Arc-Jet Computational Simulations of Ablators for the Mars Science Laboratory Program

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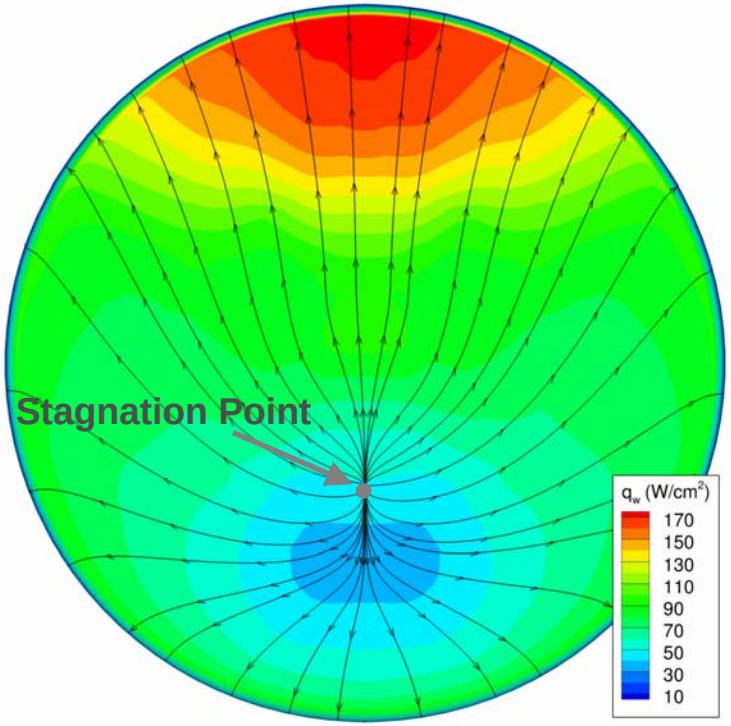
Roadmap

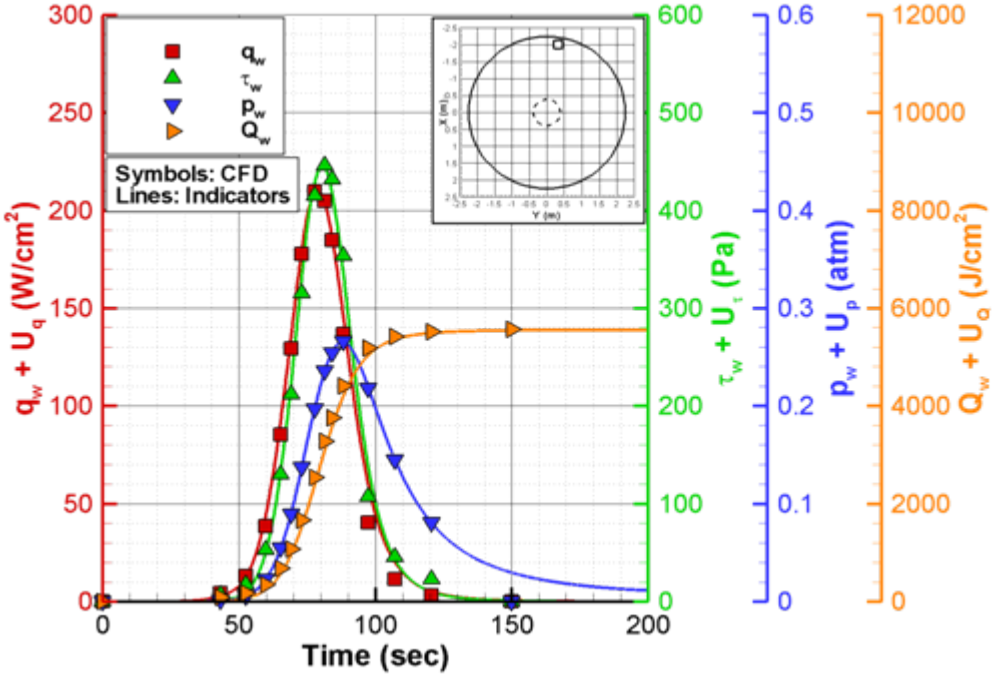
- MSL Overview & Trajectory
- MSL TPS Selection & Testing
- AEDC H2 Arc-Jet Testing
  - Nozzle Flow at AEDC
  - Numerical Methods for Arc-Jet Simulations
  - Inclined Wedge Calibration Tests at AEDC
- Arc-Jet Testing in IHF
  - IHF Swept Cylinder Environments
  - Comparison of Experimental and CFD determined environments
- Conclusions

MSL Overview and Trajectory

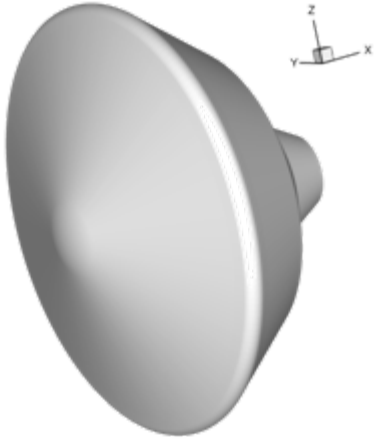


Margined (Turbulent) Environment at leeward location

Plot courtesy of Karl Edquist, NASA LaRC

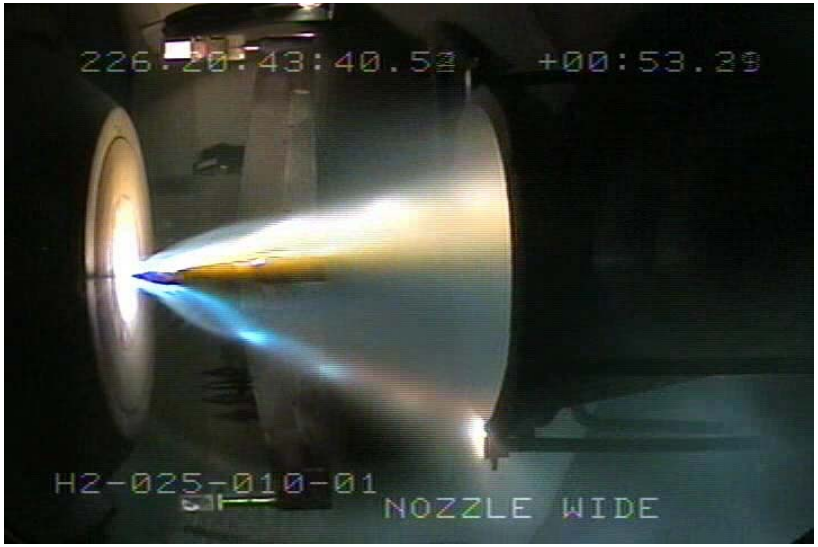


- MSL heatshield is 70º sphere-cone configuration. At 3,400kg and 4.5m in diameter, it will be the largest probe to enter Mars atmosphere.
- Surface roughness and long running lengths transition to turbulent flow on leeward side of heat shield.
- Therefore testing at high heat-flux high shear conditions is important to qualify thermal protection system (TPS).



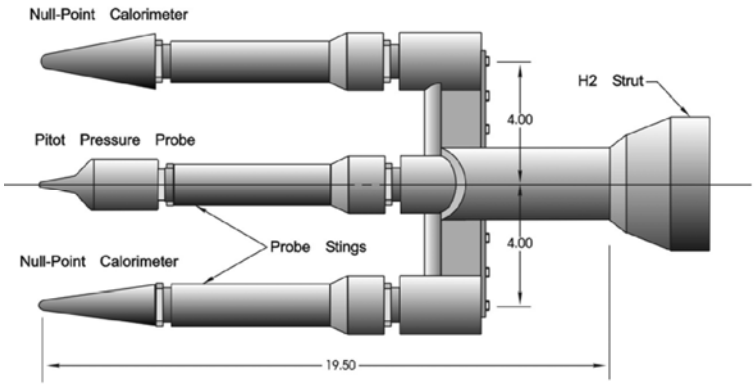
MSL TPS Selection and Testing

- Ground-based facilities are used to test TPS material at environments similar to those encountered during entry.
- Many Arc-jet tests are of stagnation articles, but for MSL shear testing at high heat rates is also necessary. For such conditions, inclined wedges and swept cylinders are used.
- MSL Arc-Jet shear testing has been performed primarily in Ames Interactive Heating Facility (IHF) and at AEDC's HEAT H2.
- Two main TPS materials tested for MSL have been SLA (Super Lightweight Ablator) and PICA (Phenolic Impregnated Carbon Ablator).

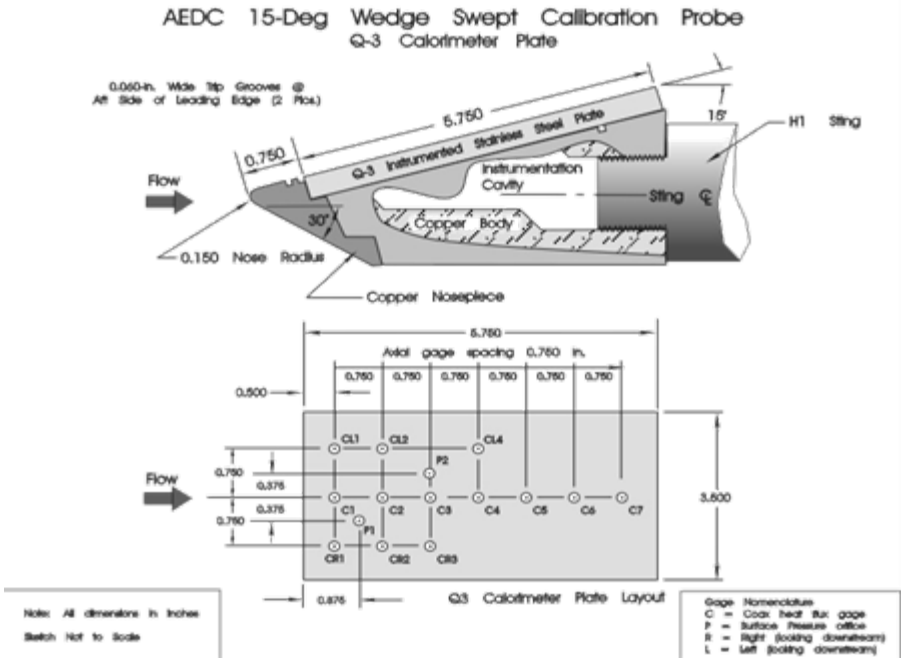


AEDC Arc-Jet Testing

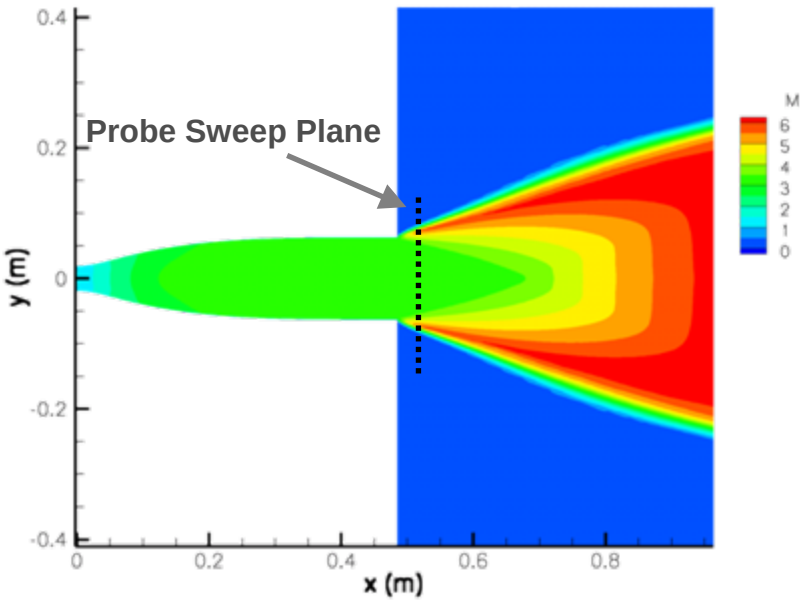
- AEDC HEAT-H2 at Arnold AFB, TN
  - Uses N-4 Huels type arc heater with evacuated test-cell.
  - MSL testing with Mach 3.4 contoured nozzle, in the flat enthalpy mode.
  - Chamber pressures range from 16atm to 23atm for MSL tests.



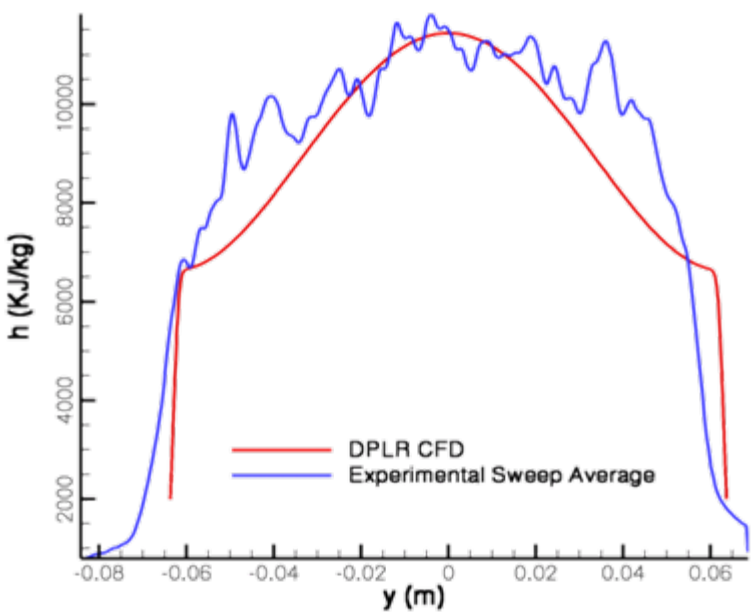
- Calibration in AEDC H2 by null-point calorimeter and pressure probe sweeps.
- Wedge calibration plate provides pressure and heat flux measurements to characterize flow over test articles.

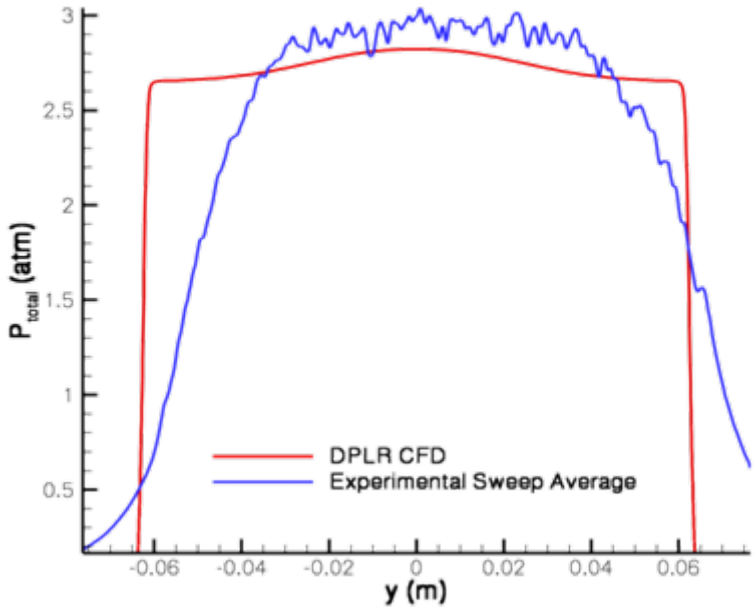


AEDC Nozzle Flow



- Fay-Riddell provides inferred enthalpy profile from averaged experimental data sweeps.
- Laminar Nozzle solutions calculated axisymmetrically.
- DPLR CFD total pressure calculated with Rayleigh pitot formula.





Numerical Simulation Methods

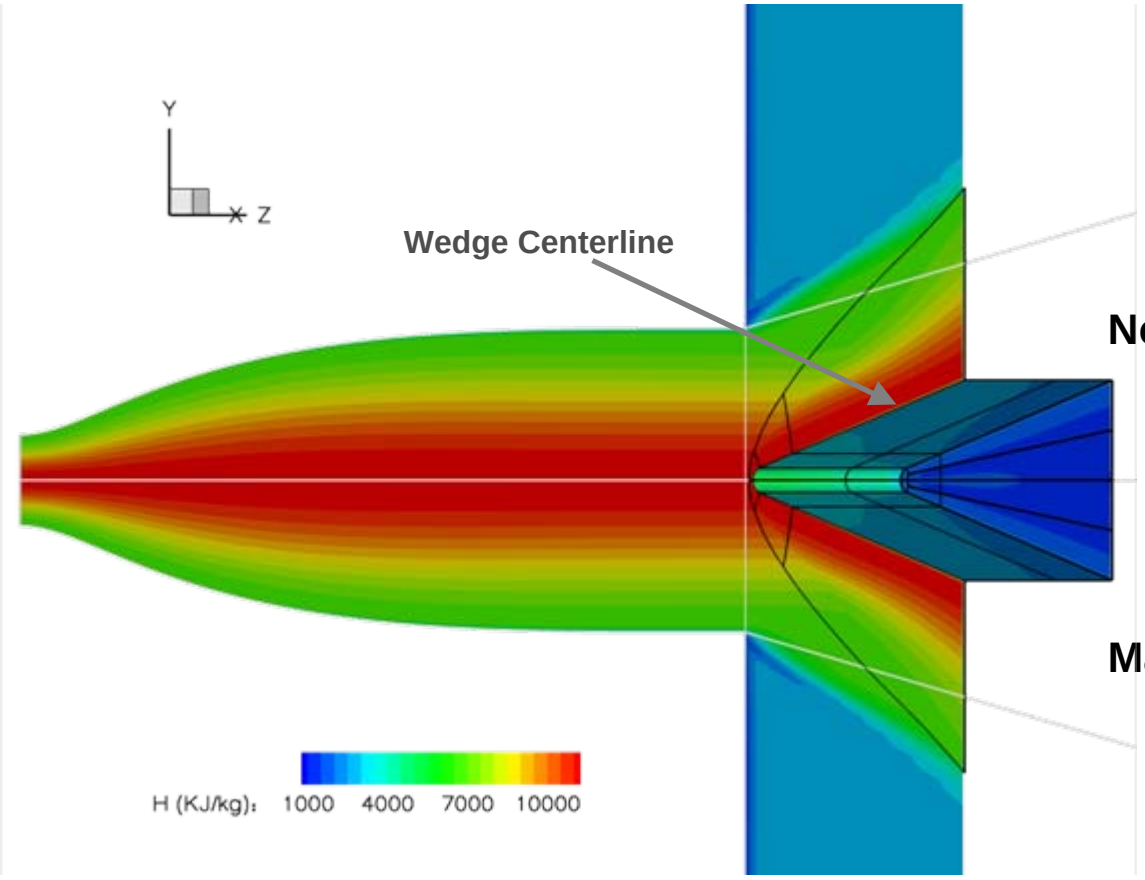
Flow Solver, DPLR 3.05.0

- 3D parallel real-gas hypersonic flow solver.
- Arc-jet simulations performed with 5-species air model (N_2 O_2 NO N O), based on Park's 1990 model.
- Assuming steady-state flow.
- Turbulent solutions use Baldwin-Lomax model.

Equilibrium Sonic Throat, NOZZLE_THROAT_CONDITIONS:

- Formulation by Tahir Gökçen, implementation by David Saunders and Gary Allen, based on CEA.
- Used to determine upstream nozzle boundary condition, based on equilibrium gas compositions at a specific frozen Mach number.
- Determined typically by specifying total enthalpy and mass flow rate at a planar sonic throat.
- Can be created based on analytical distribution functions (Gaussian, sinusoidal or point specified) for pair of flow variables for non-uniform inflow profiles.

AEDC Arc-Jet Testing of Inclined Wedges, p1



Nozzle Modelling Assumptions

- **Sinusoidal peaked enthalpy** profile using NOZZLE_THROAT_CONDITIONS program.
- Planar sonic throat, with **uniform mass flow** rate.
- Match **bulk enthalpy** to experiment energy balance.
- Match inferred **peak enthalpy** at centerline.

Nozzle -> Wedge Approach

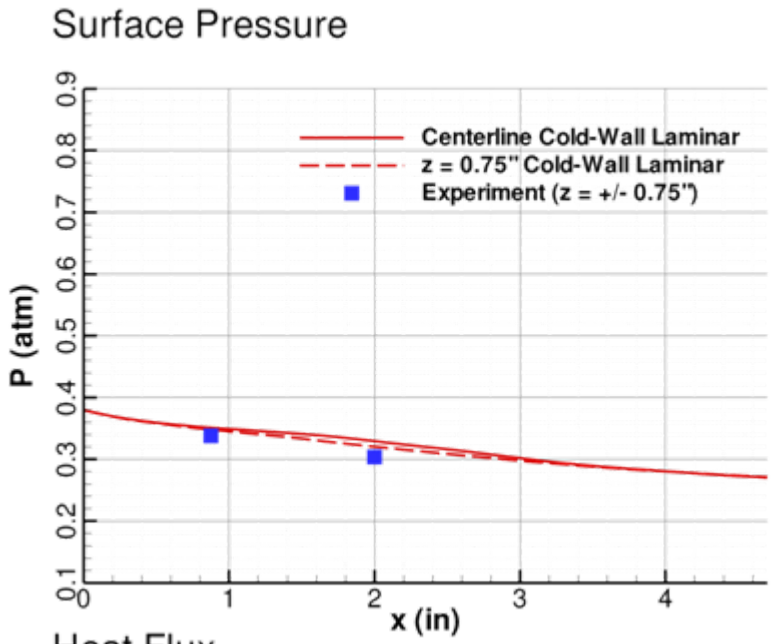
- Nozzle and chamber at H2-025-012 condition simulation run axisymmetrically.
- 3D wedge simulation inflow boundary conditions interpolated from the nozzle-chamber simulations.

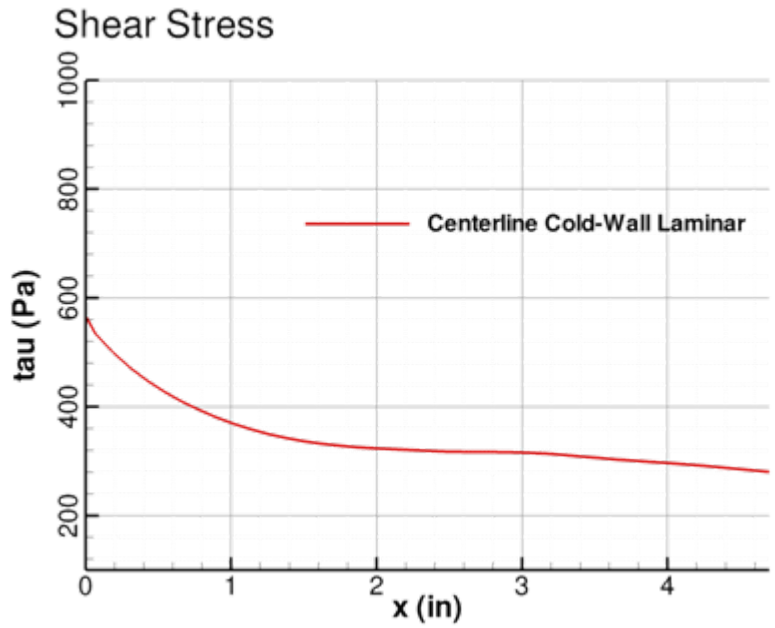
Material Properties for CFD

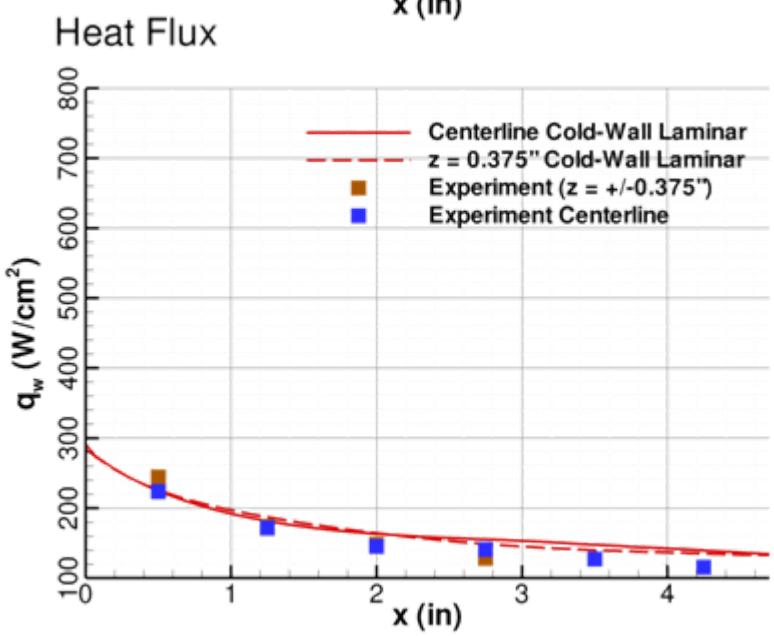
- Entire **cal plate wedge** is isothermal T=350K.

Values along and parallel to centerline will be shown

AEDC Arc-Jet Testing of Inclined Wedges, p2



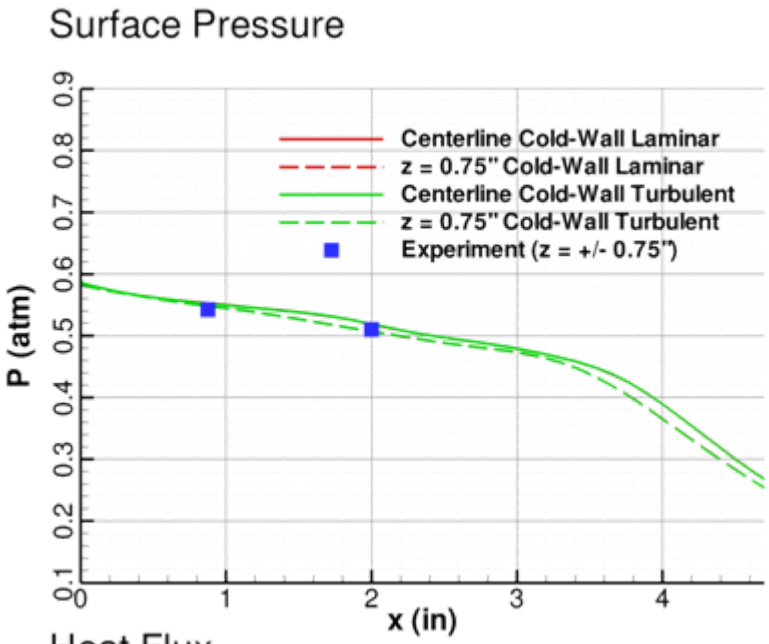


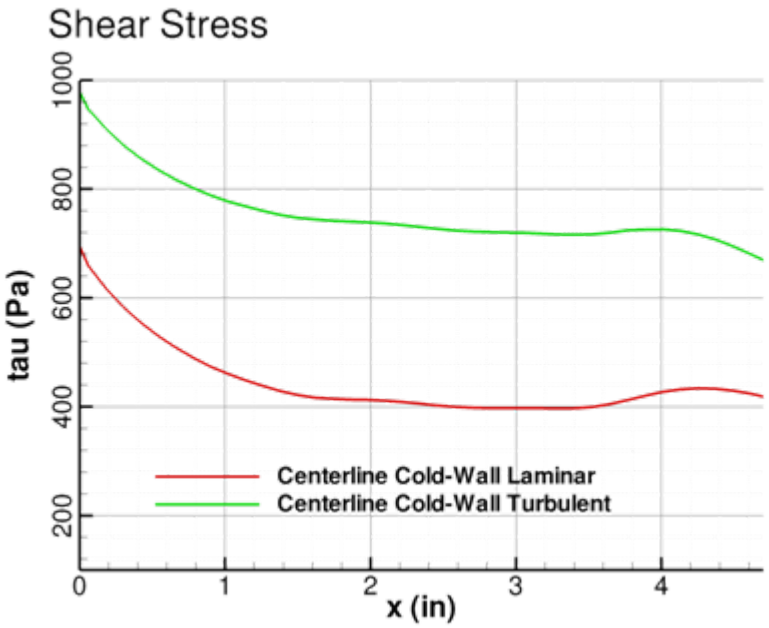


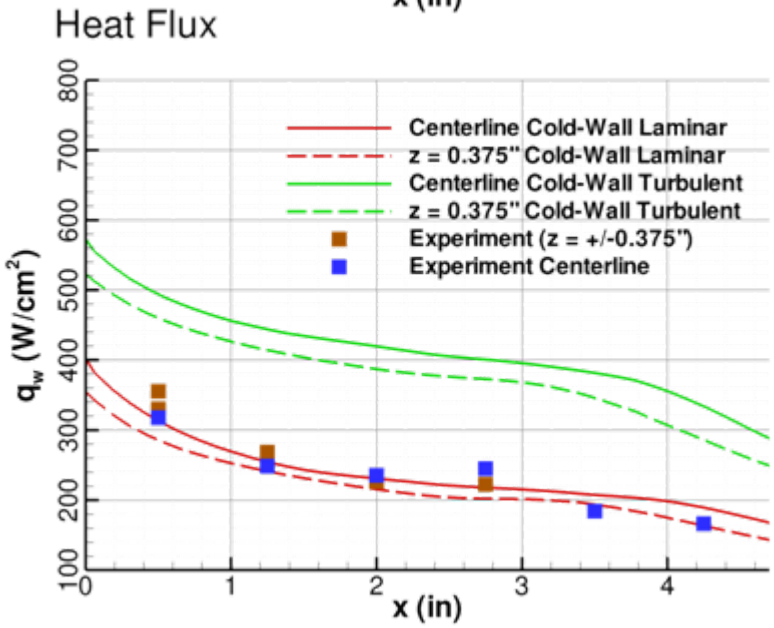
16atm Chamber Pressure:

- Heating from laminar CFD matches calibration wedge calorimetry.
- Good agreement with pressure and heat flux.
- Higher conditions desired to represent MSL conditions.

AEDC Arc-Jet Testing of Inclined Wedges, p3





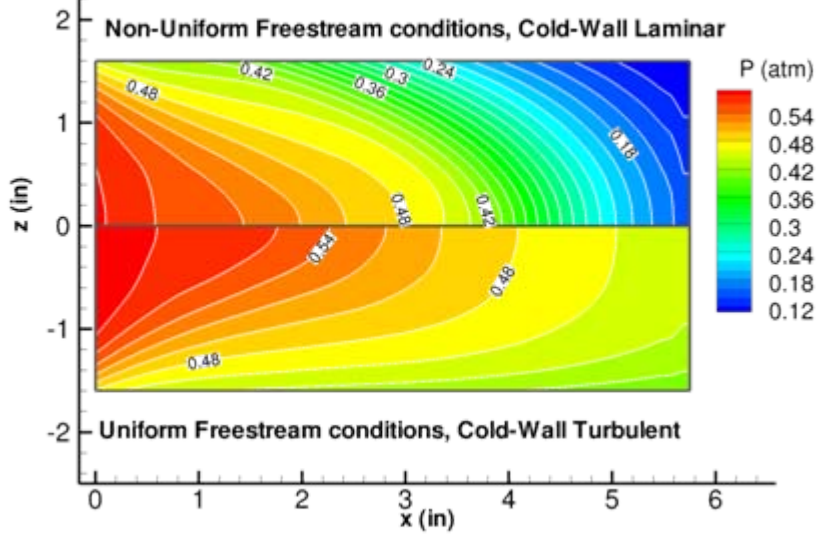


20atm Chamber Pressure:

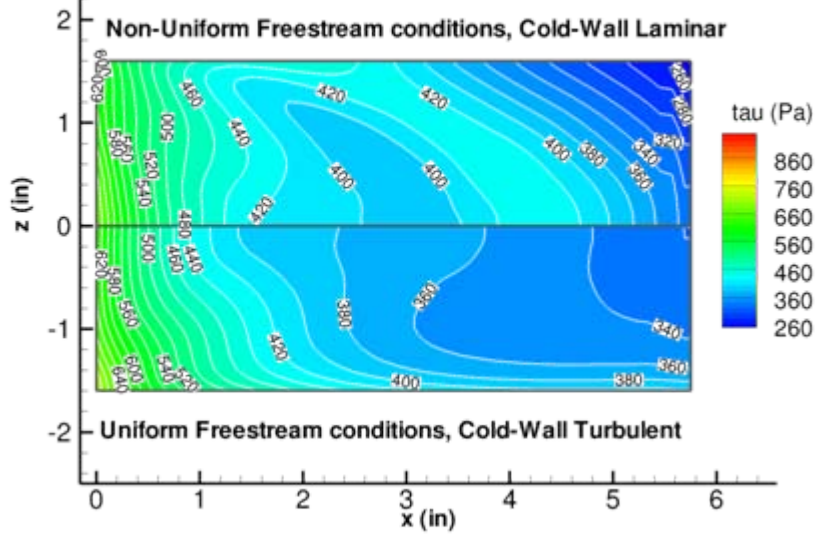
- CFD predictions again indicates laminar flow on calibration wedge, not turbulent.
- Still good agreement with pressure and heat flux in trend—does including nozzle non-uniformity help?

AEDC Arc-Jet Testing of Inclined Wedges, p4

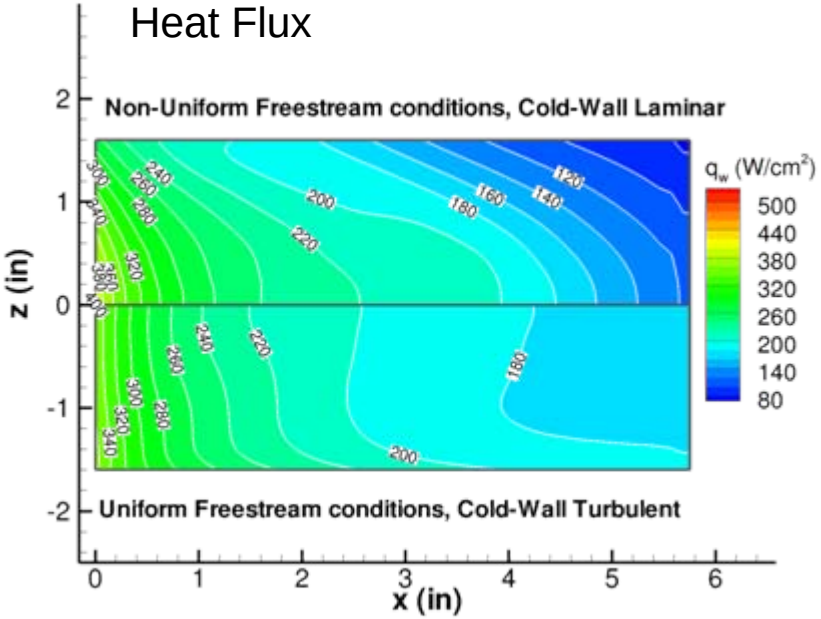
Surface Pressure



Shear Stress



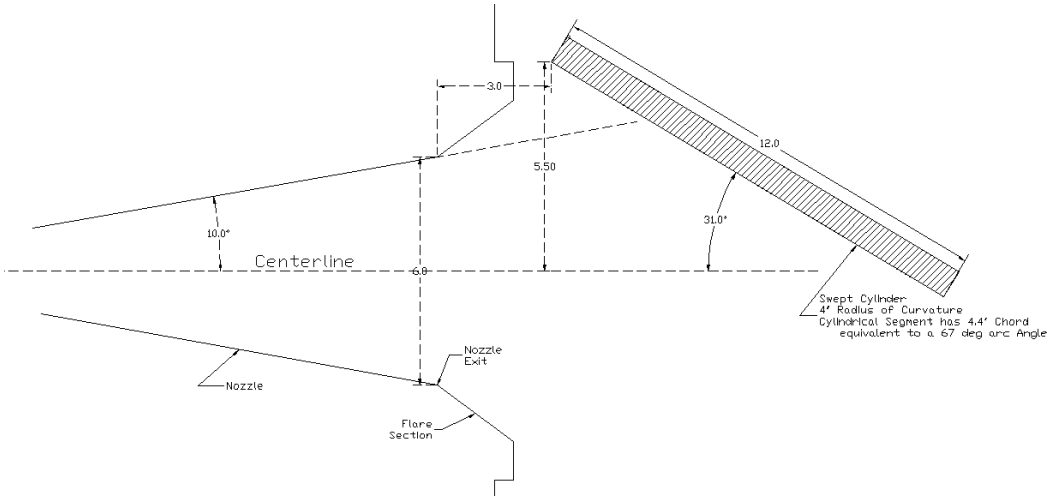
Heat Flux

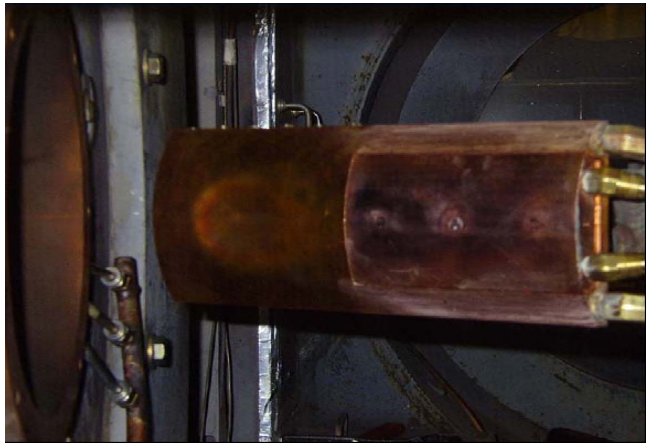


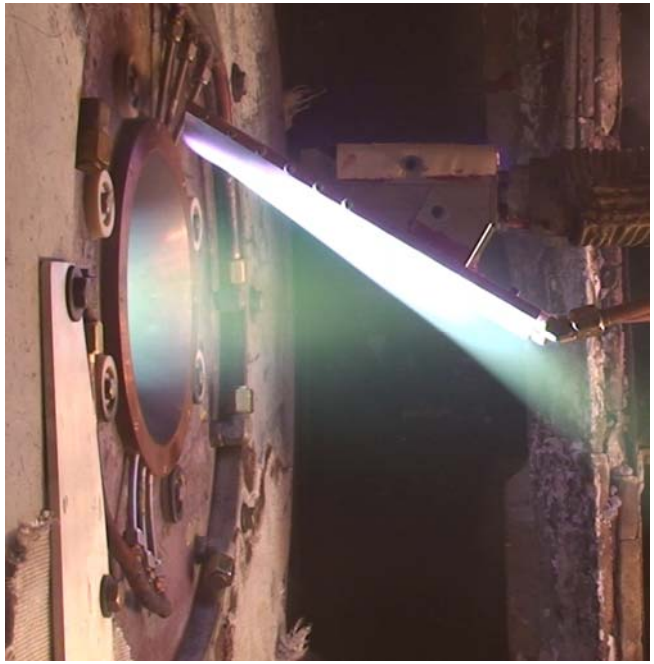
Calibration Plate at 20atm:

- Nozzle expansion fan impingement impacts shear and pressure primarily.
- Non-uniform freestream conditions effect plate environments, most noticeably after x = 2”.
- Effects from both enthalpy distribution and fan impingment included in non-uniform approach.

Interactive Heating Facility (IHF) Swept Cylinder Tests





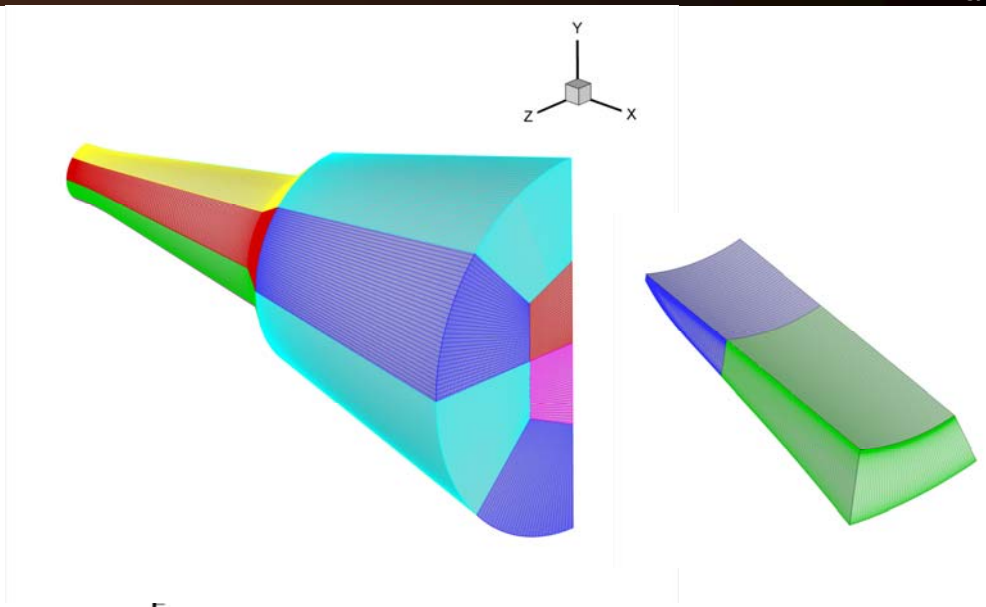


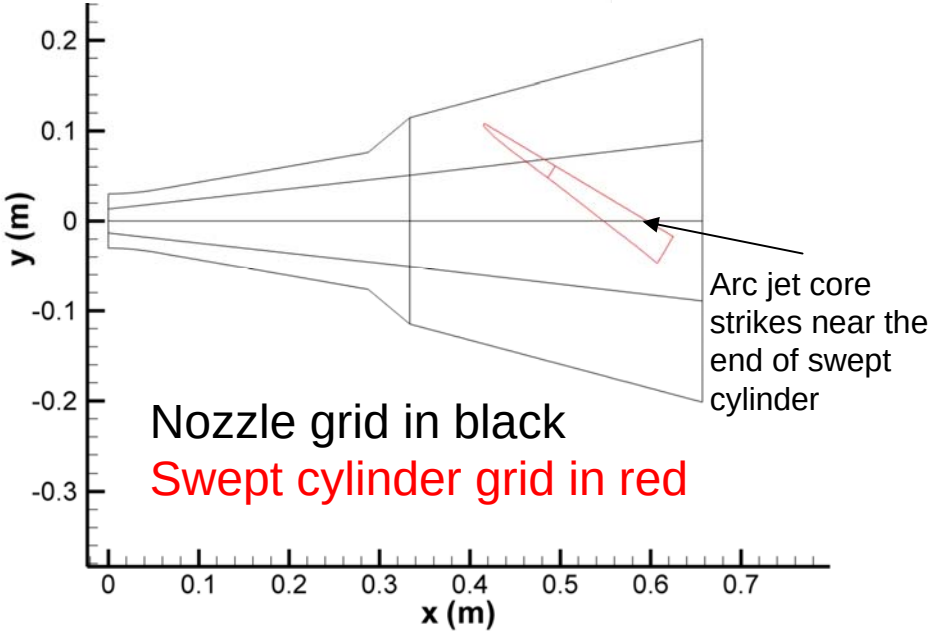
- 60 MW arc jet facility at NASA Ames
- Total pressures of 1-9 atm
- Total enthalpies of 7-47 MJ/kg (air)
- 6-inch conical nozzle used for 30 deg swept cylinder test

CFD Methodology

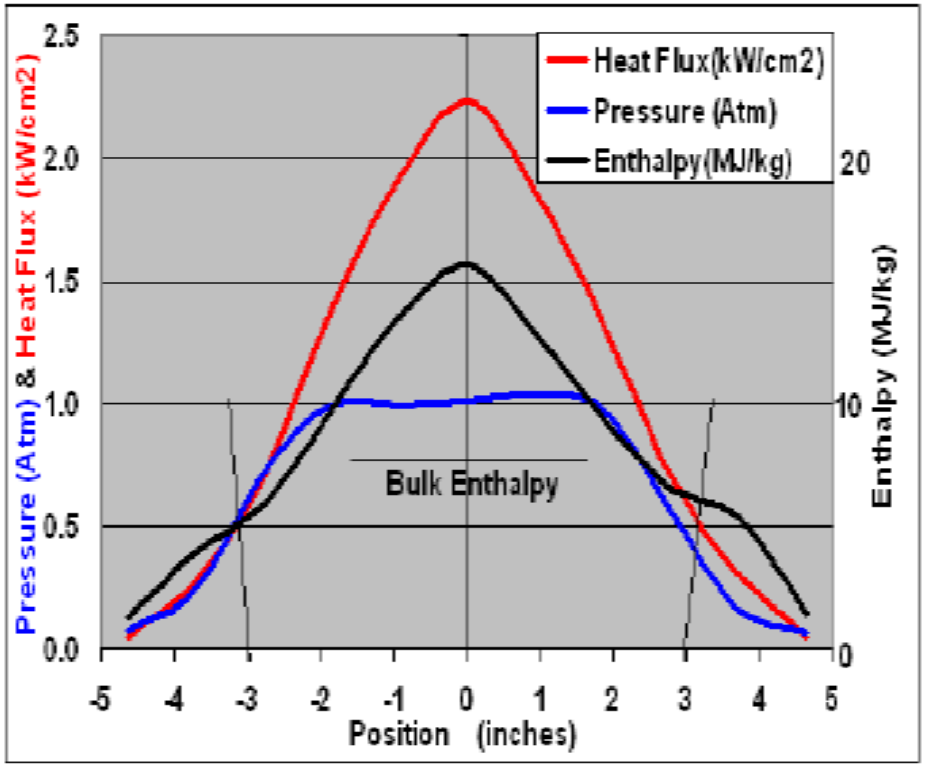
- All simulations computed using *DPLR version 3.05.0*
- Gas modeled as 6 species air (N_2, O_2, NO, N, O, and Ar)
- Nozzle flow modeled using non-uniform enthalpy and mass profiles at sonic throat (provided by Dr. Dinesh Prabhu)
- Nozzle simulations computed as 3D flow and independent of swept cylinder geometry
- Nozzle solution interpolated on cylinder grid and used as far-field boundary conditions
- Cold Wall (fully cat., T_w = 400 K)

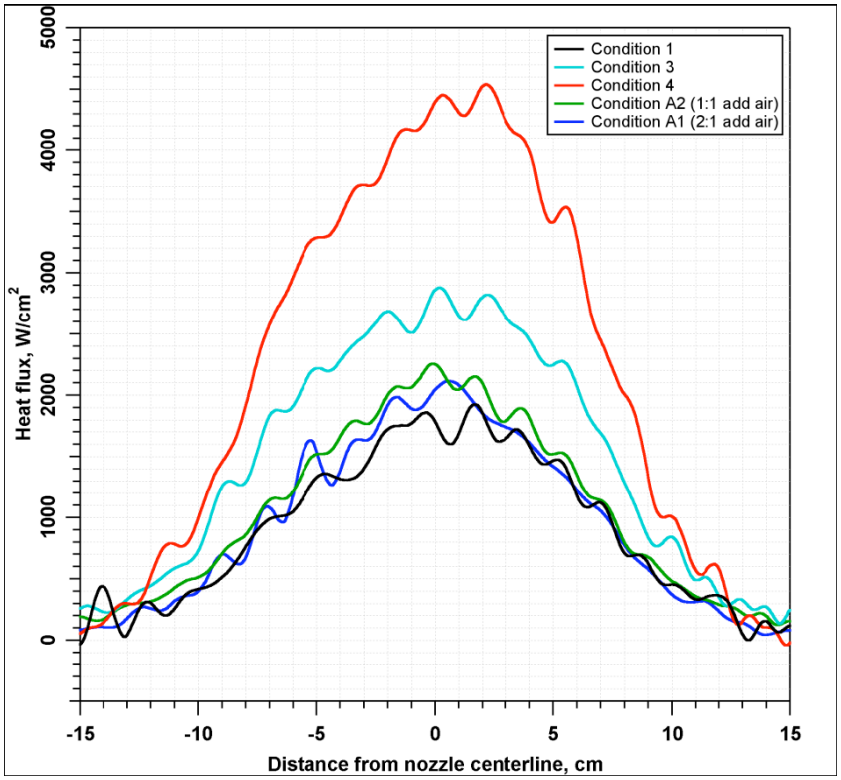
  Hot Wall (fully cat., radiative eq)





IHF Nozzle Survey





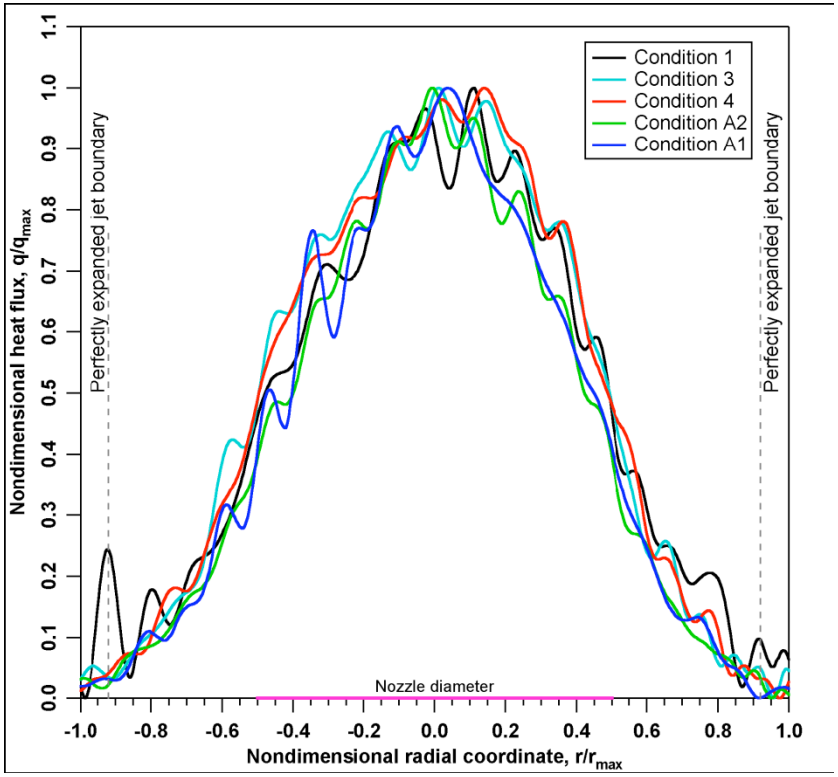
Data provided by T. Oishi, J. Fu, and E. Carballo

Condition A1 (Bulk H = 8.7 MJ/kg)

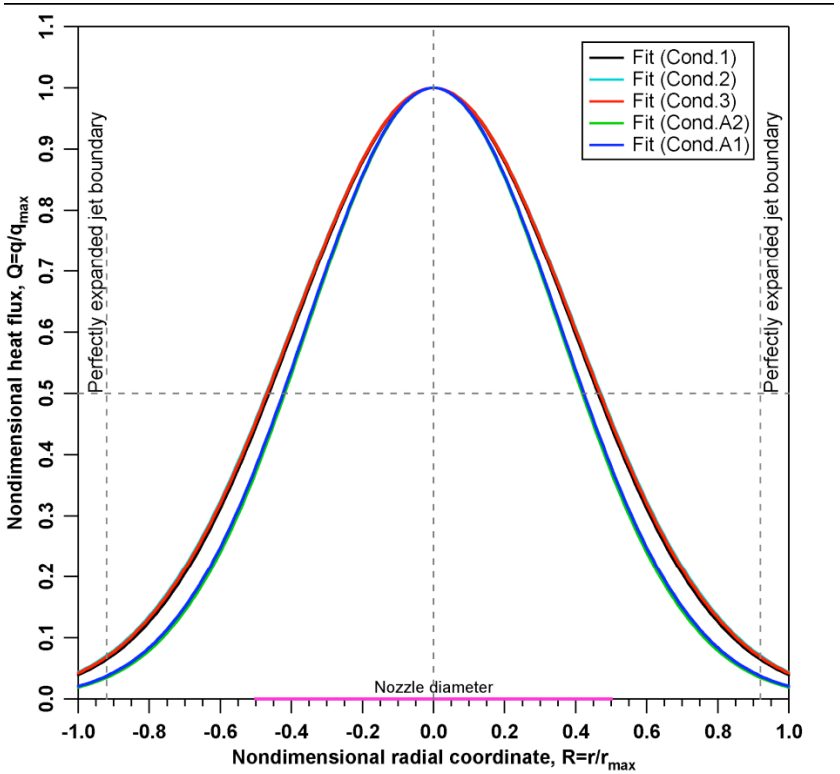
Heat Flux at Conditions 1,3,4,A1,A2

Enthalpy distribution deduced using a variant of Fay-Riddell (Heating corrected for round-tip and flat-tip probes)

Nozzle Heat Flux Profiles



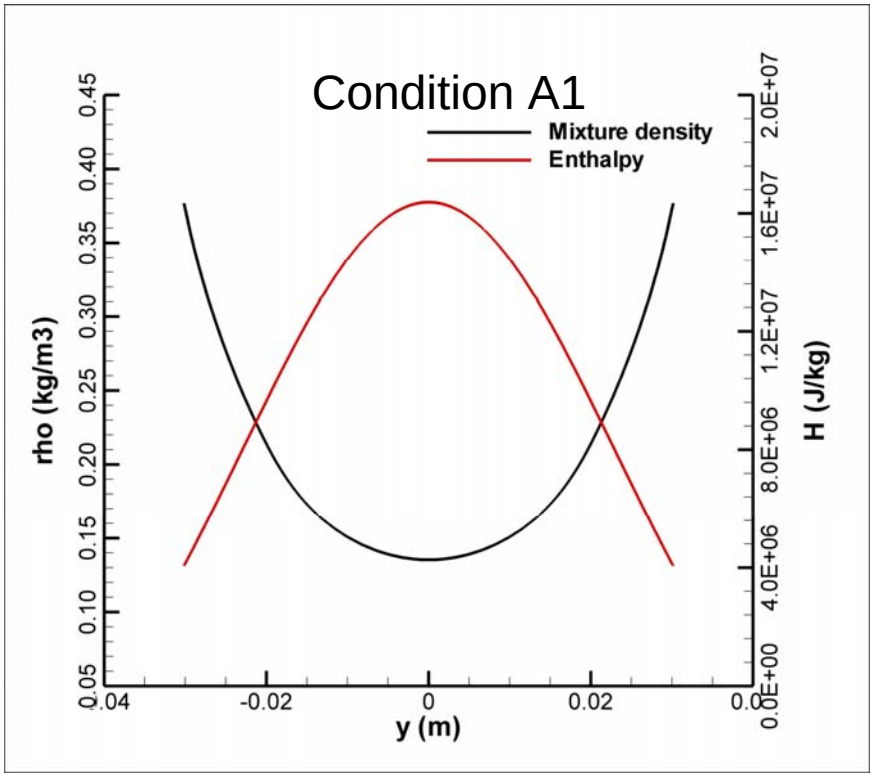
Heat Flux normalized by q_{max}



Gaussian Heat Flux Curve Fits

Profiles assumed to be axially symmetric and Gaussian

Nozzle Inlet ρ and H Profiles

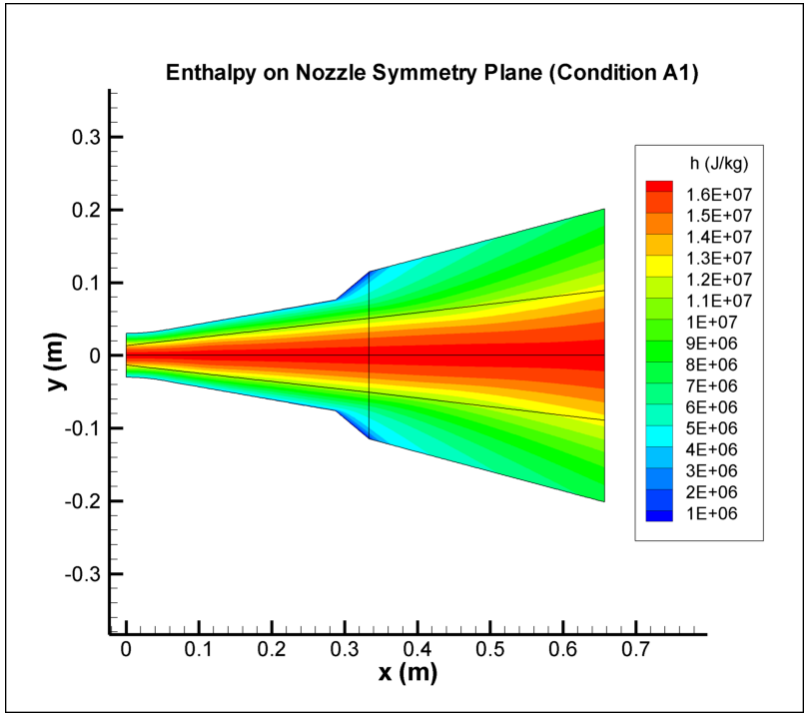


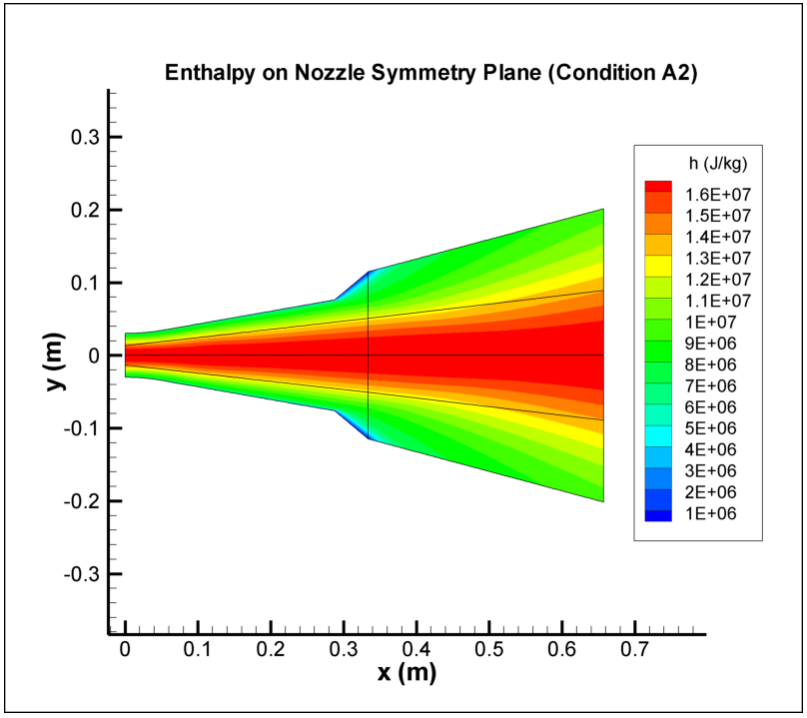
$$H_{bulk}\left(\pi R_{throat}^2\right) = 2\pi \int_0^{R_{throat}} r\Phi_H(r)dr$$

$$\left(\frac{\dot{m}_{total}}{\pi R_{throat}^2}\right)\left(\pi R_{throat}^2\right) = 2\pi \int_0^{R_{throat}} r\Phi_m(r)dr$$

- Heat flux converted to enthalpy via Fay-Riddell correlation with measure pitot pressure and appropriate “effective radius”
- Mass flux profile constructed as an “inverse” of the enthalpy profile (assumption that density varies inversely to temperature for a fixed pressure)
- Constructed profiles satisfy bulk inflow enthalpy and mass flow constraints

Enthalpy Contours at Symmetry Plane of Nozzle



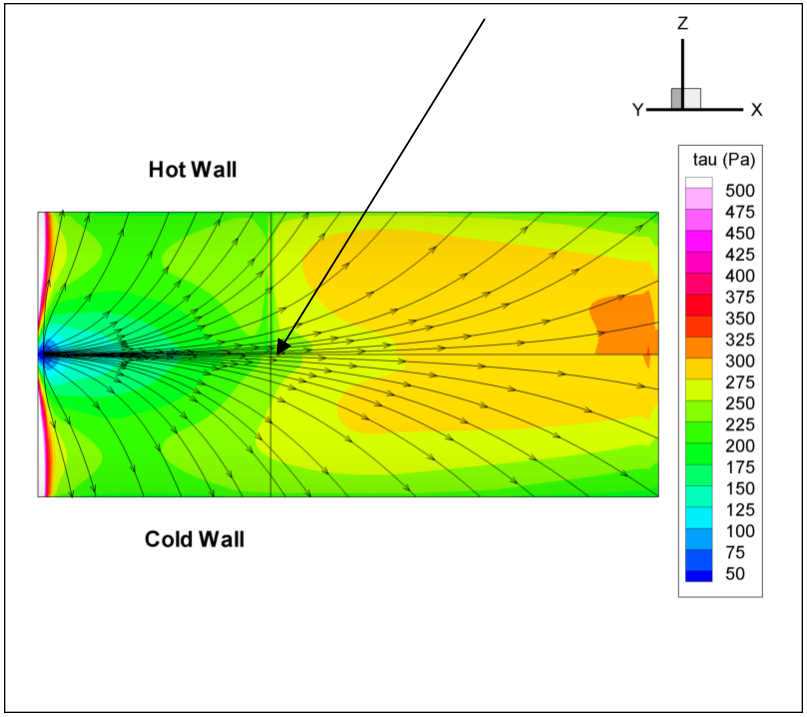


Condition A1 (Bulk H = 8.7 MJ/kg)

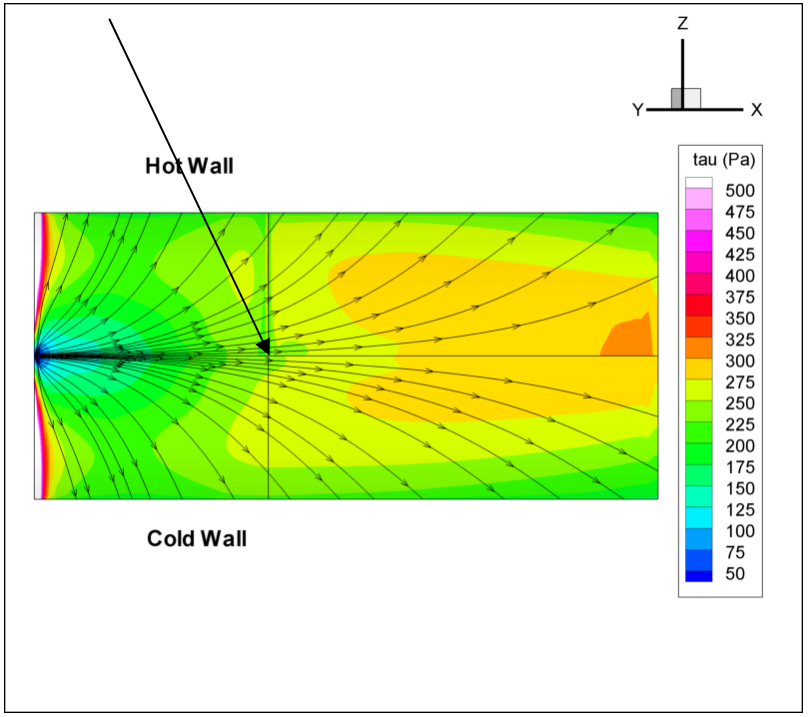
Condition A2 (Bulk H = 13.3 MJ/kg)

Shear Stress Contours on Swept Cylinders

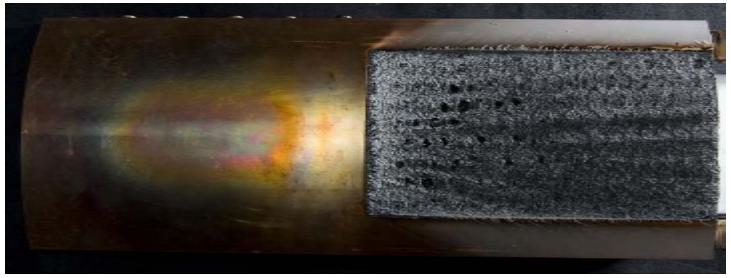
Transition location from cold wall to hot wall BC for hot wall simulations



Condition A1

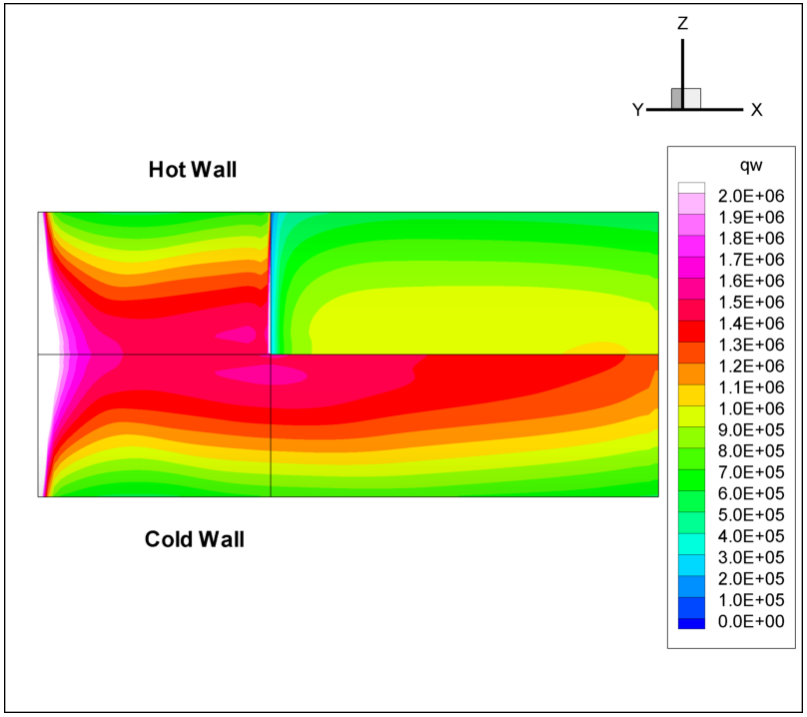


Condition A2

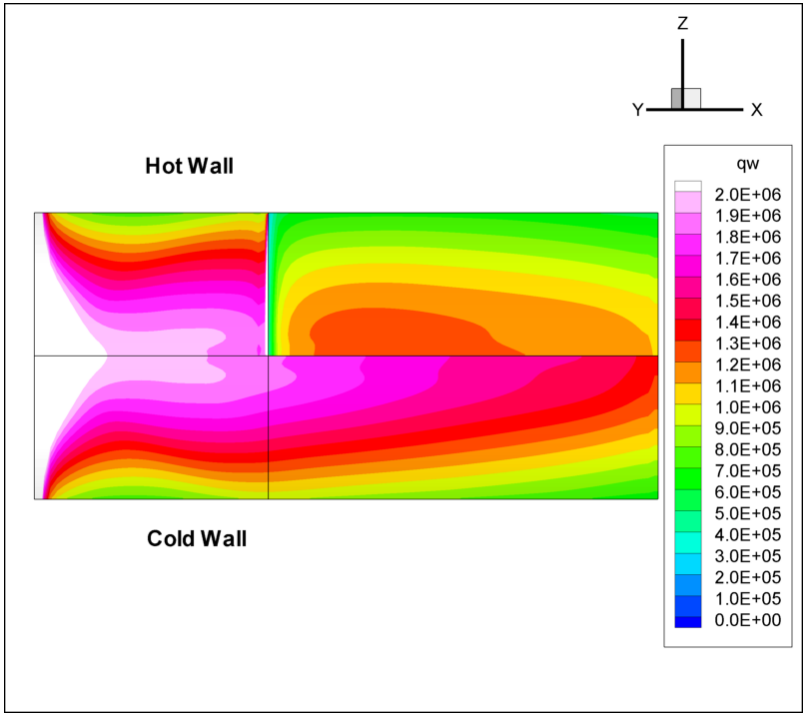


Swept Cylinder after test (condition 4)

Heat Flux Contours on Swept Cylinders

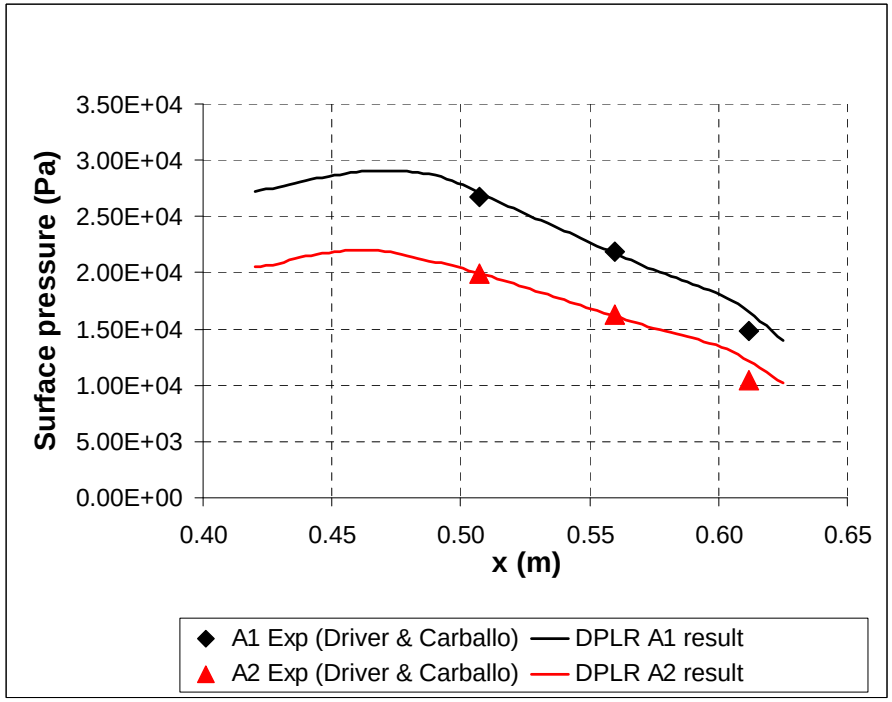


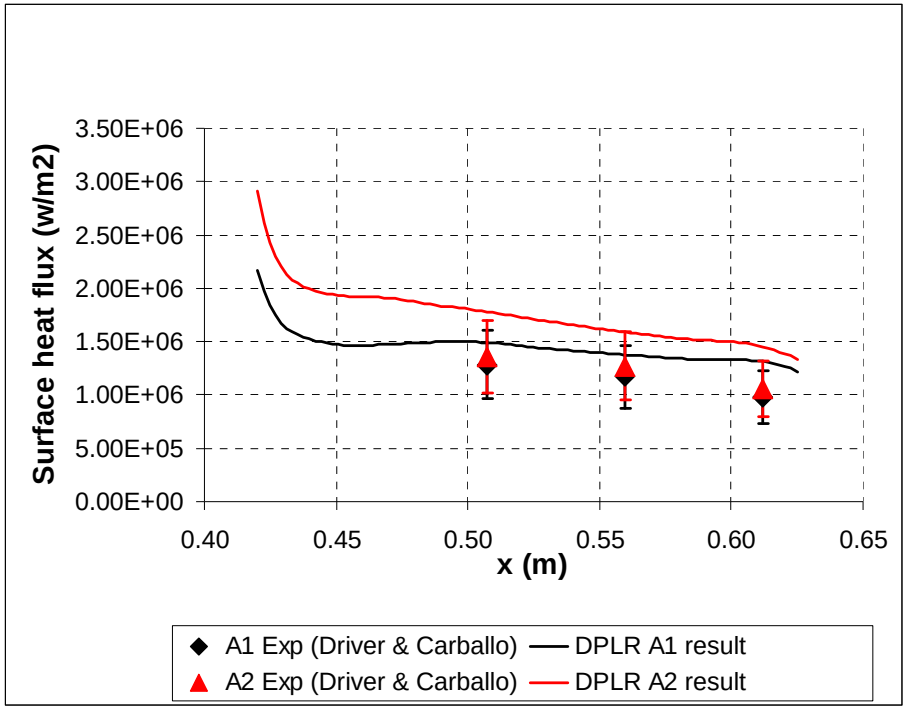
Condition A1



Condition A2

Comparison of Surface Pressure and Heat Flux





- Laminar calculations using cold wall BC
- Finite edges of the swept cylinder are not modeled in these simulations
- Centerline of the nozzle corresponds to x = 0.596 m on swept cylinder

Summary of Swept Cylinder Solutions

Conditions	Test_Run	Bulk enthalpy (MJ/kg)	CW Q1 Measured (W/cm^2)	CW Q1 Computed (W/cm^2)	HW Q1 Computed (W/cm^2)	CW P1 Measured (kPa)	CW P1 Computed (kPa)	diff in CW Q1	diff in CW P1	Computed Q_{cw}/Q_{hw}
A1	187_26	8.7	128	149	90	26.7	27.1	16%	1%	1.66
A2	187_29	13.3	136	177	118	19.9	19.9	30%	0%	1.50
3	187_23	16.5	214	349	266	18.6	19.4	63%	4%	1.31
4	187_24	17.0	261	398	300	25.0	25.5	52%	2%	1.33
7b	187_25	20.4	348	568	440	33.3	33.9	63%	2%	1.29

- Good agreement between computed and measured pressure (< 4%) for all test conditions
- For low enthalpy conditions (A1 and A2), reasonable agreement between computed and measured heat flux
- Large differences in heat flux (> 50%) for high H test conditions (3, 4, and 7b)
- Possible sources for the discrepancies:
  - Gardon gages in a high shear environment
  - Fully catalytic assumption for Gardon gages
  - Uncertainties in bulk enthalpy
  - Enthalpy and mass flux profiles are asymmetric

Conclusions and Future Work

- Current techniques are useful for pre and post test analysis, but some large uncertainties still exist.
- Simulations benefit from null point sweep data, especially for non-stagnation off-centerline test articles.

- Potential Numerical Modeling Improvements
  - Modeling of arc-jet plenum combined with nozzle and test article.
  - Including sensors in simulations (mainly for catalytic effects).
  - Coupled material response with blowing, including blowing of ablation products.
  - Account for shape change for ablators during tests.
  - Use of overset grid topologies for more complex test articles.

Acknowledgements

- The presenters would like to thank the MSL project. Many thanks to Dinesh Prabhu, Dave Driver, Robin Beck, Mike Wright, Helen Hwang, Karl Edquist, Tahir Gökçen, and David Saunders.

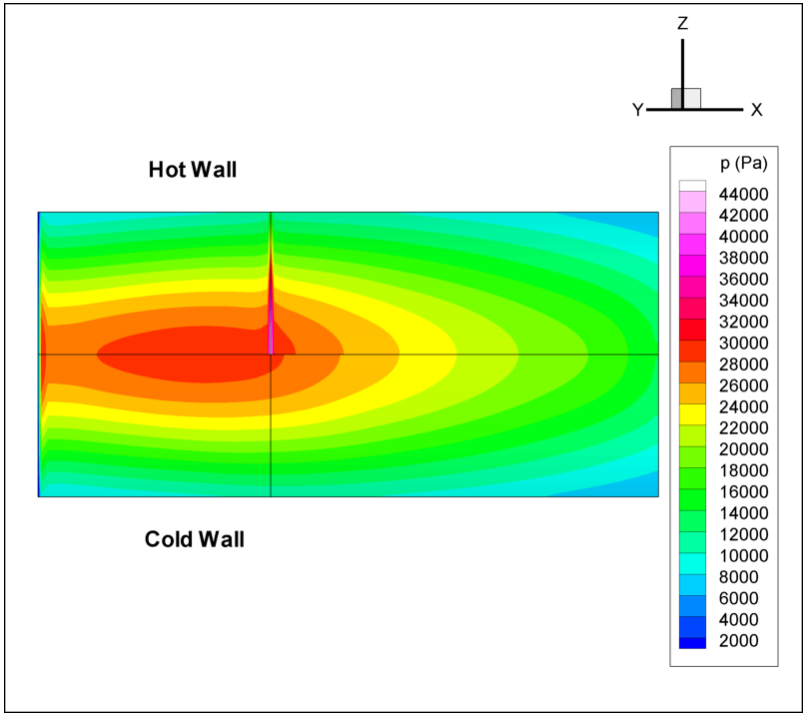
- Portions of this work were performed under NASA contract NNA04BC25C to ELORET Corporation.

Abstract:

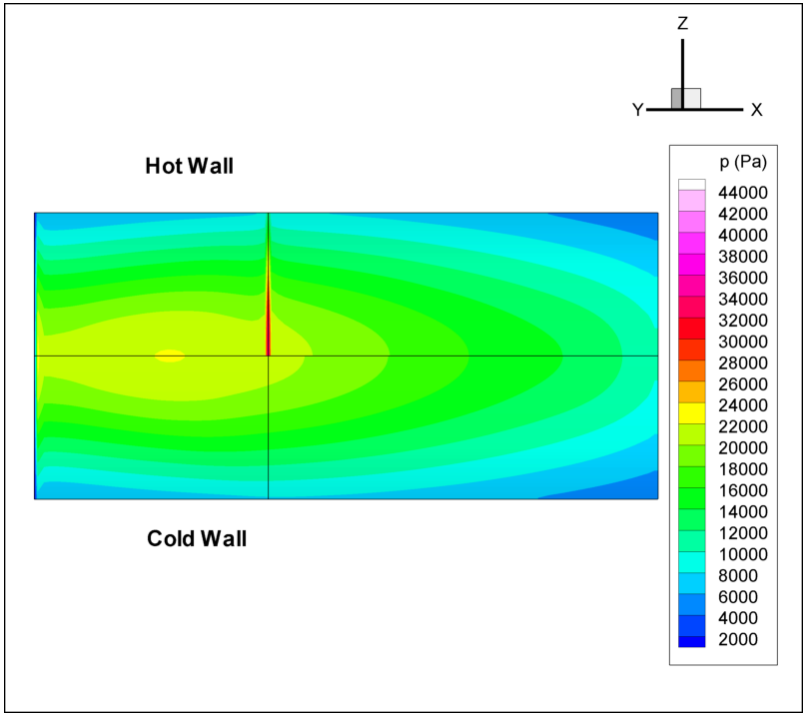
The NASA Ames team working with the Mars Science Laboratory (MSL) project has recently been involved in arc-jet tests to characterize the material response of candidate ablators to the high heat flux and high shear stress conditions that the MSL probe is likely to experience during entry into the Martian atmosphere. These tests have been conducted at the NASA Ames Aerodynamic Heating Facility (AHF), the NASA Ames Interaction Heating Facility (IHF), and the H2 arc-jet at Arnold Engineering Development Center (AEDC). The arc-jet experiments included high speed flow on stagnation pucks, inclined wedges, and swept cylinders. Complementary Computational Fluid Dynamics (CFD) and material response simulations were computed to assess the agreement between measured and predicted aerothermal quantities on the various test articles.

New techniques have been employed for the pre and post test analysis of the arc-jet aerothermal environments using in-house codes developed at NASA Ames. Specifically, these methods address the modeling of non-uniform enthalpy and mass profiles in the arc-jet facilities, and the coupling of the nozzle flow with the test articles. Simulations of inclined wedges at AEDC H2 test conditions and swept cylinder at IHF test conditions using the DPLR code will be presented. In particular, the agreement between CFD predicted environments and those measured on the test articles will be discussed. These comparisons will highlight some of the uncertainties that exist in modeling the arc-jet environment.

Pressure Contours on Swept Cylinders



Condition A1



Condition A2