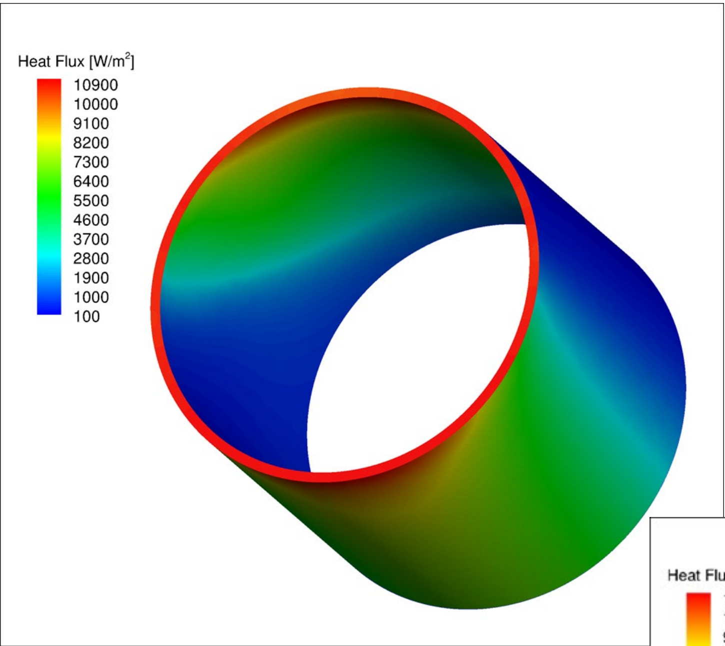
$$HC_1 = \frac{\dot{m}_{thru}}{\rho_\infty V_\infty A_{inner}} \qquad HC_2 = \frac{\dot{m}_{thru}}{\rho_\infty V_\infty A_{outer}}$$

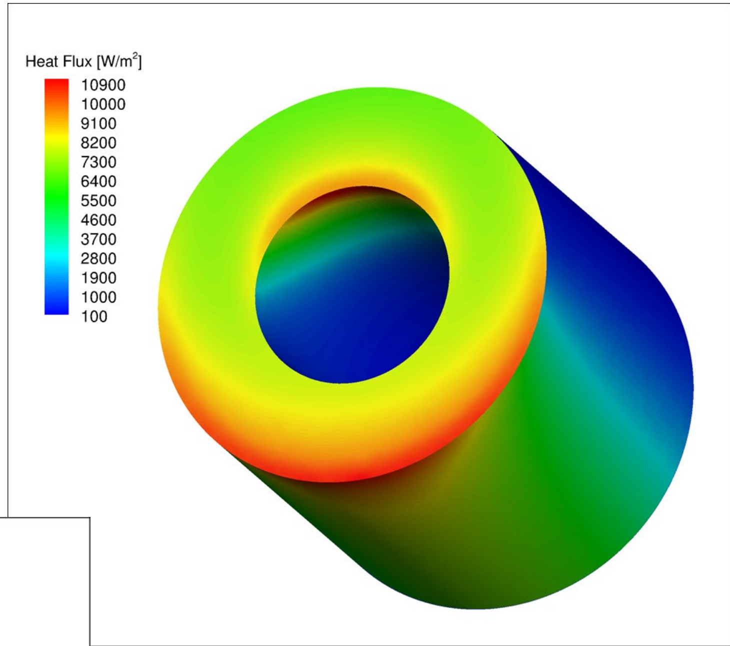
Input Quantity	Value
Altitude (km)	111.375
Freestream Speed (m/s)	7800
Freestream Density (kg/m3)	7.61E-08
Freestream Temperature (K)	256.5
Wall Temperature (K)	300
Knudsen Number	0.2, 1, 10
Outer Diameter (m)	0.1, 1, 5
ID/OD ratio	0.1, 0.5, 0.95
Angle of attack (°)	0, 45, 90
Fineness ratio (Length/Diameter)	0.1, 0.5, 1

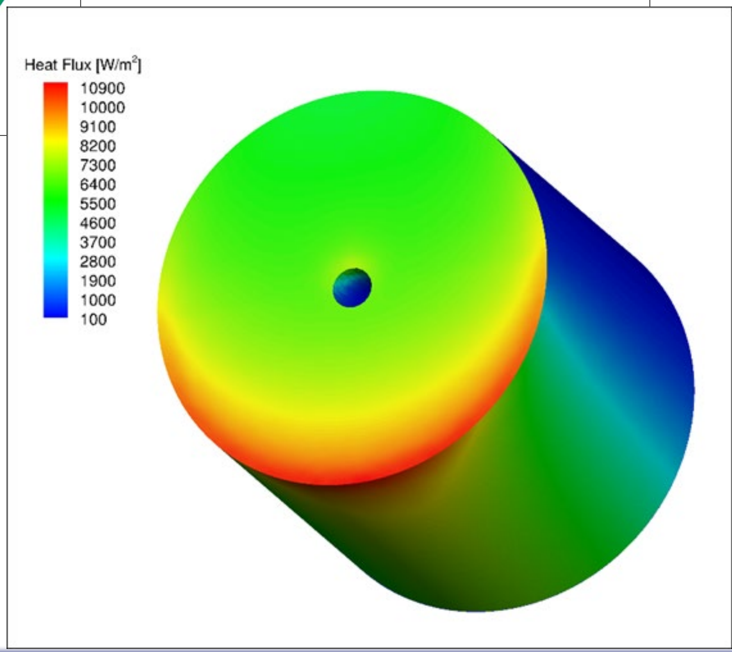
Results (1/7)

- Current total of 81 cases
- DAC simulations results shown:
  - Cylinder and Square Prism
  - 45^o AoA
  - ID/OD = 0.1, 0.5, 0.95
  - Fineness ratio (L/D) = 1.0, 0.5, 0.1
  - Drag Coefficient carpet plots (function of ID/OD and L/D)
    - Kn = 10, 1.0, 0.2
  - Velocity contours (centerline slices) for Cylinder at 0^o AoA
    - ID/OD = 0.1, 0.5, 0.95

Results (2/7)

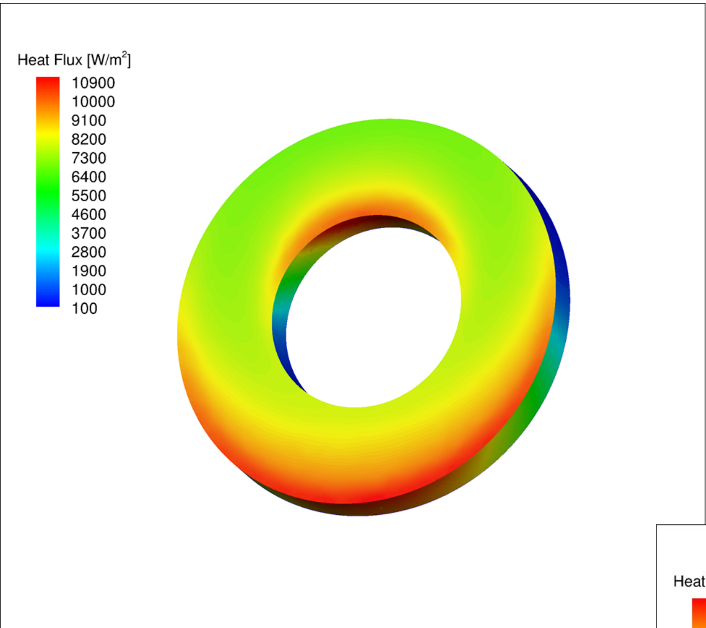


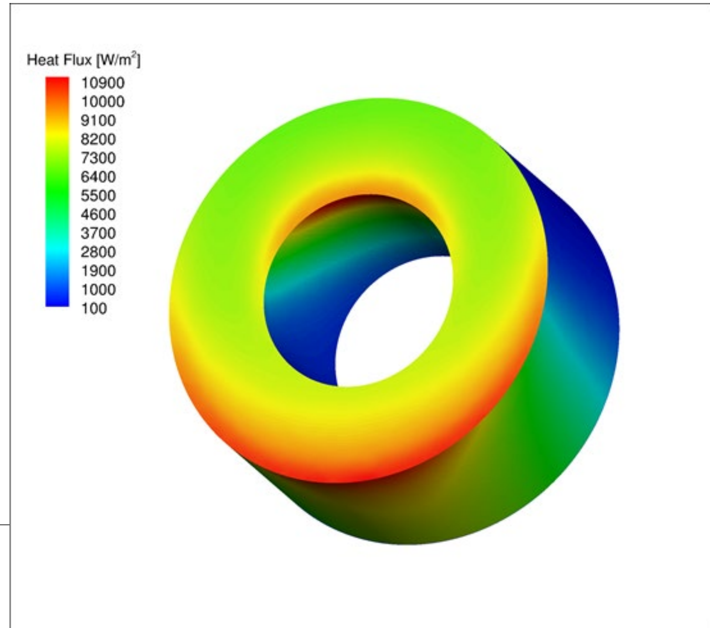


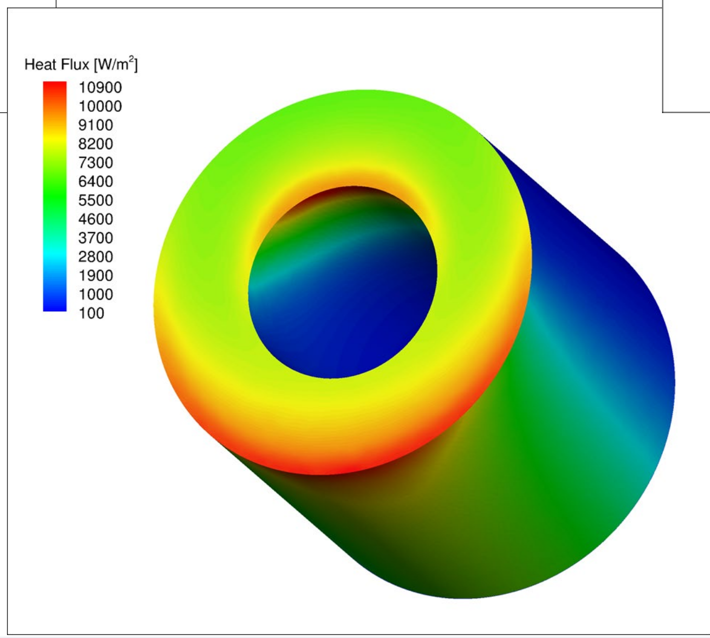


Same Kn
Same L/D
Varying ID/OD

Results (3/7)

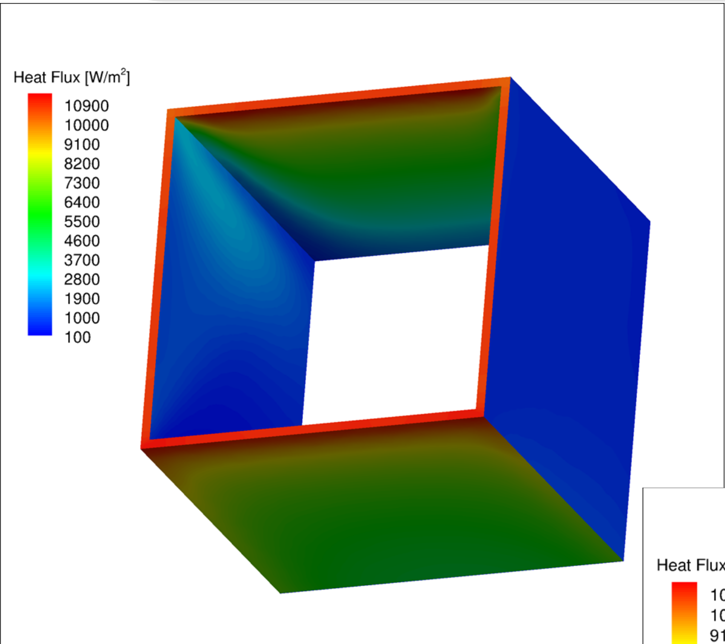


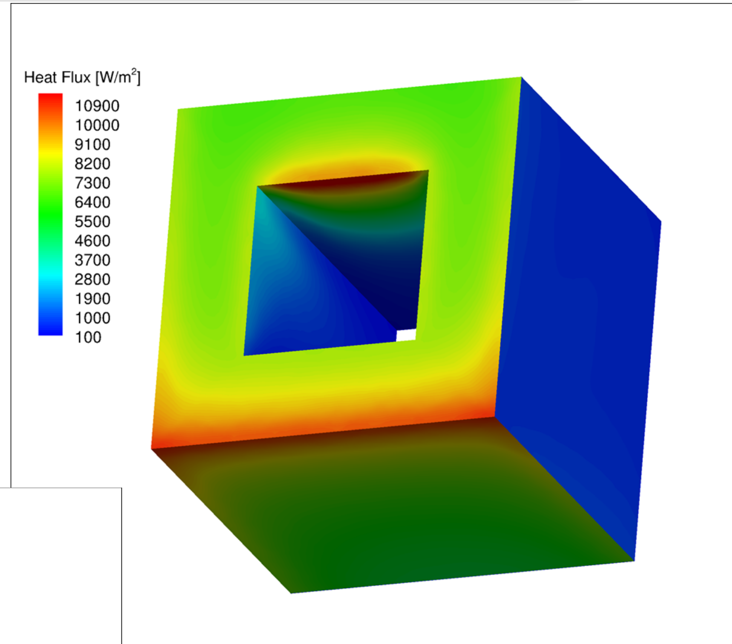


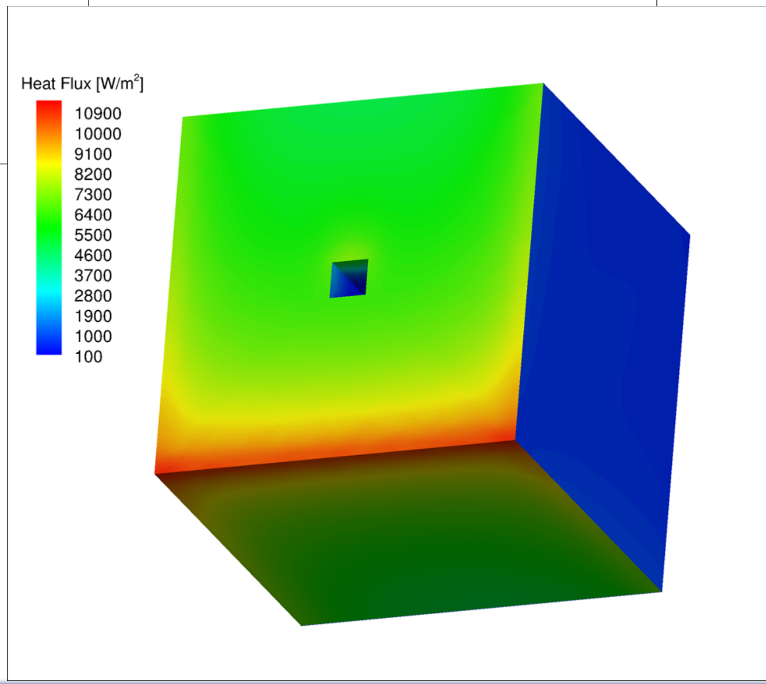


Same Kn
Same ID/OD
Varying L/D

Results (4/7)

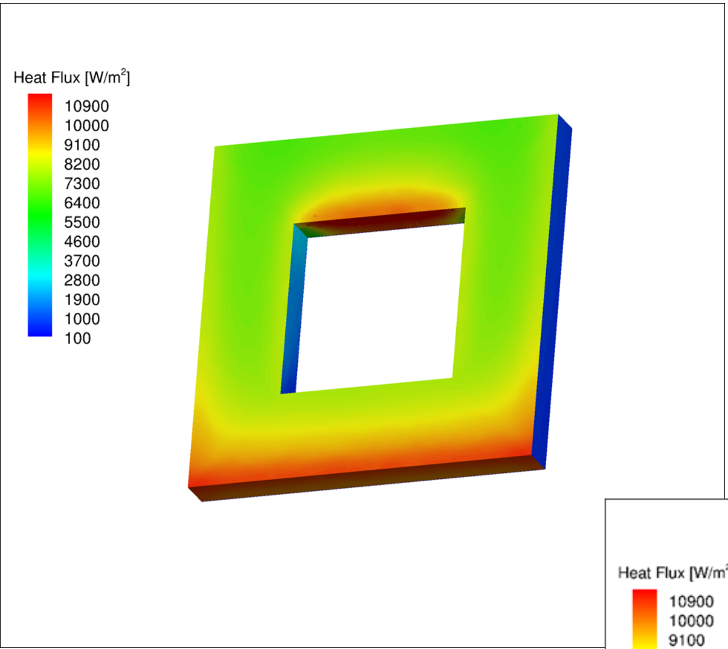


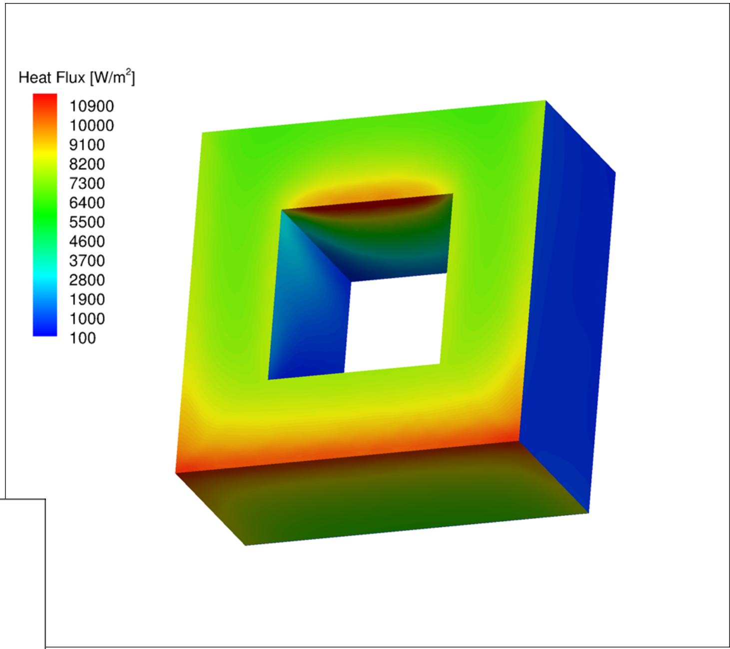


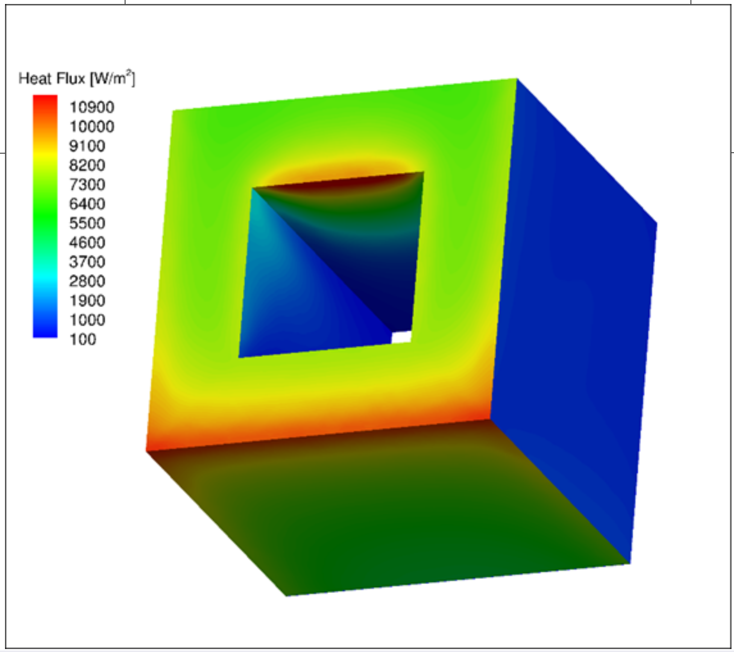


Same Kn
Same L/D
Varying ID/OD

Results (5/7)

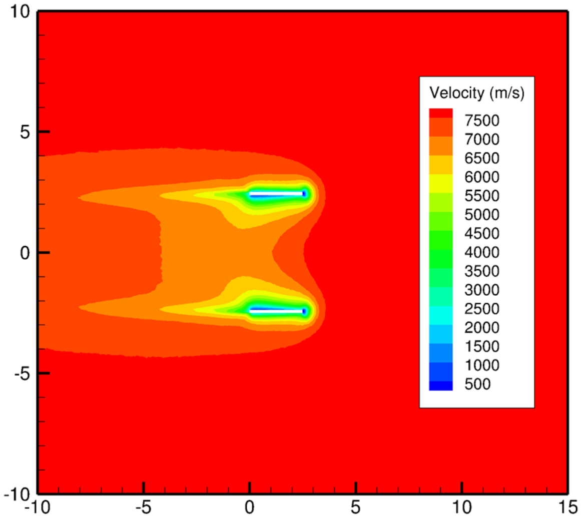


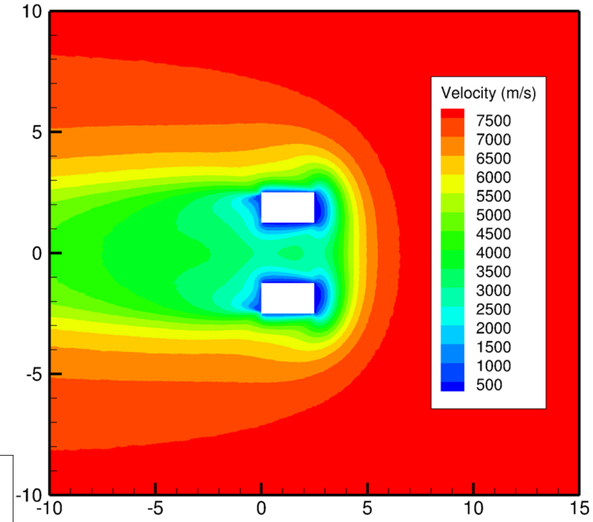


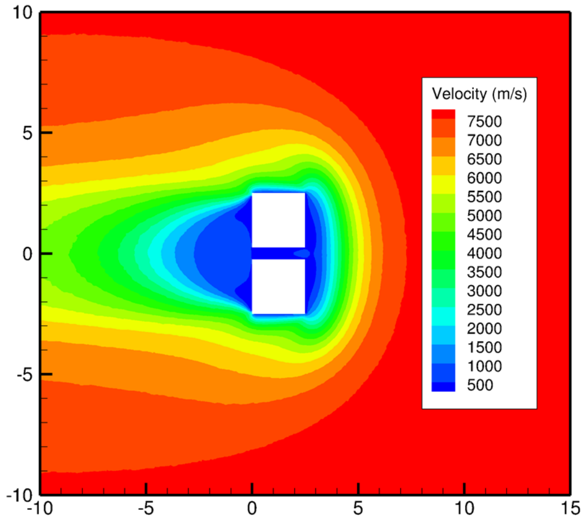


Same Kn
Same ID/OD
Varying L/D

Results (6/7)

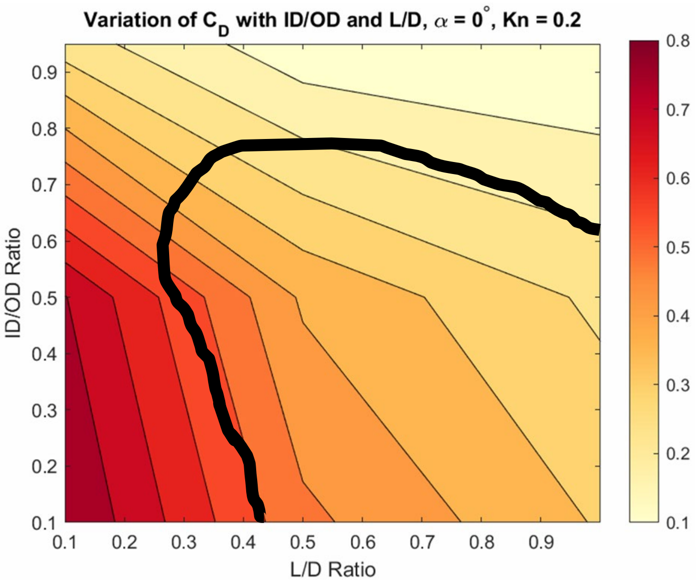


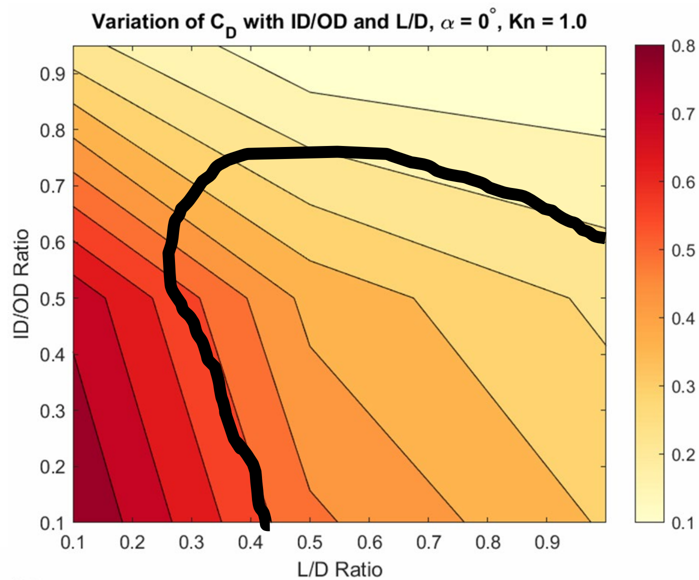


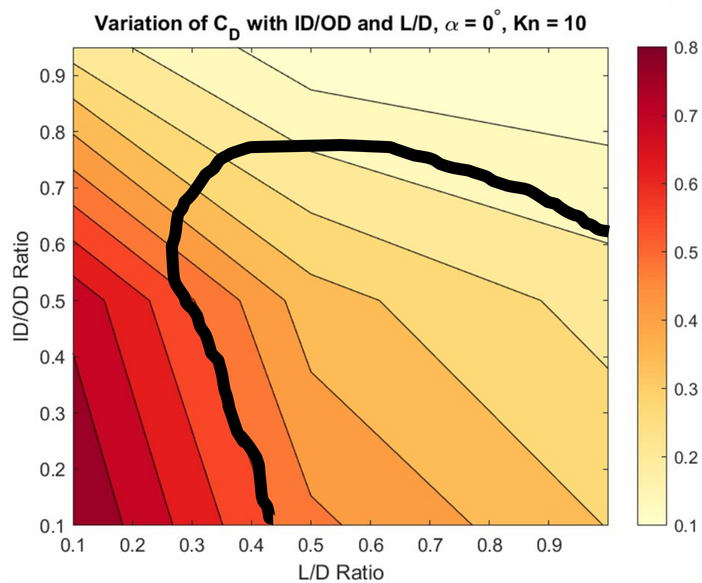


Same Kn
Same L/D
Varying ID/OD

Results (7/7)


Variation of C_D with ID/OD and L/D, $\alpha = 0^{\circ}$, Kn = 0.2
ID/OD Ratio
L/D Ratio
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9


Variation of C_D with ID/OD and L/D, $\alpha = 0^{\circ}$, Kn = 1.0
ID/OD Ratio
L/D Ratio
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9


Variation of C_D with ID/OD and L/D, $\alpha = 0^{\circ}$, Kn = 10
ID/OD Ratio
L/D Ratio
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Approach (Phase II)

- Continue DAC simulations of solid and hollow-bodied cylinders and prisms in rarefied flow
  - Determine drag and heating coefficients from results
    - Validate current transition flow model for solid bodies, expand hollow body model
  - Implement multi-dimensional database for use in ORSAT 7.0

Input Quantity	Value
Altitude (km)	95-112 km
Wall Temperature (K)	300
Knudsen Number	0.1, 0.5, 1, 5, 10
Outer Diameter (m)	1
ID/OD ratio	0.1, 0.5, 0.95
Angle of attack (°)	0, 22.5, 45, 67.5, 90
Fineness ratio (Length/Diameter)	0.1, 0.5, 1, 2, 5

1000 DAC simulations to be run

Summary

- DAC simulations were used to determine drag and heating coefficients for hollow bodied cylinders and square prisms with varying parameters
- Began quantifying effect of flow through hollow body to establish a “hollowness” criterion
- Developed sparse data tables to be used in the ORSAT aerodynamic and aerothermodynamic models
- Phase II includes new Knudsen numbers, geometric ratios and object orientations

Questions?

References

- **See Marichalar, J. and C. Ostrom (2019)**
  - https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6019.pdf

- **Scanlon et al. 2015:**
  - "Simulations of rarefied and continuum hypersonic flow over re-entry objects," 8th European Symposium on Aerothermodynamics for Space Vehicles, Lisbon, Portugal, ESA Conference Bureau, 2015.