Internal Heat Transfer Measurements on Hollow Bodies in Rarefied Flow

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Motivation & Experimental Facility

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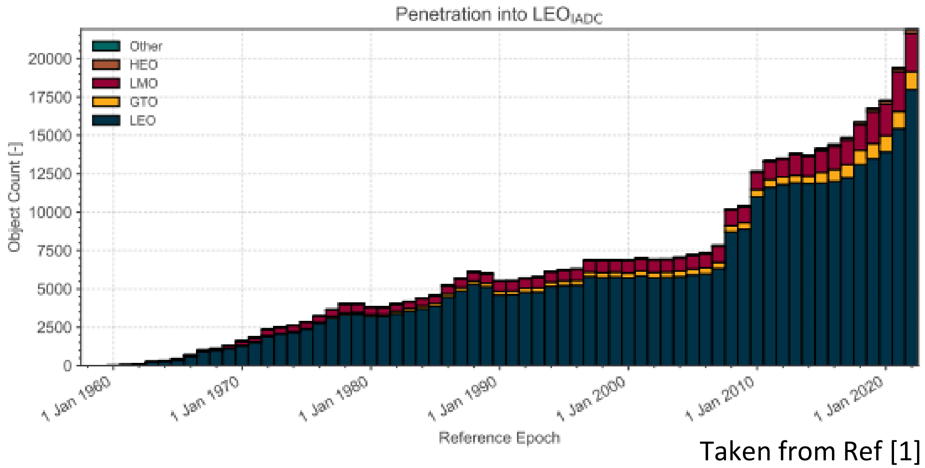
Motivation

- Need to anchor satellite destructive entry calculations with high-quality experimental data

Aim

- Provide heat transfer data for hollow geometries in the hypersonic rarefied slip and transition regimes
- Extend experimental capability to thin-shells and multiple cameras

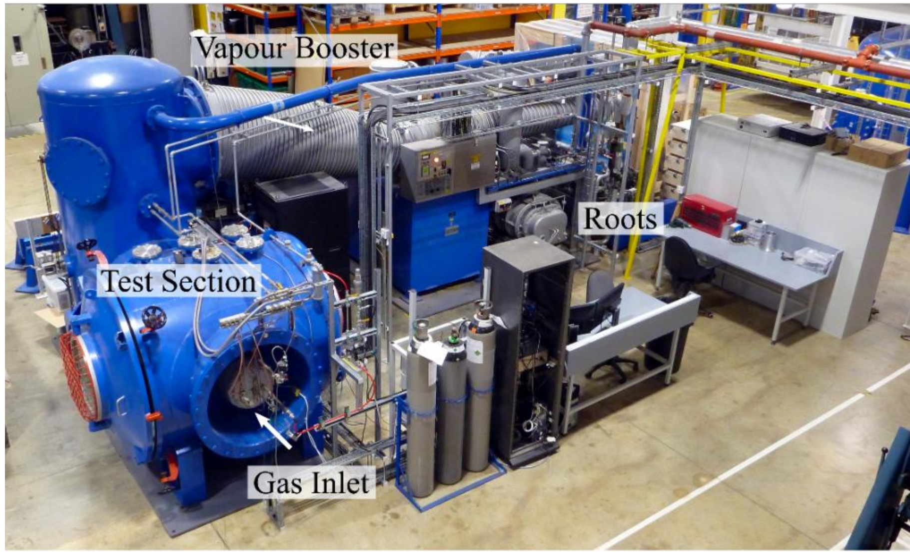


Taken from Ref [1]

Facility: Low Density Tunnel*

- Continuous facility; 3-stage vacuum pump
- Test gas: dry air at w = 25 SLPM
- Contoured nozzle; exit diameter 108 mm

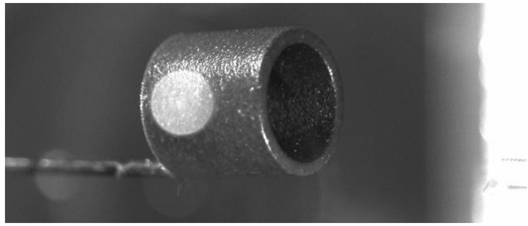
Property	Unit	Value
Nozzle supply pressure	Pa	2705
Pitot Pressure	Pa	110
Total temperature	K	363
Knudsen number	-	0.02
Mach number	-	5.5



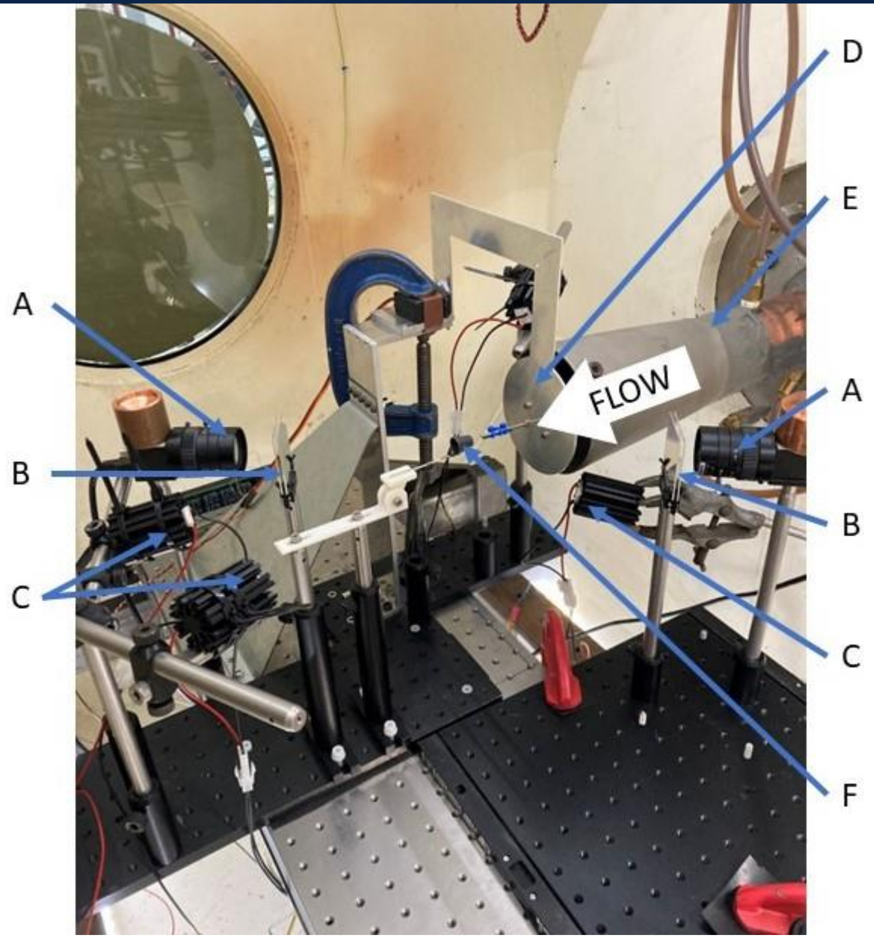
*see Ref [2] and poster for details

Experimental Setup

- Thermochromic liquid crystals (LX)
  - Pressure invariant
  - Relatively simple experimental set up but complex analysis
- Cameras
  - 2 x Ximea 3.1 Mpix (2064 x 1544)
- LEDs (x4)
- Alignment
  - Difficult to avoid glare

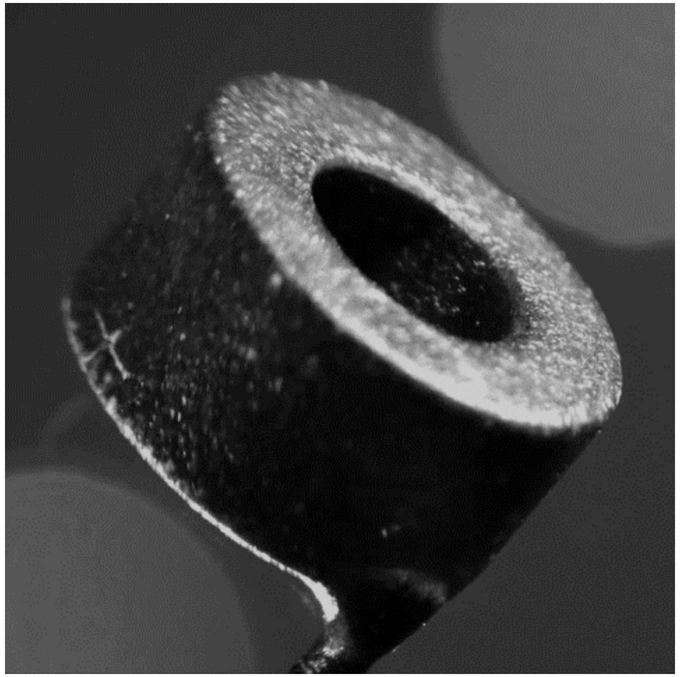


Diameter = 15 mm

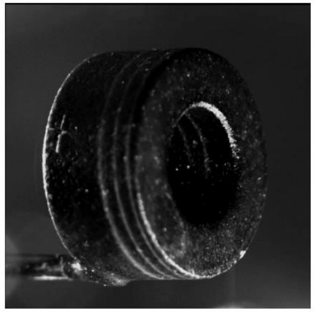


A – camera; B – optical filter;
C – LED; D – Flow Shield; E – Nozzle;
F - Model

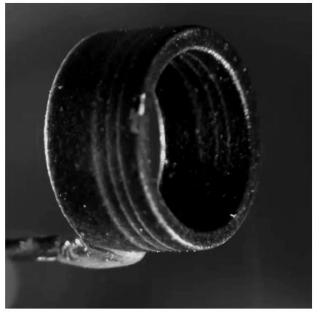
Results: Raw Video



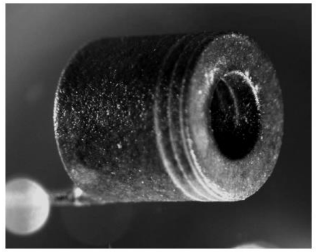
LX transition temperatures = 30°C, 35°C, 40°C



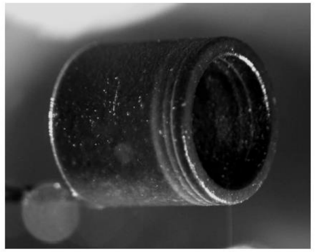
(a) AR05_DR05



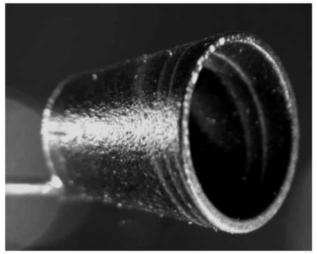
(b) AR05_DR08



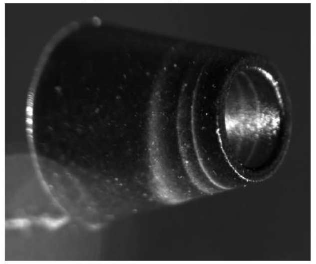
(c) AR10_DR05



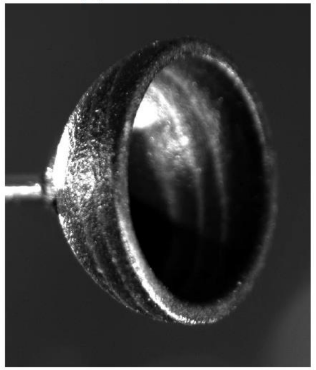
(d) AR10_DR08



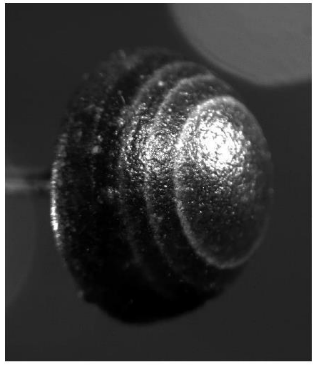
(e) CS_Wide



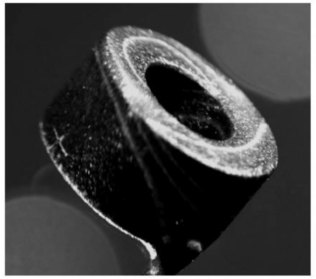
(f) CS_Narrow



(g) HS_Open



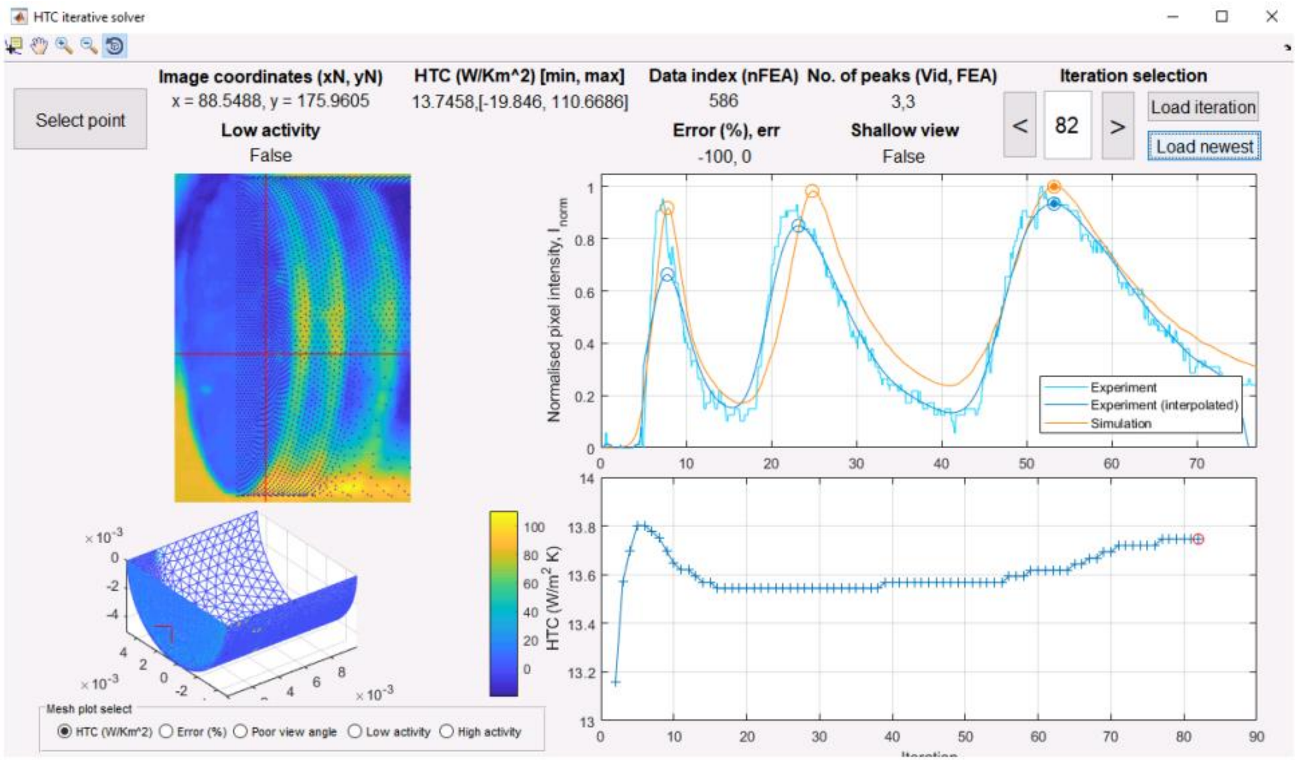
(h) HS_Closed



(i) AR05_DR05_AOA45

Results: Processing

- Assumes a step change in flow temperature
- Surface temperature transiently increases to eventually match the (local) adiabatic wall temperature
- In-house code (3DHTCS) coordinates COMSOL finite-element transient heating simulation:
  - Developed by Donaldson [3,4] for 3D geometries based on work of Ryley [5], Ireland [6] and Schultz and Jones [7]
  - Iterative, pixel-by-pixel analysis → groups of pixels are mapped onto FEA model
  - Extended in this work to thin-shells and multiple-cameras



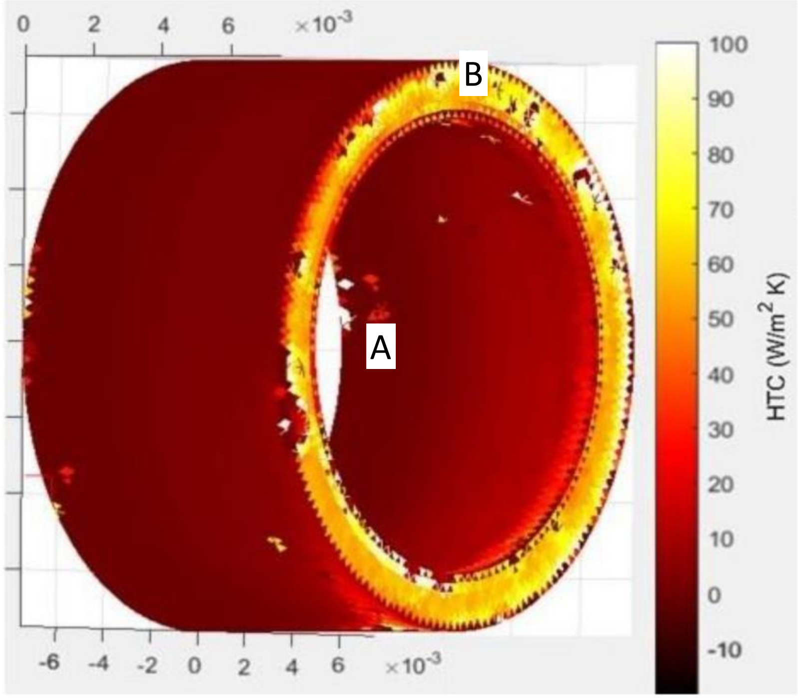
MATLAB based user interface

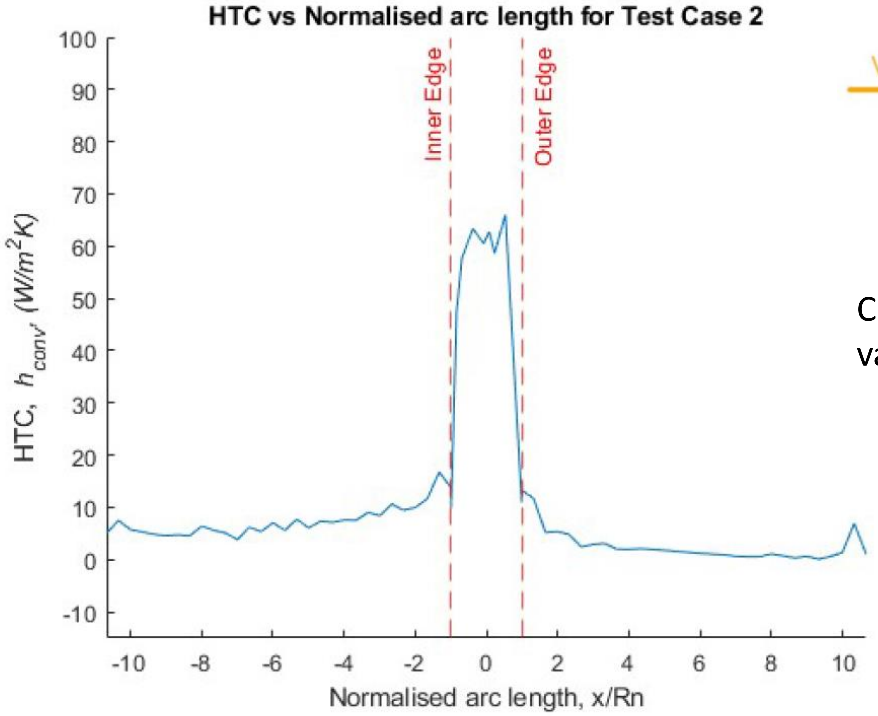
→ Don't need to assume semi-infinite 1D conduction

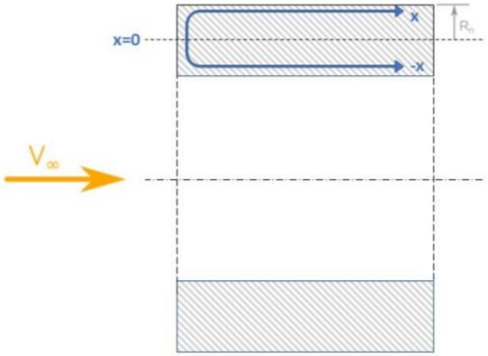
→ Enabling technique for complex geometries

Results: Cylinder

Aspect (length) ratio = 0.5, diameter ratio = 0.8







Coordinate system. Normalising value Rn = half thickness.

(A) Numerical anomalies (vibrations, glare) → peak not detected → need further improvements to setup
(B) Discontinuities → individual peaks not resolved → need higher framerates or larger Δ between LX

- Internal surface has higher HTC than external surface
- Front face HTC is higher than prior measurements for solid cylinder (under same flow condition). See Ref [].

References

1. ESA Space Debris Office, (2022), “ESA’s Annual Space Environment Report”, Issue 6.0, Reference GEN-DP-LOG-00288-OPS-SD
2. Donaldson, N.L., Doherty, L.J., Ivison, W., Wilson, C.F., McGilvray, M., Ireland, P.T. (2019), “Refurbishment and Characterisation of the Oxford Low Density Hypersonic Wind Tunnel”, *Int’l Conference on Flight Vehicles Aerothermodynamics and Re-entry Missions & Engineering (FAR)*, url: https://ora.ox.ac.uk/objects/uuid:eb4c863f-b92e-4a78-b8c6-f1e9c53df6ca
3. Donaldson, N.L., “Hypersonic Modelling and Testing of Space Debris During Planetary Entry,” Ph.D. dissertation, University of Oxford, 2019.
4. Donaldson, N.L., Doherty, L.J., Ireland, P.T., Merrifield, J. (2021), “Measurements of Heat Transfer on Hemispheres at Rarefied Flow Conditions using Liquid Crystals”, *8th European Conference on Space Debris*, url: https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/275
5. Ryley, J., “Turbine Blade Mid-Chord Internal Cooling,” Ph.D. dissertation, University of Oxford, 2014.
6. Ireland, P.T. and Jones, T.V., “Liquid crystal measurements of heat transfer and surface shear stress,” *Measurement Science and Technology*, vol. 11, no. 7, Jan. 2000.
7. Schultz, D.L. and Jones, T.V., (1973), “Heat-Transfer Measurements in Short-Duration Hypersonic Facilities,” AGARDograph No. 165, NATO.