Calorimeter Heat Flux Measurements During Arcjet Tests

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Thermal and Fluids Analysis Workshop
August 18–22, 2008
San Jose State University
San Jose, California

Acknowledgement

The authors would like to thank the Thermo-Physics Facility Branch, and, in particular Imelda Terrazas-Salinas, Ernie Fretter, and Frank Hui, for their cooperative effort in providing the wide variety of arcjet data that made this study possible.

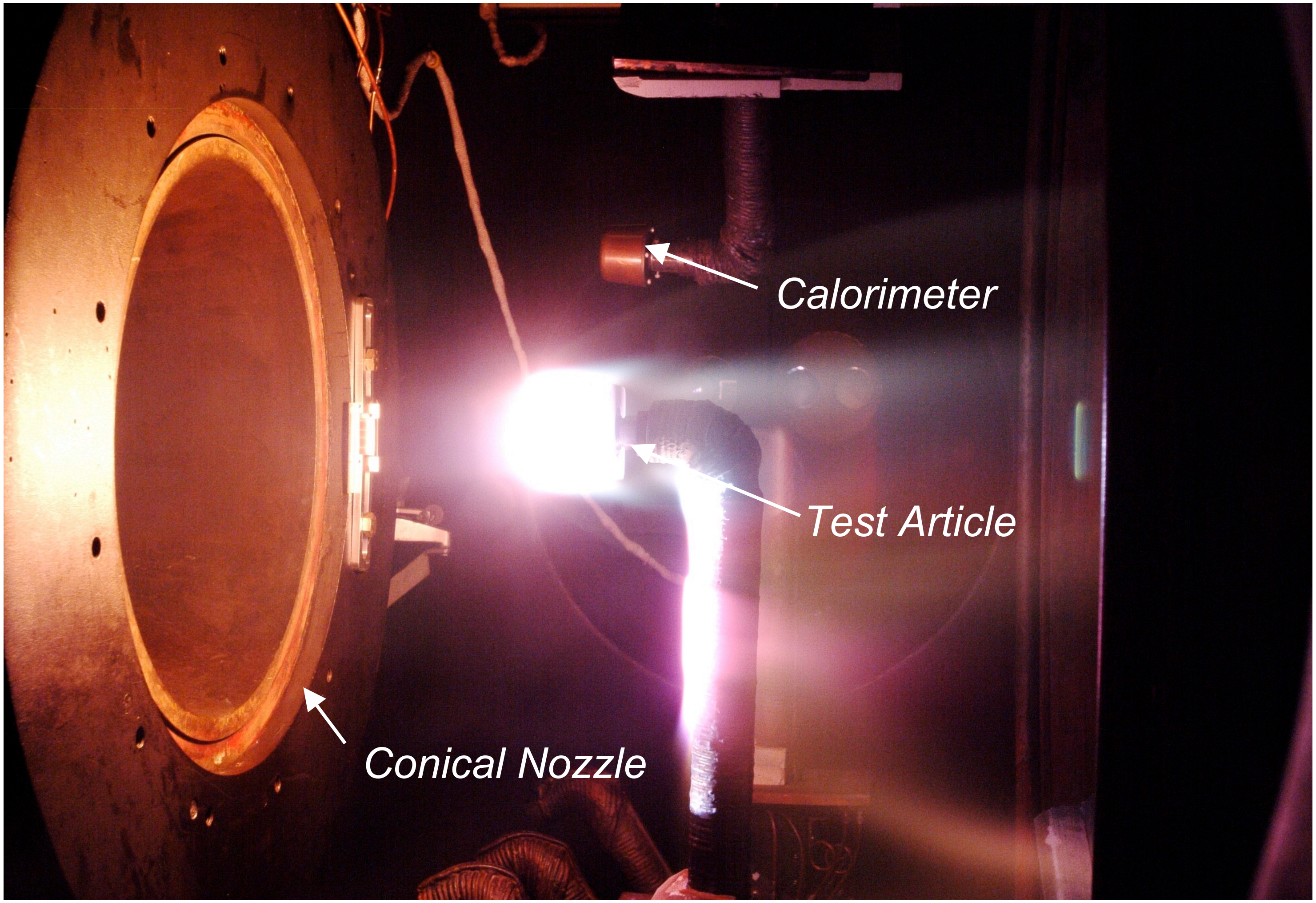
Background

- Thermal protection on vehicles used for high-speed planetary entry include both passive (shuttle TPS) and active (ablator) systems. The arcjet facility was developed in the early 1960’s to simulate a high-energy hypersonic flow environment to test these systems.
- The arcjet facility uses a electrical arc to create a reservoir of high enthalpy gas that, in turn, is expanded through a nozzle to hypersonic speed. The flow passes through the test section over a test article and then into a diffuser, which reduces the speed of the gas to subsonic flow.
- Since the heat flux to an ablator cannot be directly measured *during* the arcjet test, a calorimeter measurement is taken and used to correlate its performance with that during atmospheric entry.

Objectives

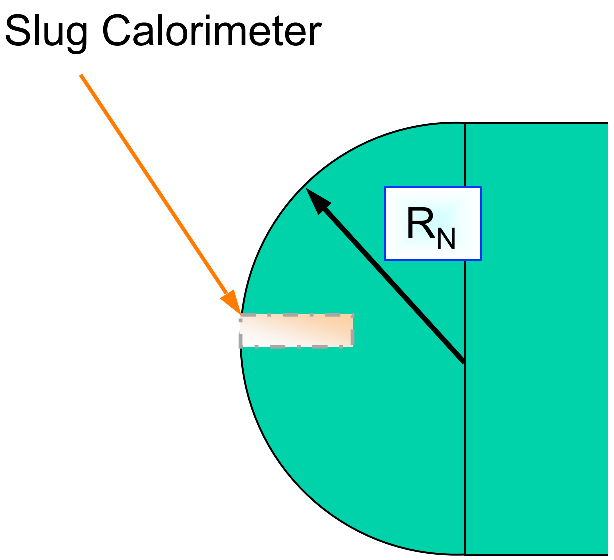
- Predict the stagnation point heat transfer rate to a slug calorimeter during arcjet tests using a system energy balance approach.
- Review data from hemispherical calorimeters in the NASA Ames Aerodynamic Heating Facility (AHF) and Interaction Heating Facility (IHF) — using several different nozzles, covering a wide range of test conditions.
- Correlate calorimeter measurements with predicted values obtained from the SCFC (frozen chemistry) and Data Parallel Line Relaxation Code (DPLR) (non-equilibrium chemistry).
- Compare measured recession on a graphite test article with values predicted by coupled solutions of DPLR and TITAN a implicit finite element code (*T*wo-dimensional *I*mplicit *T*hermal Response and *A*blatio*n* Program) — as a check of the cold-wall calorimeter measurement.

Test Article Exposed to Hypersonic Stream in Aerodynamic Heating Facility

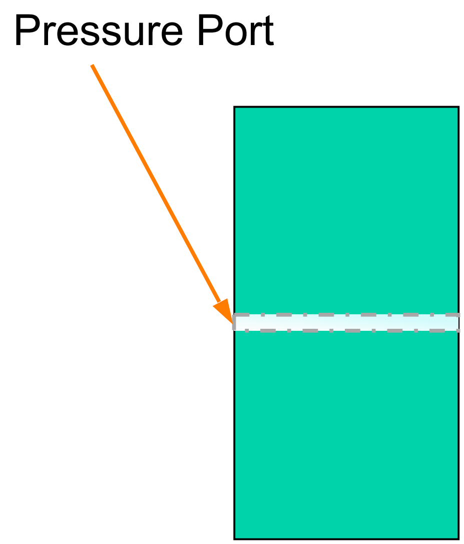


Test Article
(Copper Hemispheres)

($0.79\text{-cm} < R_N < 5.08\text{-cm}$)



a) Hemisphere



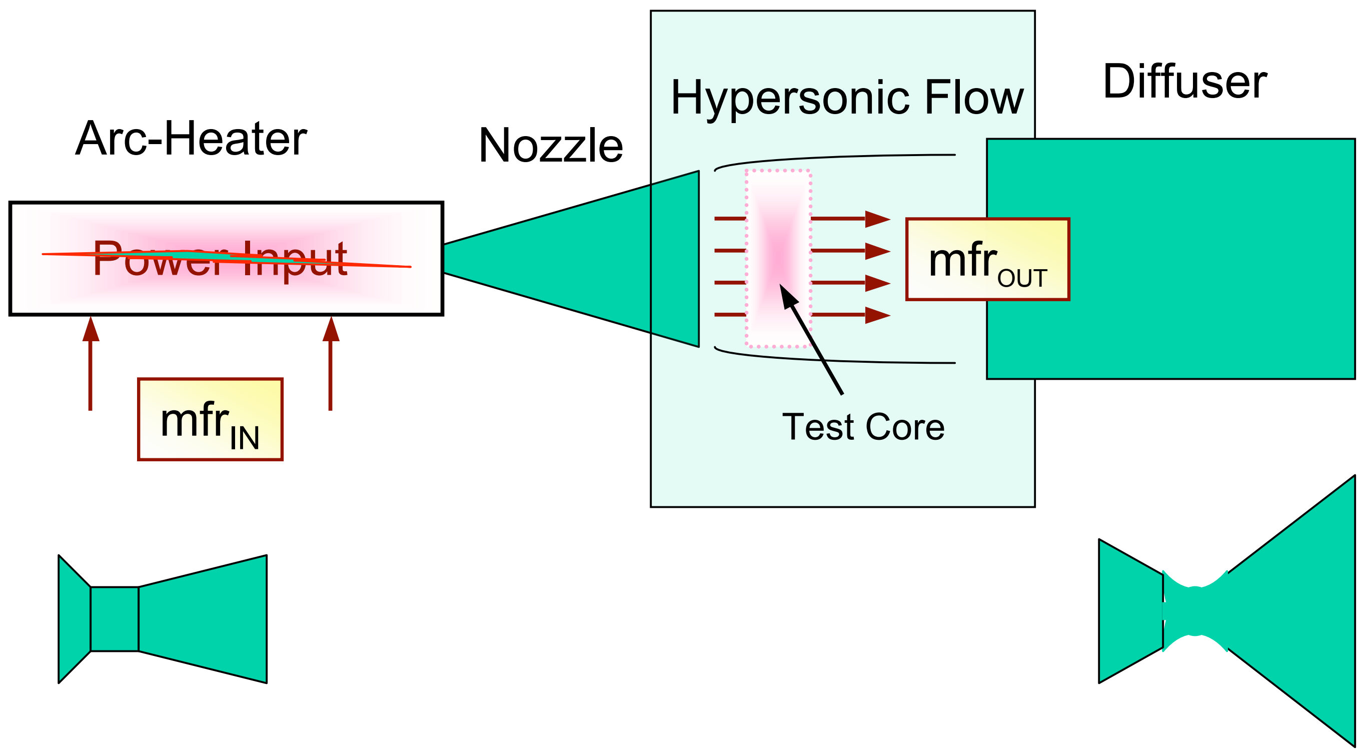
b) Flat-face Cylinder

Basic Arcjet Facility Configuration

mass flow rate (mfr)

$$mfr^{\circ}_{IN} = mfr_{OUT}$$

$$\text{Enthalpy} = \text{Efficiency}(\text{Power}/\ mfr_{IN}) - \text{Heat loss}$$



a) AHF

b) IHF

Computational Tools

SCFC Code — Frozen chemistry

Nozzle Flow

Input

- Chamber pressure
- Enthalpy (iterate on mass flow rate)
- Effective area ratio

Heat Flux

- Surface temperature
- Atom recombination coefficients (oxygen & nitrogen)
- Body geometry, nose radius
- Goulard's theory

Output

Stagnation point heat flux

DPLR Code — Non-equilibrium chemistry

Nozzle Flow

- Chamber pressure
- Enthalpy (SCFC code)
- Nozzle geometry
- Enthalpy and mass flux profiles (throat)

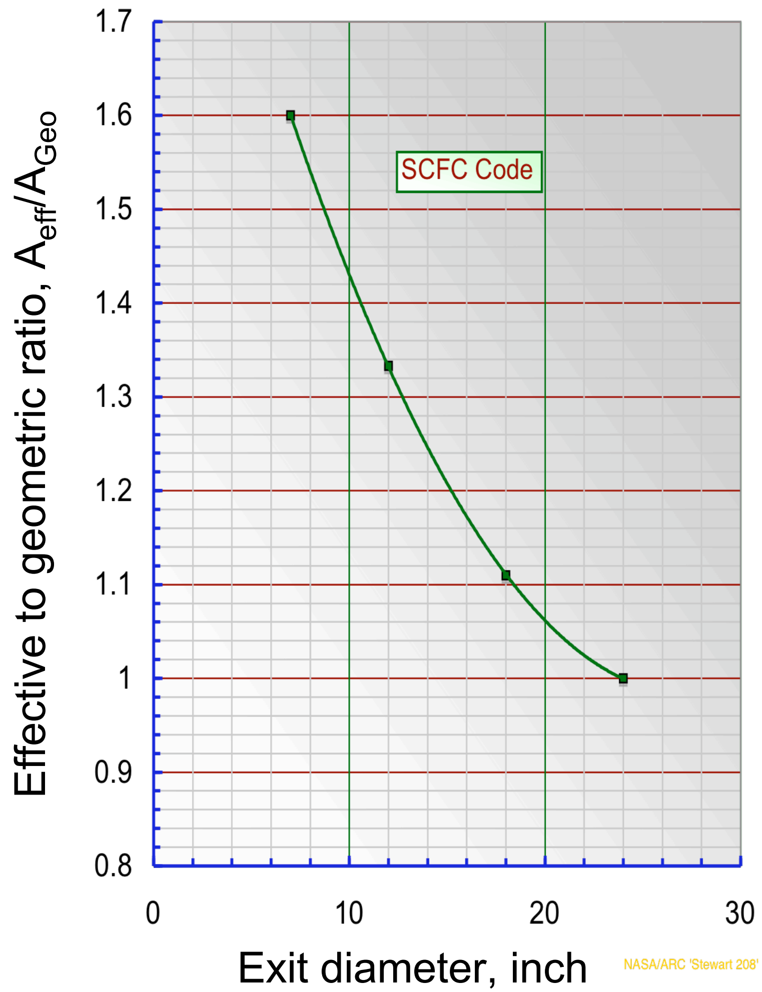
Heat Flux

- Surface temperature
- Atom recombination coefficient (air)
- Body geometry + position
- 3-D Navier-Stokes solution (transport properties)

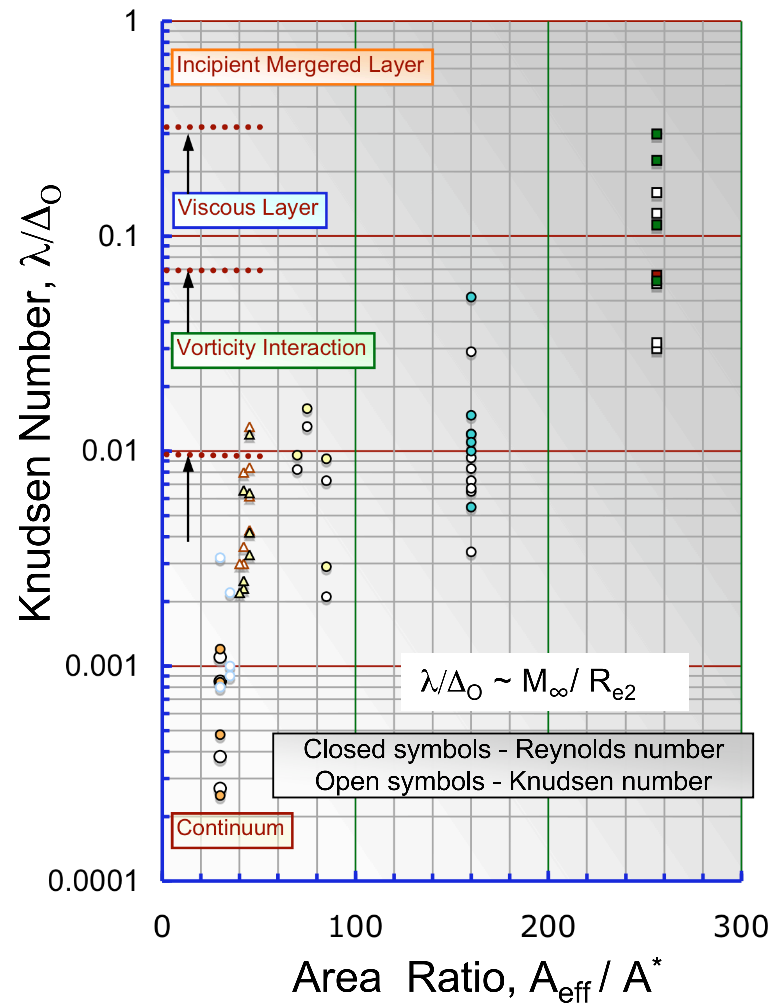
Output

Total heating distribution

AHF Conical Nozzle Test Environment

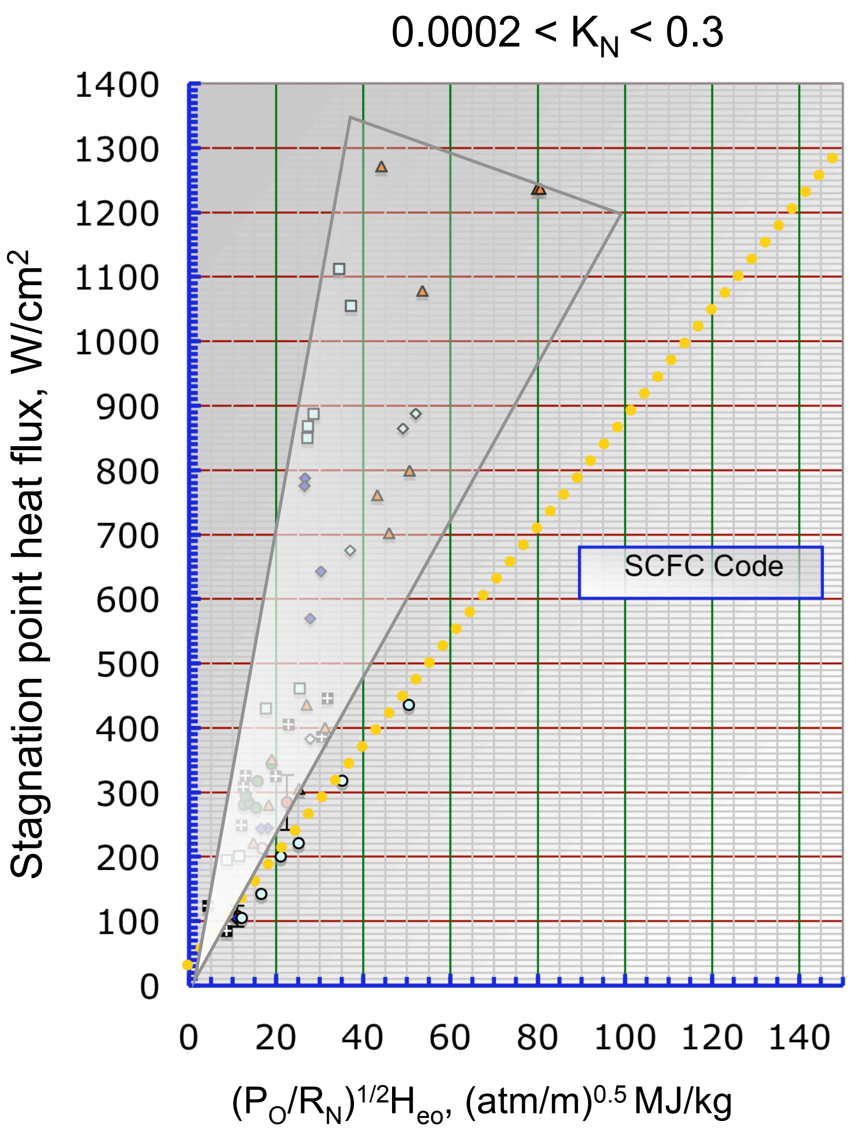


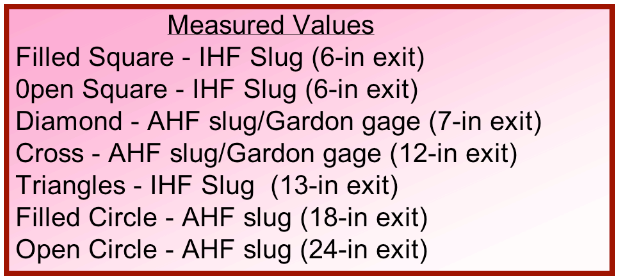
a) Test core size



b) Shock layer flow

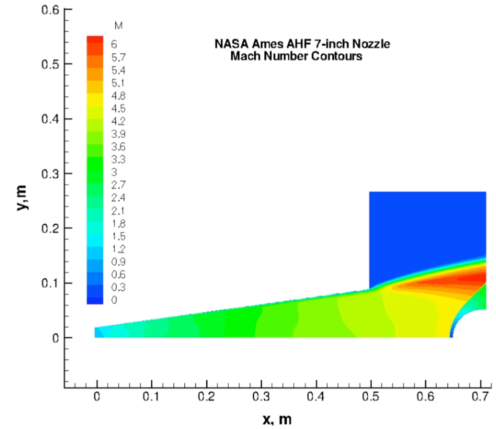
Measured and Predicted Stagnation Point Heat Flux on a Hemisphere



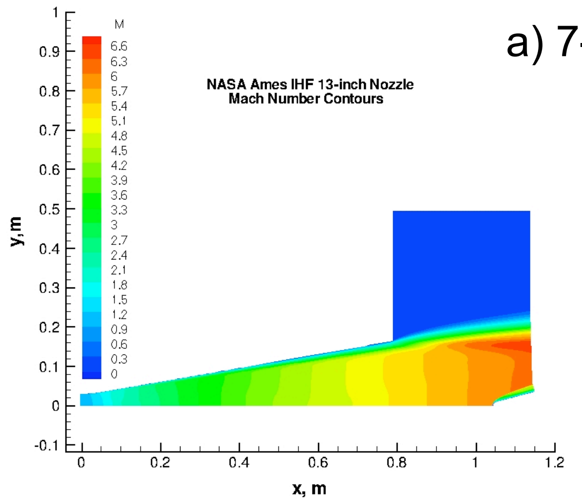


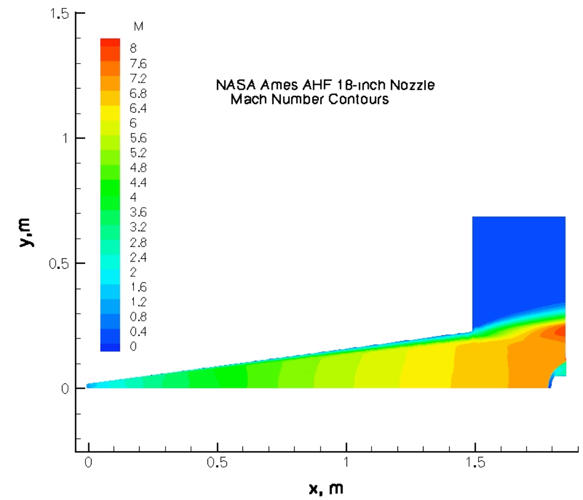
Predicted Mach Number Contours Through AHF and IHF Nozzles

Distance from nozzle centerline, Y, m



a) 7-inch nozzle



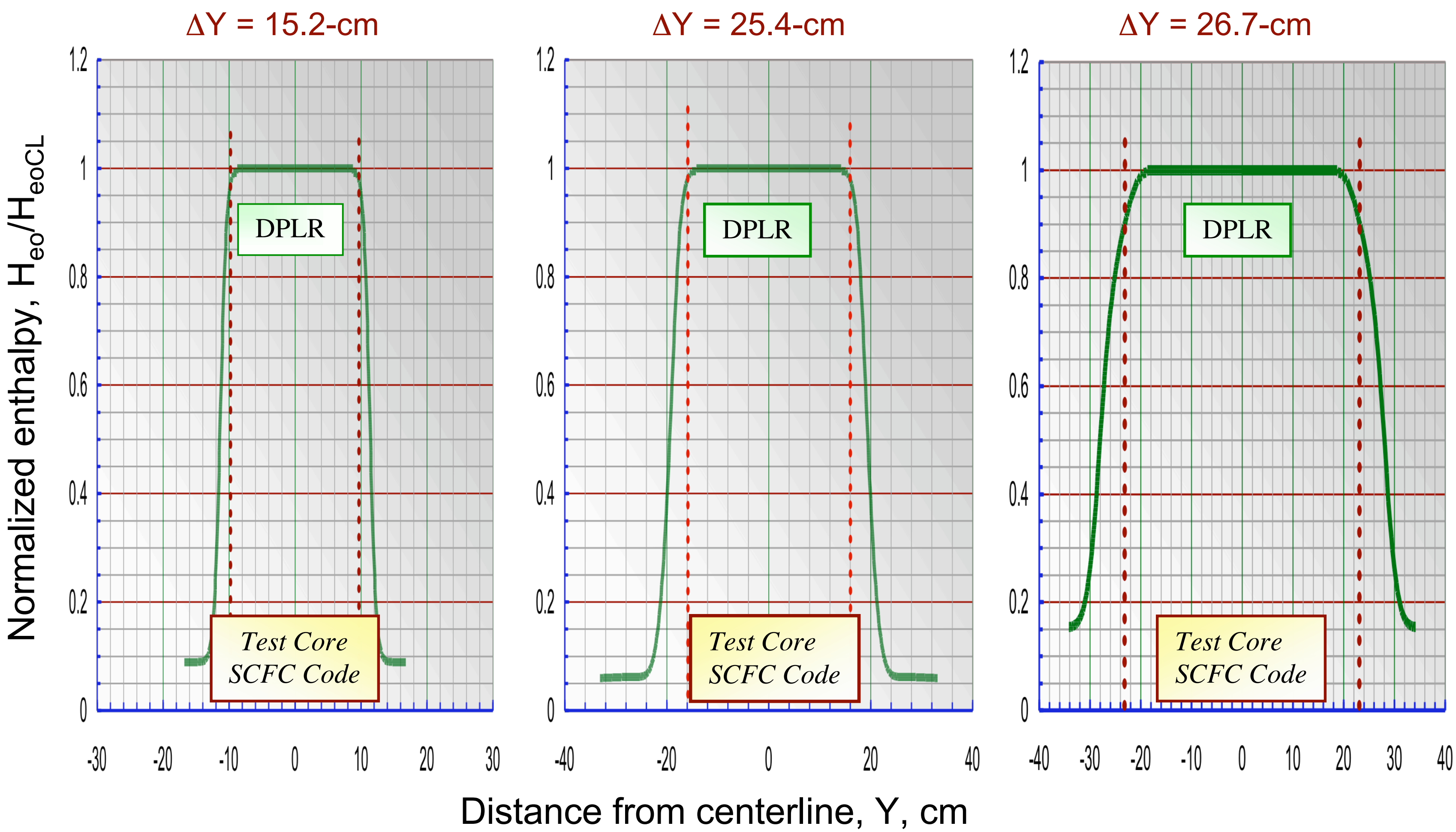


Distance from nozzle throat, X, m

b) 13-inch nozzle

c) 18-inch nozzle

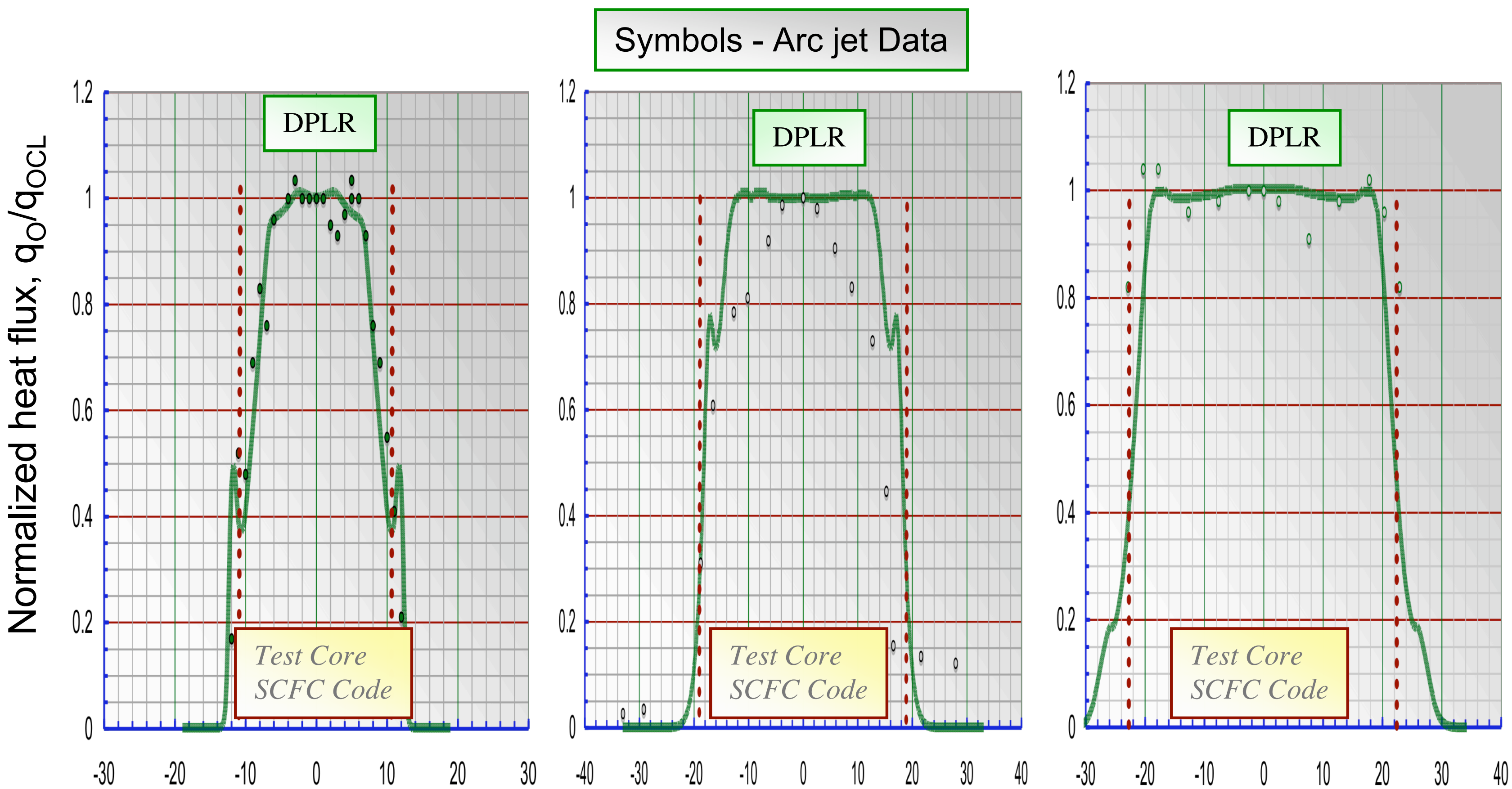
Enthalpy Profiles Across Test Cores



a) AHF, 7-inch nozzle b) IHF,13-inch nozzle c) AHF, 18-inch nozzle

Heating Profile Across the Test Core

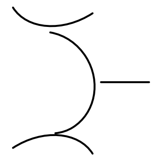
ΔY = 15.2-cm ΔY = 25.4-cm ΔY = 26.7cm



Distance from centerline, Y, cm

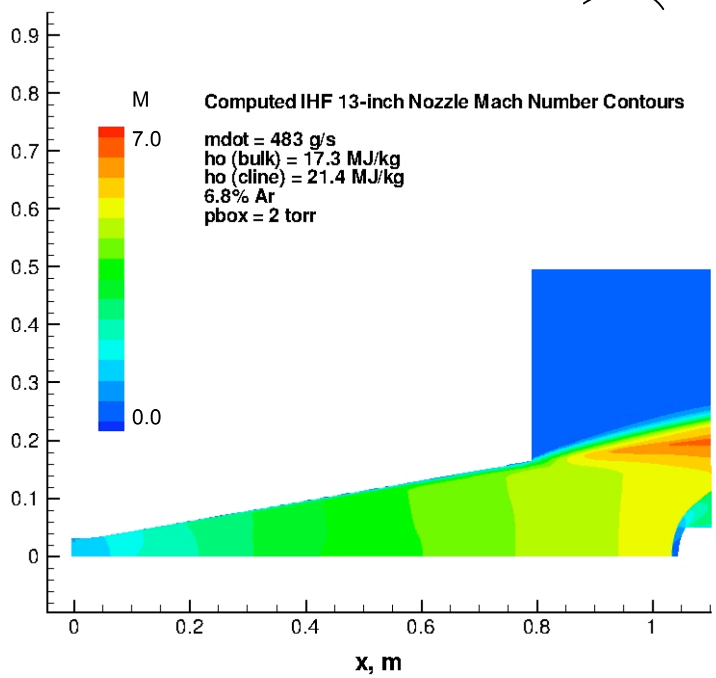
a) AHF, 7-inch nozzle b) IHF, 13-inch nozzle c) AHF, 18-inch nozzle

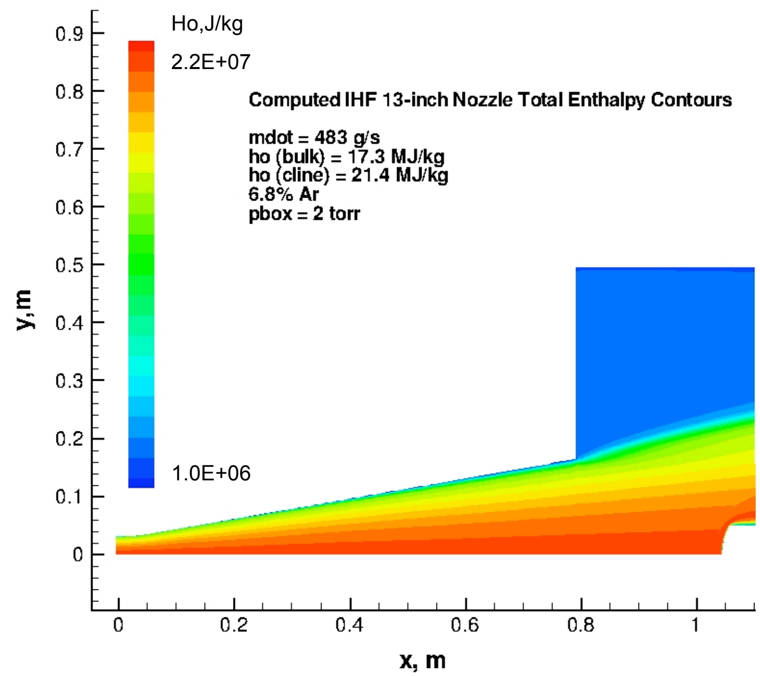
Effect of Throat Enthalpy Profile on Nozzle Performance



Non-Uniform Profile across the nozzle throat

Distance from centerline, Y, m





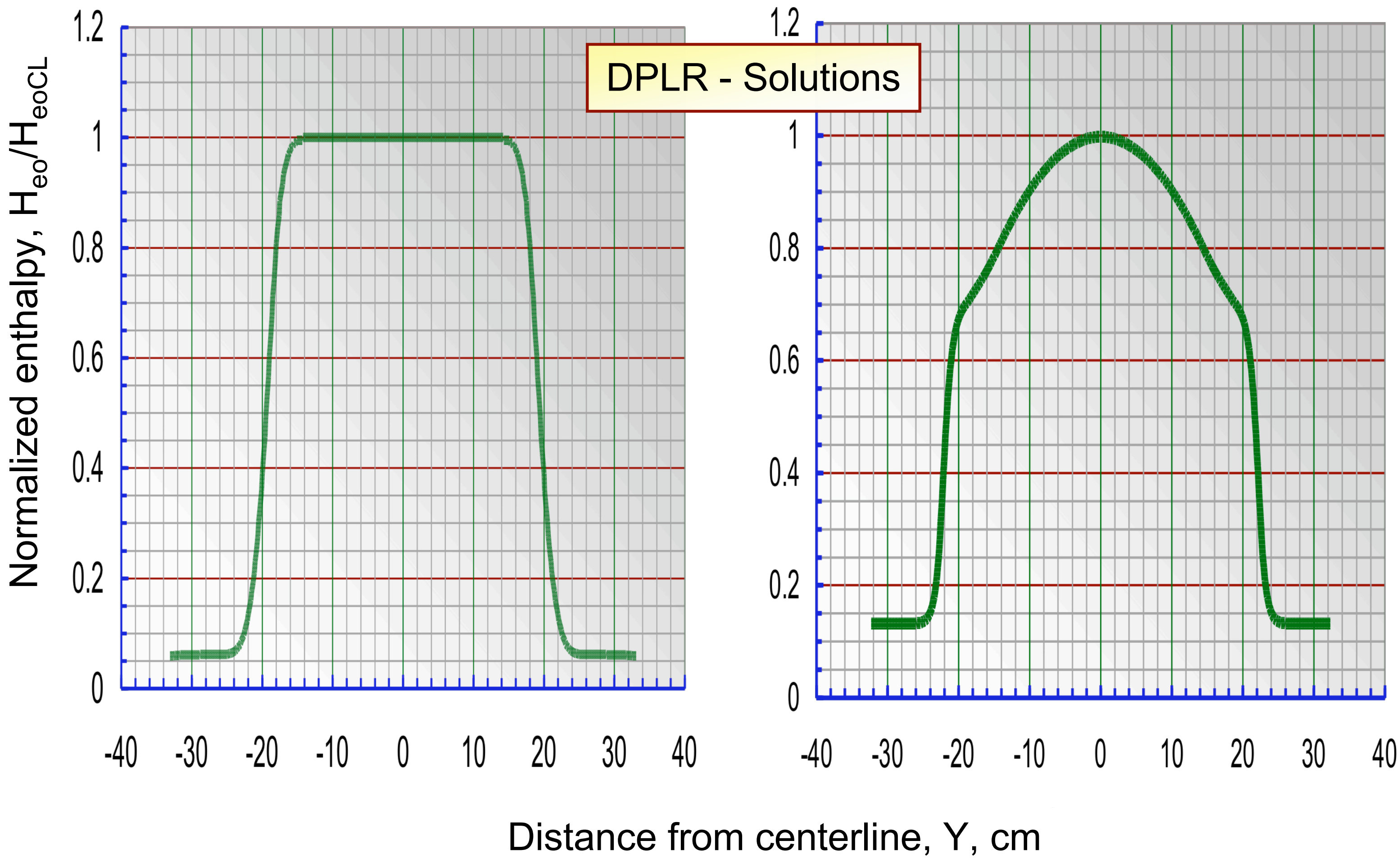
Distance from throat, X, m

a) Mach Number

b) Enthalpy

Effect of Nozzle Flow on Enthalpy Profile Across Test Core

Distance from 13-inch nozzle exit = 25.4 cm

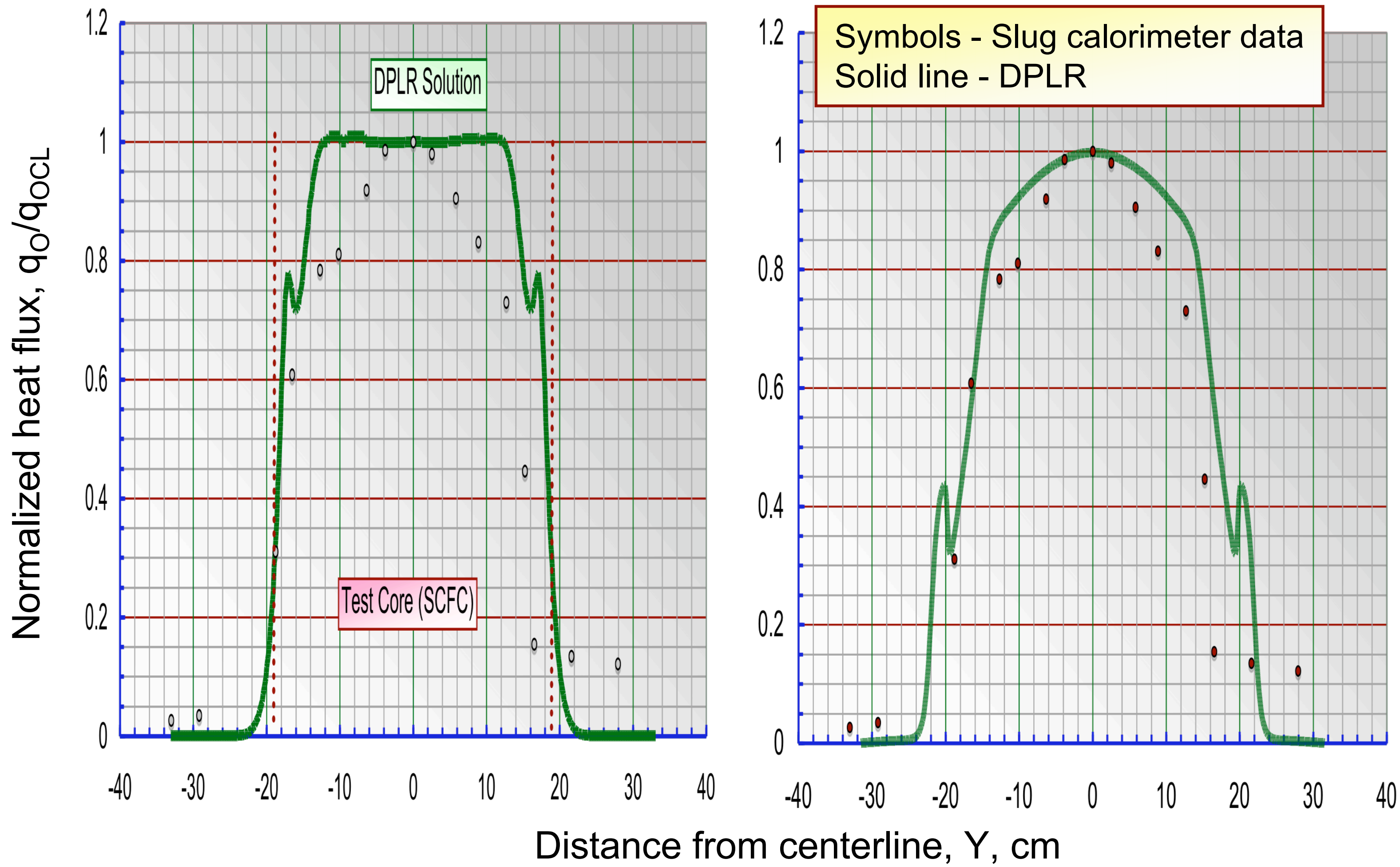


a) Uniform Profile

b) Non-uniform Profile

Effect of Nozzle Flow on Heating Profile Across Test Core

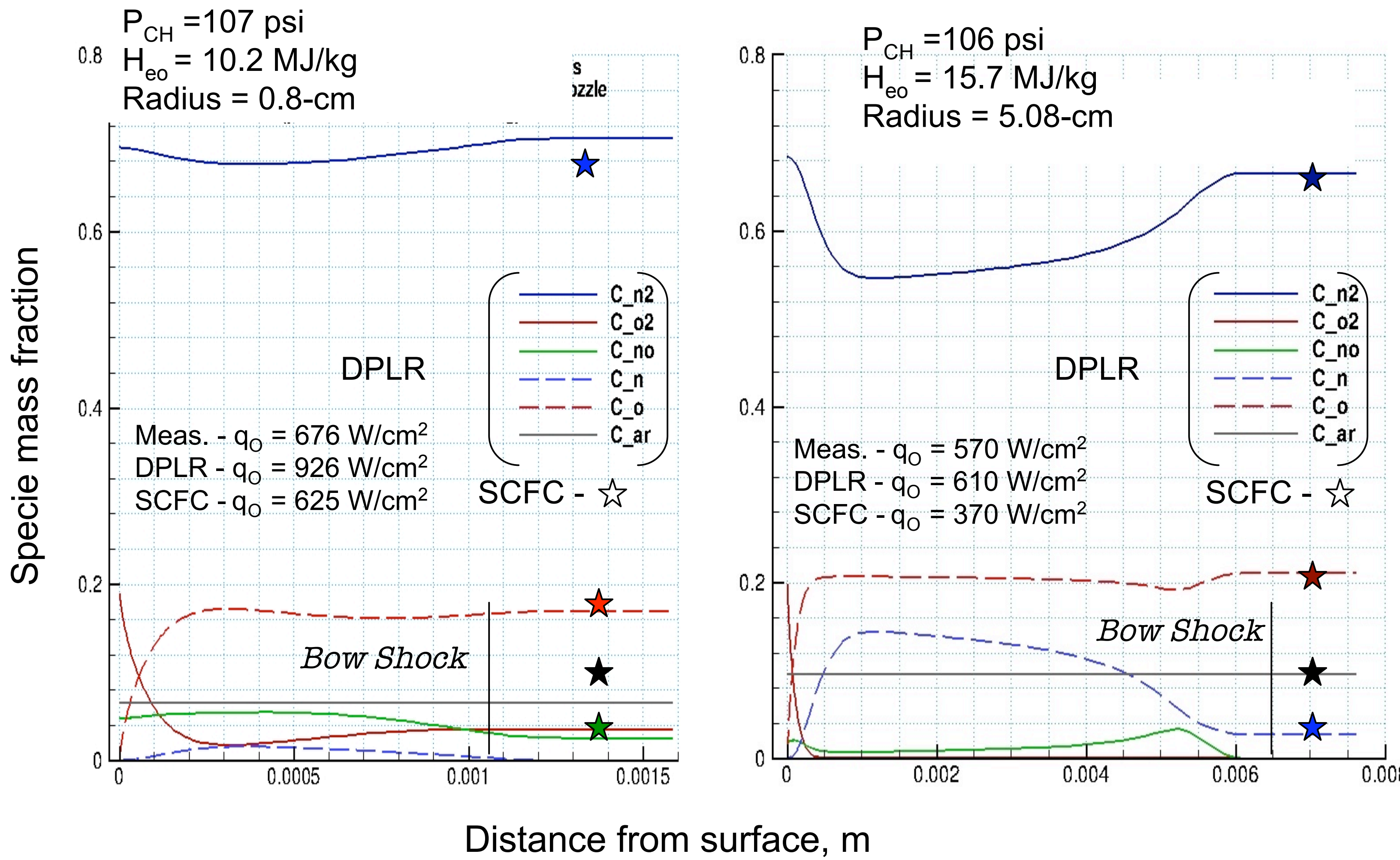
Distance from 13-inch nozzle exit = 25.4 cm



a) Uniform Flow

b) Non-uniform Flow

Species Profiles Between the Shock and Model Surface (AHF 7-Inch Nozzle)

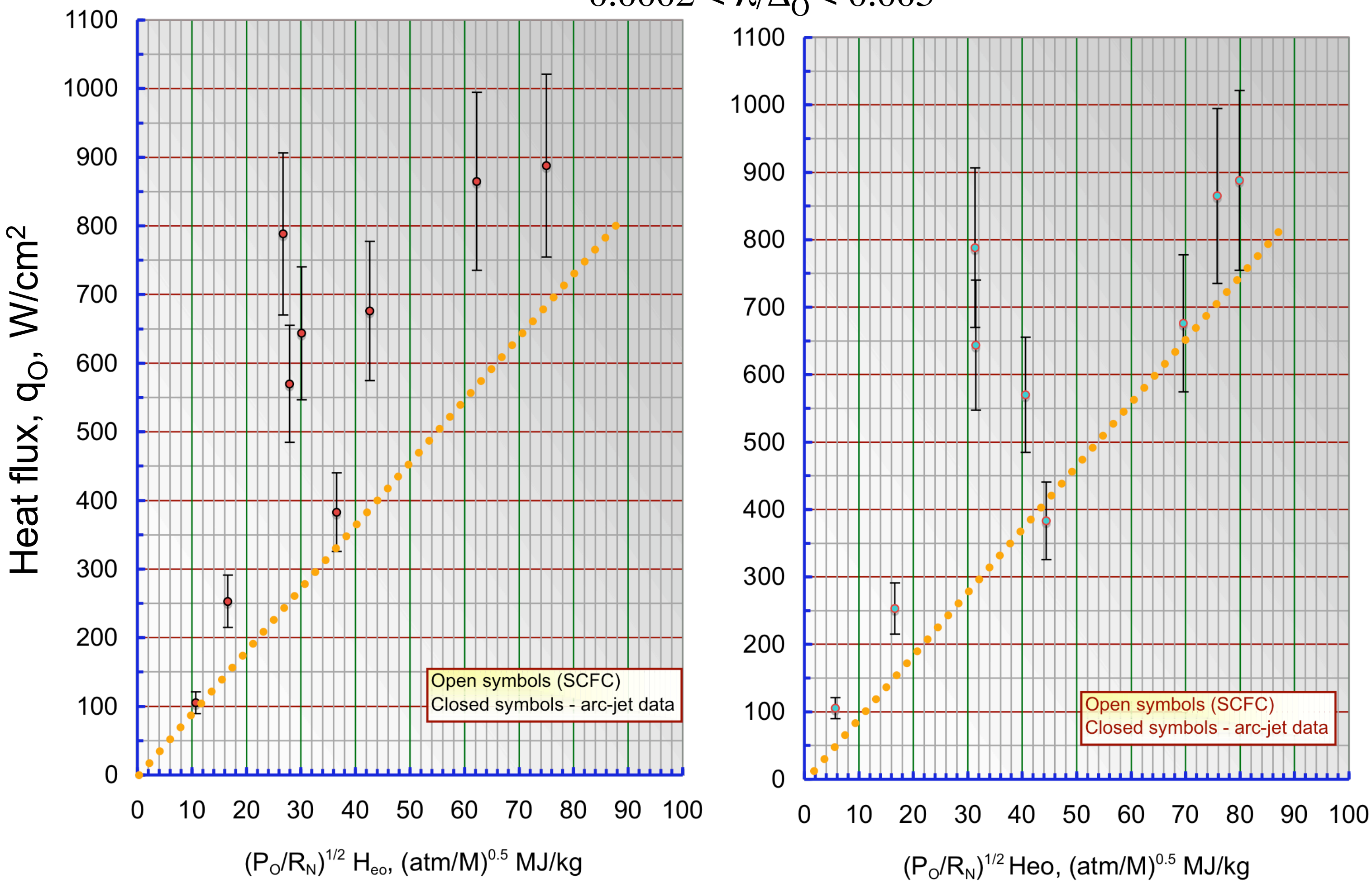


a) Frozen b) Non-equilibrium

Comparison of Measured and Predicted Heat Flux

AHF 7-inch Nozzle

$0.0002 < \lambda/\Delta_O < 0.003$



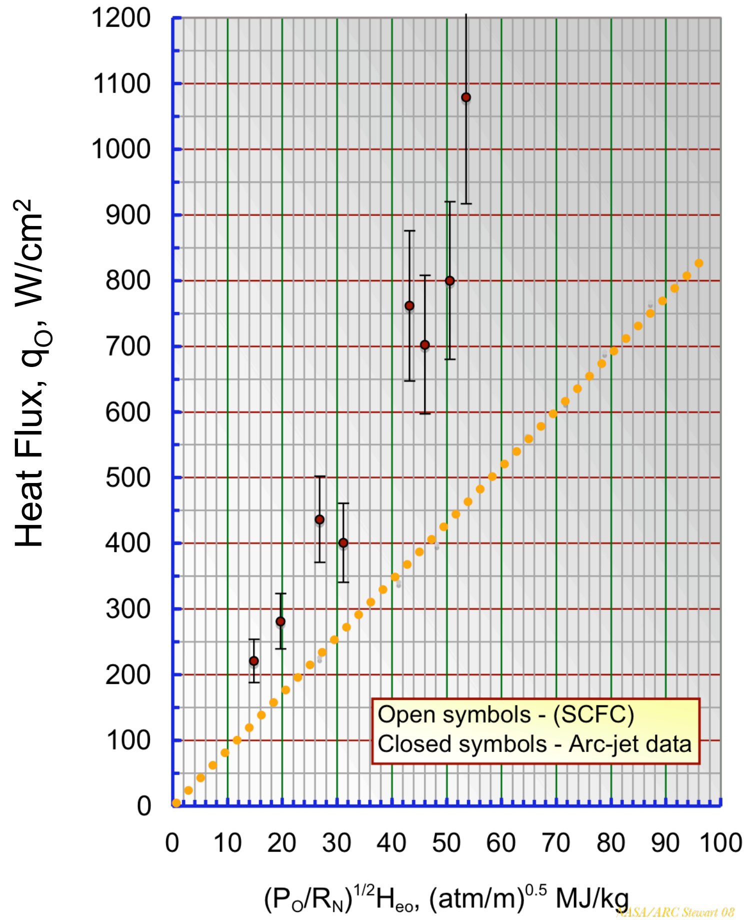
a) Arcjet Data

b) System Energy Balance

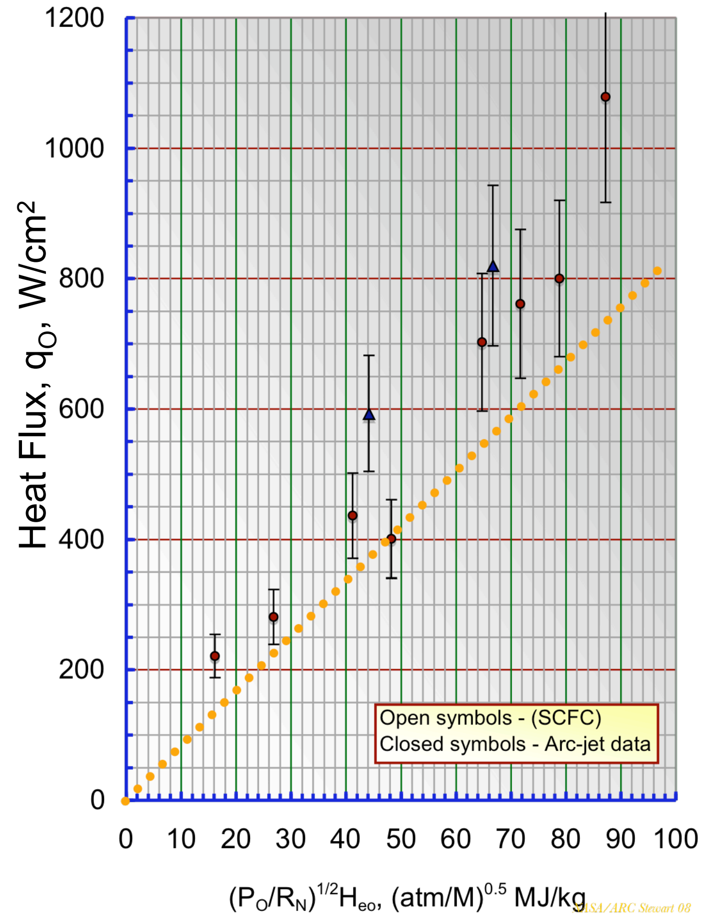
Comparison of Measured and Predicted Heat Flux

IHF 13-inch Nozzle

$0.002 < \lambda/\Delta_O < 0.01$



a) Arcjet data

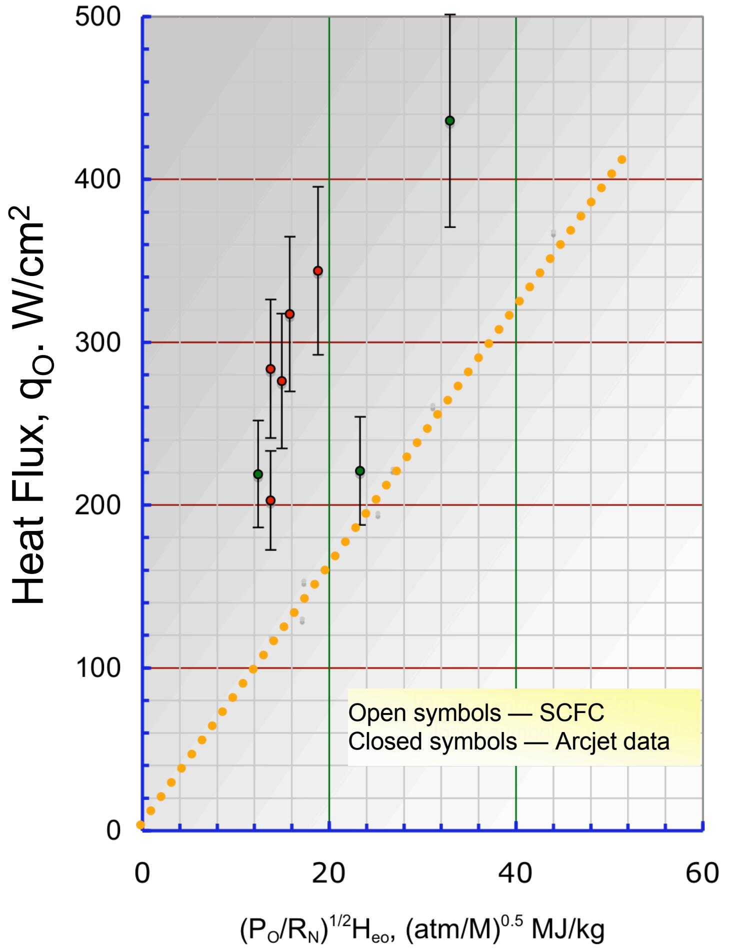


b) System energy balance

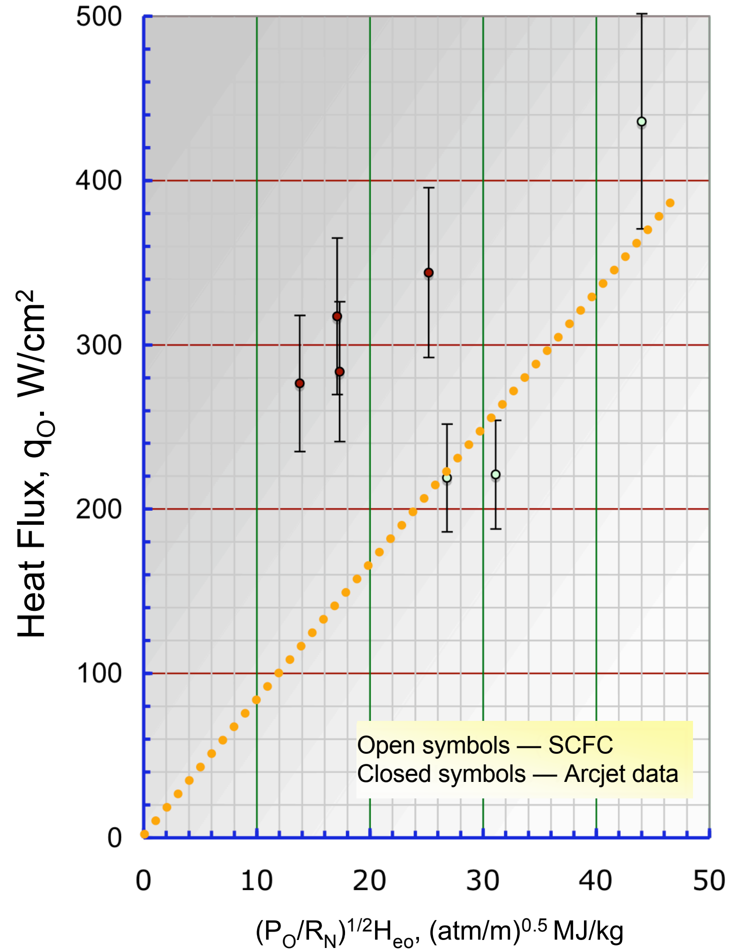
Comparison of Measured and Predicted Heat Flux

$0.003 < \lambda/\Delta_O < 0.06$

AHF 18-inch Nozzle

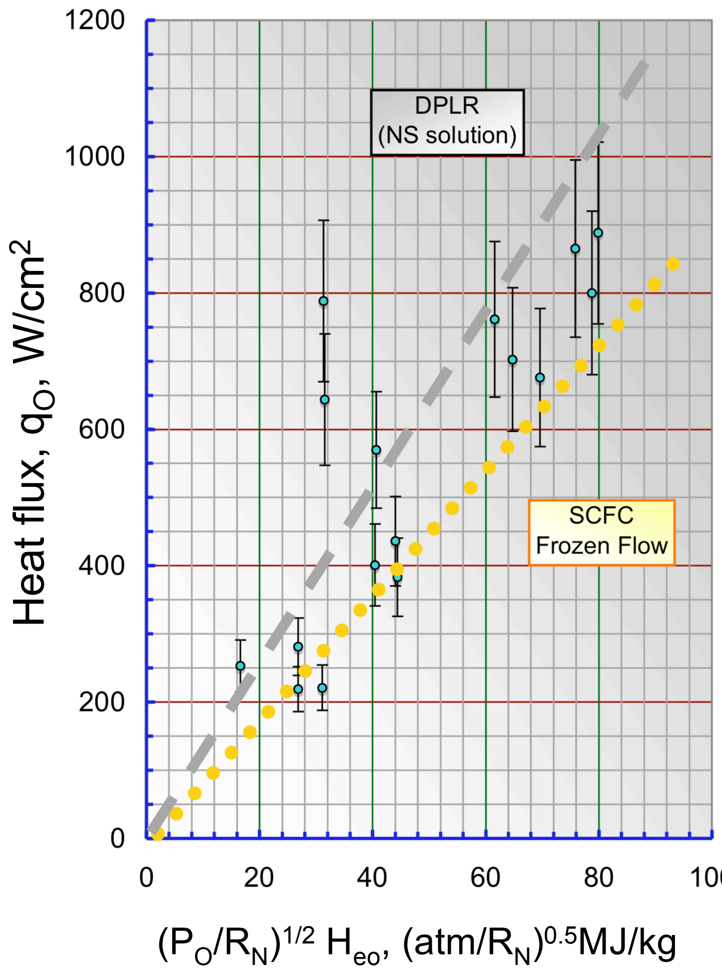


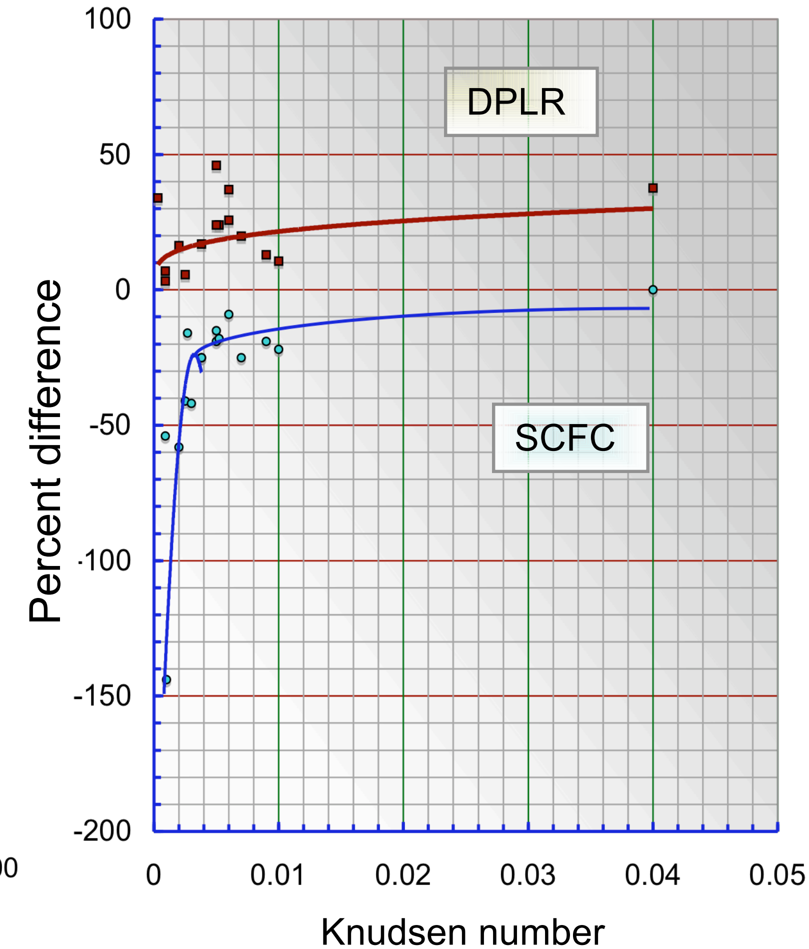
a) Arcjet data



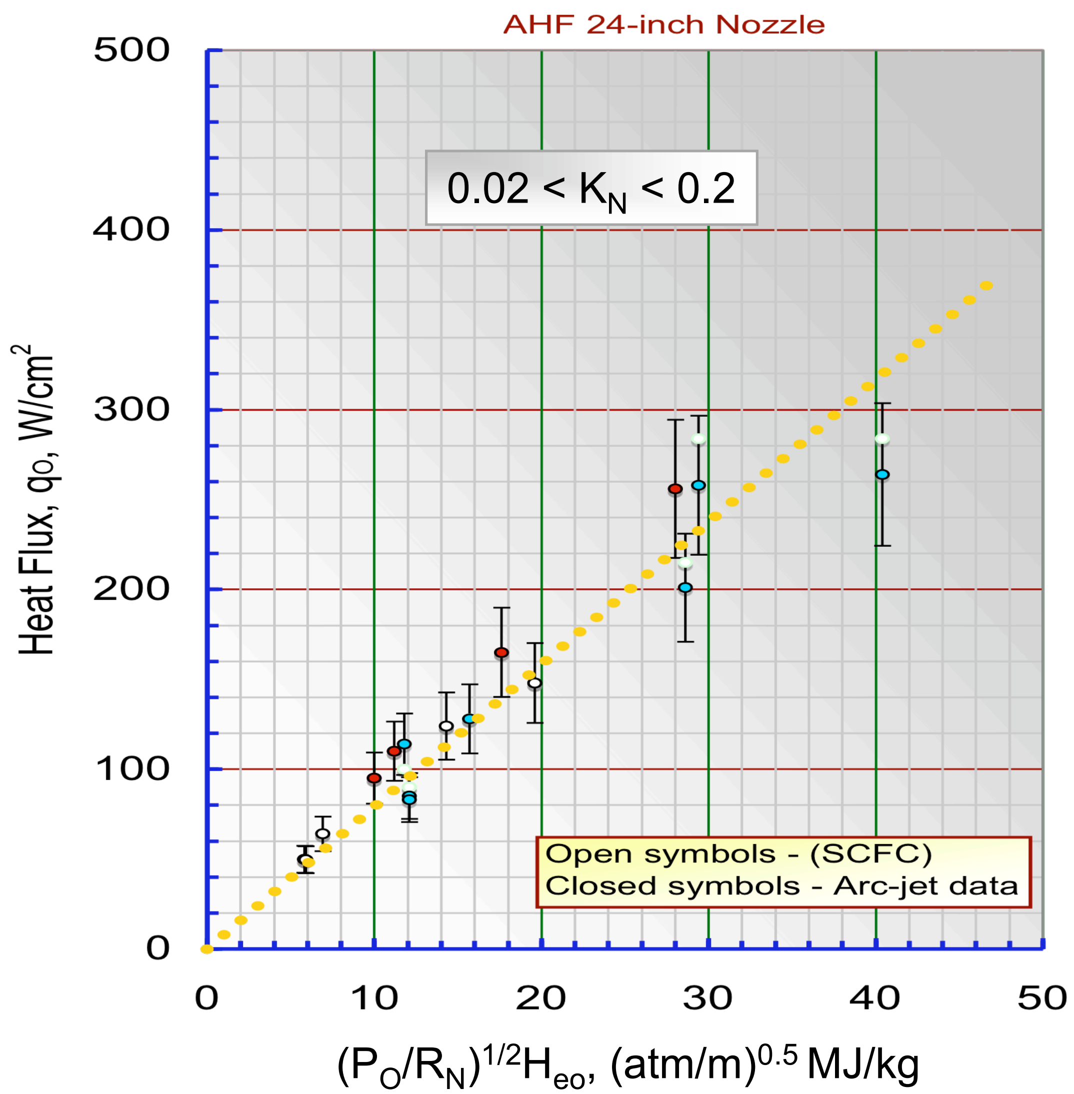
b) System energy balance

Summary of Measured and Predicted Heat Flux

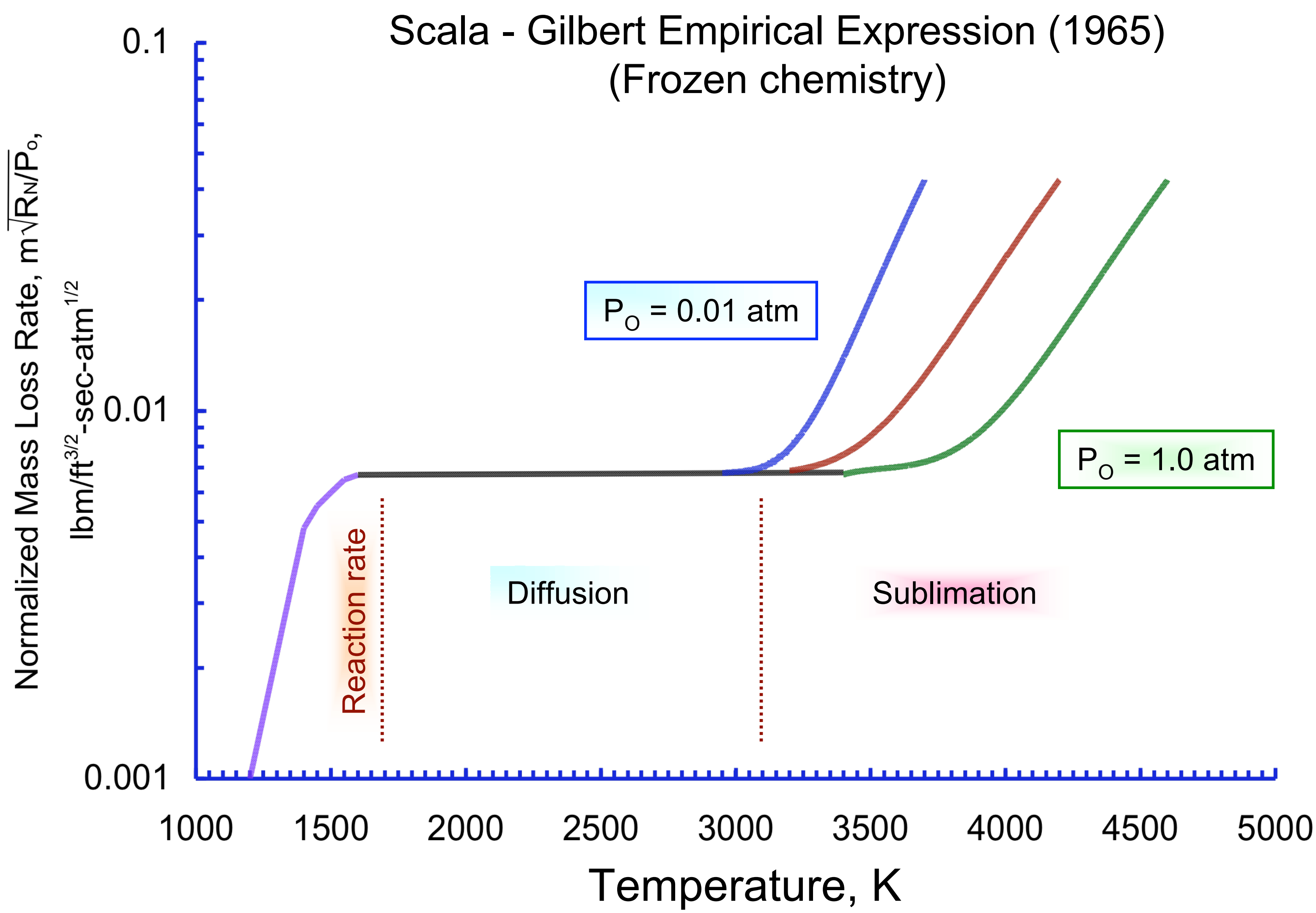




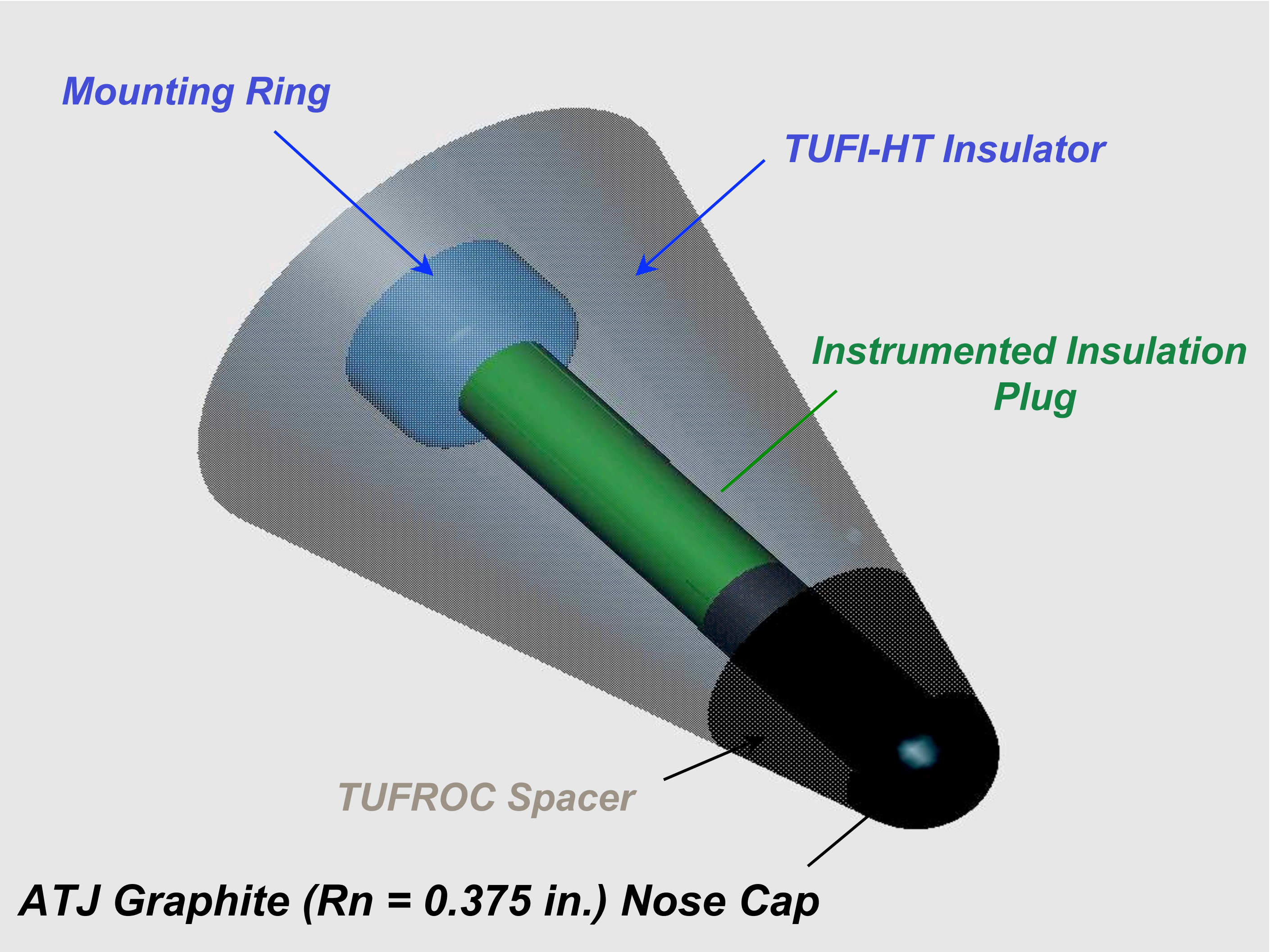
Comparison of Measured and Predicted Heat Flux



Predicted Graphite Mass Loss During Arc-jet Exposure

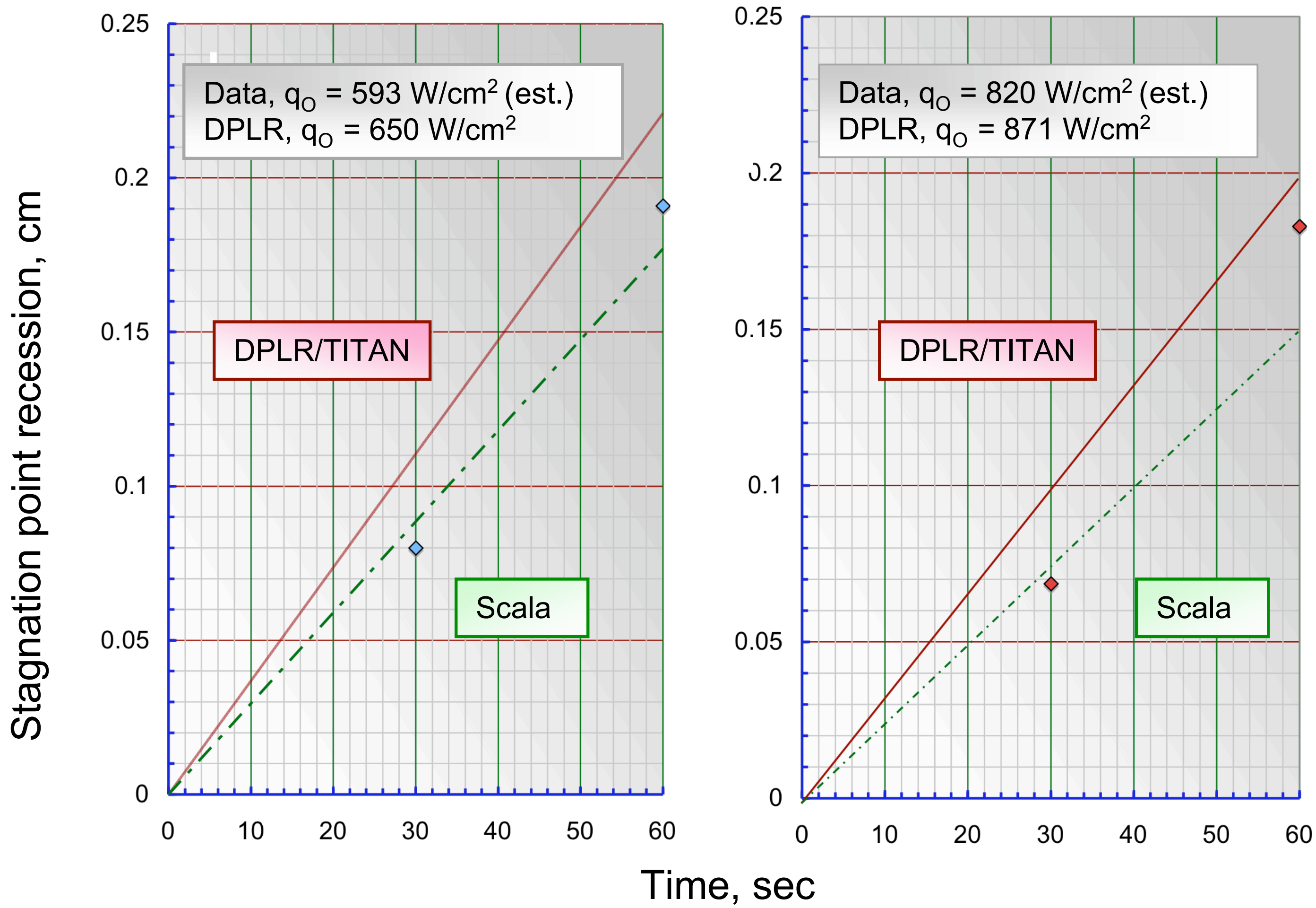


Arcjet Stream Diagnostic Probe



NASA/ARC 'Stewart' 02

Comparison of Predicted and Measured Surface Recession During Arcjet Exposure



a) Case 1, P_O = 0.05 atm

b) Case 2, P_O = 0.07 atm

Summary

- Calorimeter measurements, taken from several nozzles and two facilities, were compared with predicted values obtained from both the SCFC and DPLR codes.
- Surveys taken for several AHF nozzles (7,12,18, and 24) indicated that the flow through the test core was relatively uniform. Predicted normalized heat flux distribution across the core for these nozzles agreed well with measured values obtained from a slug calorimeter.
- For the IHF 13-inch nozzle, surveys showed that flow is non-uniform. CFD simulations showed that the non-uniform heating profile across the test core can be explained by the enthalpy profile in the nozzle throat.

Summary, continued

- Centerline free-stream properties calculated from SCFC (frozen flow) agreed well with values obtained from the non-equilibrium solutions using DPLR.
- Predicted heat fluxes from DPLR (non-equilibrium flow) were higher, and those obtained from the SCFC code (frozen flow) were lower, than the measured data. In general, both codes predicted fluxes were within ±20% of the calorimeter measurements.
- The coupled DPLR/TITAN 2-D solution resulted in a conservative estimate of the recession that occurred on a graphite test article after exposure to arcjet flow. Scala's empirical 1-D solution also agreed reasonably well with the data.