On Characterization of Flow Disturbances in Arc-Jet Testing

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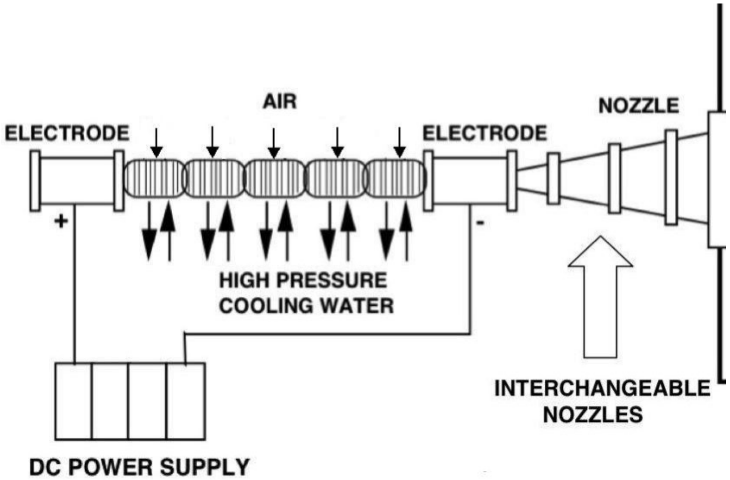
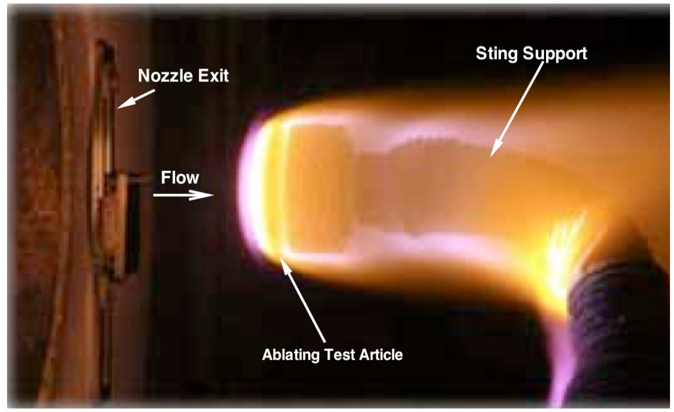
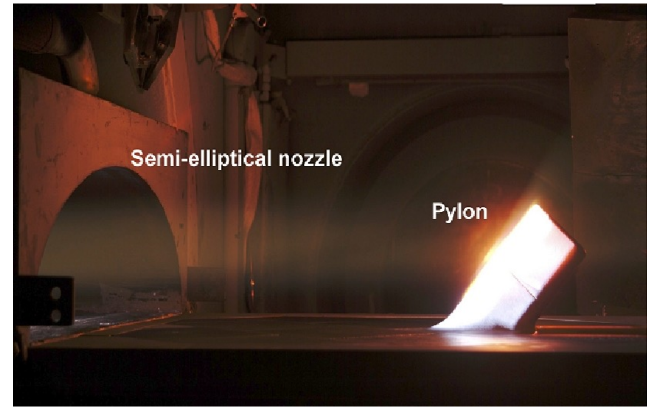
Introduction to Arc-Jets and Testing



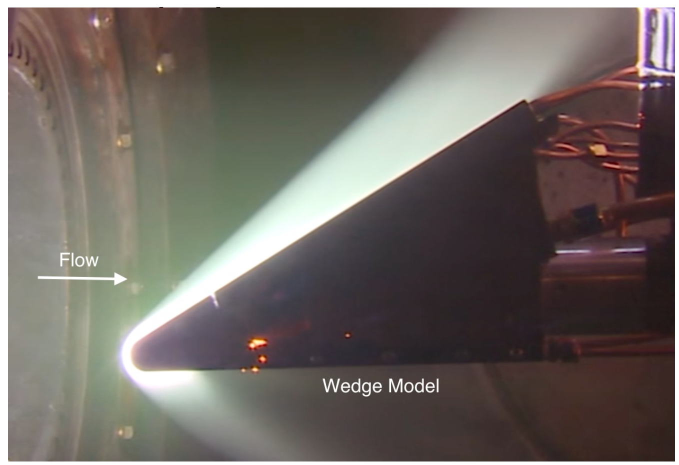
Arc-heater/nozzle sketch



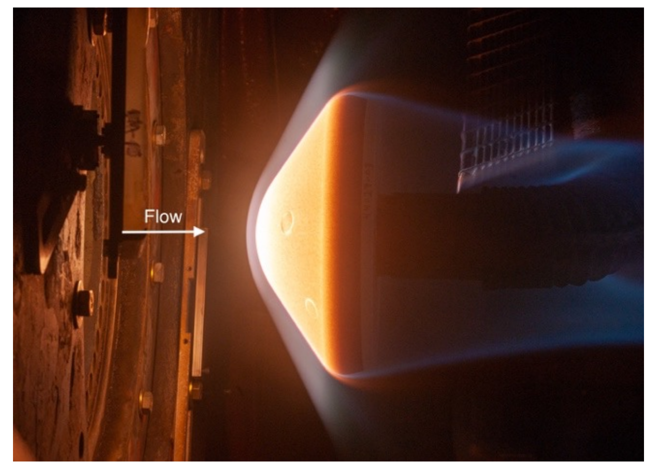
Stagnation coupon



IHF panel/pylon test



IHF wedge test



IHF sphere-cone model test

- Arc-jets are primary facilities to test the performance of thermal protection systems (TPS) in an aerothermodynamic heating environment
- Free jet test configuration with stagnation coupon or wedge models—conical nozzles
- Semi-free jet test configuration with panel test articles—semi-elliptical nozzles

Arc-jet flow characterization is important to interpret test data accurately (Flow disturbances and their detection, including CFD simulations)

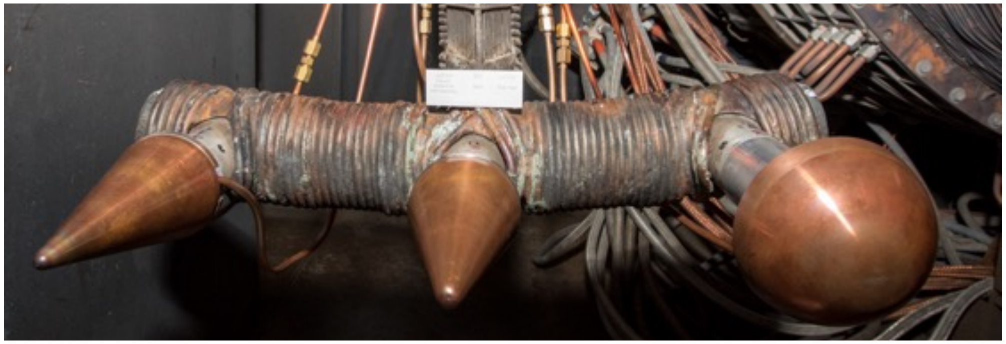
Objective and Scope

- Primary objective is to report CFD simulations and analysis of flow characterization tests in high enthalpy arc-jet facilities at NASA Ames Research Center
  - Flow disturbances and their characterization are presented through case studies
  - Three different arc heaters and nozzles: the 60-MW IHF 30-inch conical nozzle, the 10-MW TP3 15-inch conical nozzle, and the 20-MW AHF 12-inch conical nozzle
  - For each case, existence of a flow disturbance is confirmed through flow survey data using pitot pressure and heat flux probes and accompanying analysis

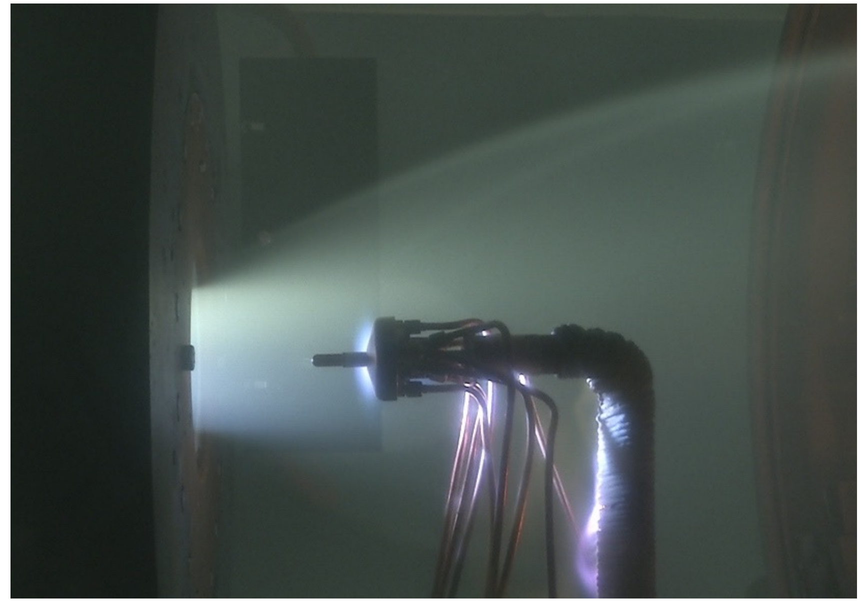
- Present analysis comprises CFD simulations of the nonequilibrium flowfield in the facility nozzle and test box, including the models tested
  - Comparisons of CFD results with the experimental measurements are presented
  - Through CFD analysis, effects of the flow disturbances on model surface quantities are assessed, and their implications for arc-jet testing are discussed

Pitot Pressure and Heat Flux Survey Probes

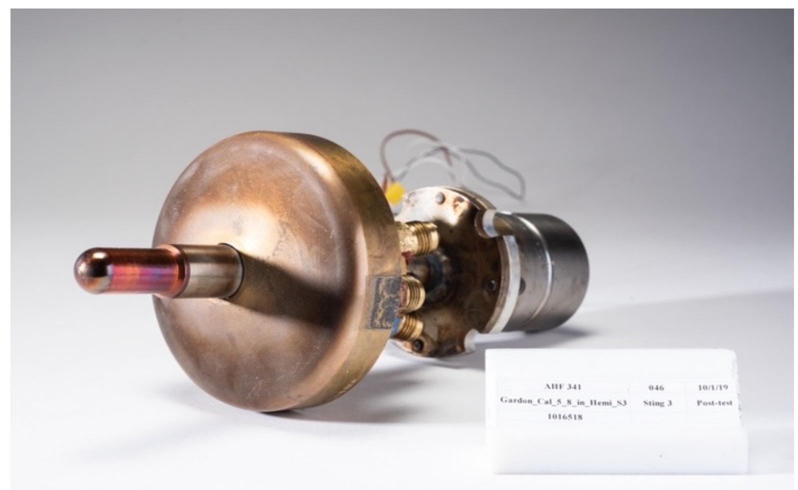
IHF 30-inch, TP3 15-inch, and AHF 12-inch nozzle flows



Trident fork with 3 survey probes used for the IHF sweeps (IHF 30-inch nozzle)

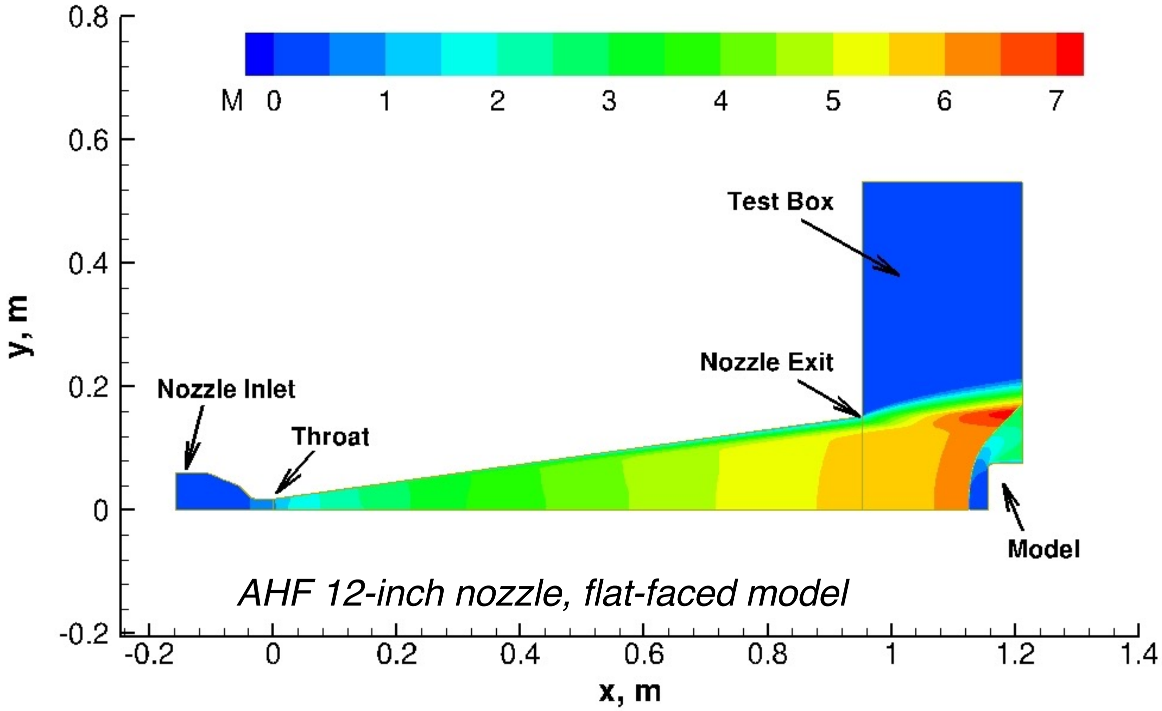


A hemisphere survey probe in an arc-jet flow

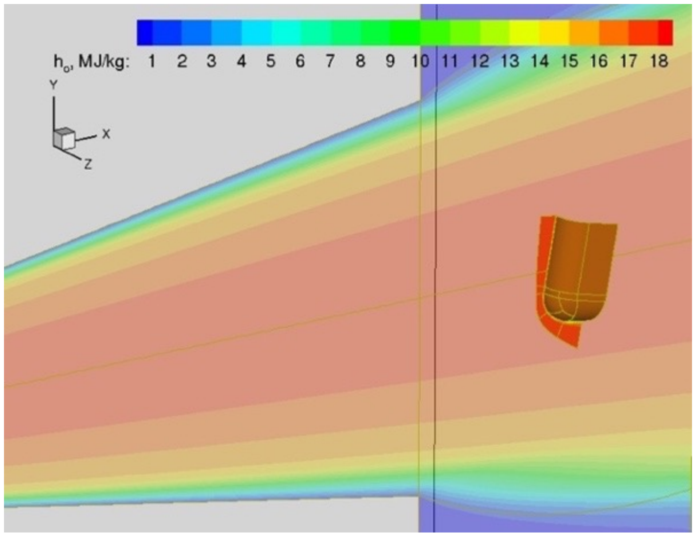


1.59-cm diameter hemisphere probes: pitot probe and Gardon gage calorimeter (TP3 15-inch nozzle, AHF 12-inch nozzle)

Computational Approach



AHF 12-inch nozzle, flat-faced model



IHF 30-inch nozzle, 10º-yawed wedge model

- CFD analysis includes simulations of the nonequilibrium flowfield in the facility nozzle and test box, including the model flowfields
- Prescribe flow profiles at the nozzle inlet with chemical equilibrium composition
- Axisymmetric or 3-D Navier-Stokes equations with nonequilibrium processes
- Thermochemical model for arc-jet flow
  - Five or six chemical species: N_2, O_2, NO, N, O, Ar (if present)
  - Two-temperature model (Park): T -translational-rotational, T_v -vibrational-electronic
- Data-Parallel Line Relaxation Method - DPLR Code

Presentation of Results

- Three case studies involving flow disturbances and their characterization in arc-jet flows
  - IHF 30-inch nozzle, 10°-yawed wedge model
  - TP3 15-inch nozzle, 10.2-cm iso-q and 20.3-cm flat-faced models
  - AHF 12-inch nozzle, 10.2-cm iso-q and 15.2-cm flat-faced models

- For each case, the existence of a flow disturbance is confirmed through flow survey data and accompanying CFD analysis
  - Test articles are placed in the jet exiting the conical nozzle
  - Pitot pressure and heat flux probes for the flow surveys
  - CFD analysis for interpretation of the survey data
  - Original source of these flow disturbances is often not known precisely, but for some cases their origin can be traced back to the nozzle throat region or locations near the nozzle joints

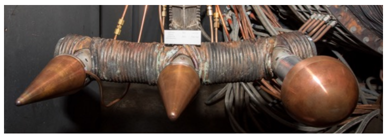
- Effects of the disturbances on test article surface quantities are presented
  - Disturbances alter the flowfield over calorimeters and test articles
  - Explanation of calorimeter measurement anomalies
  - Interpretation of the test data

Case 1, IHF 329:
IHF 30-inch nozzle, 10°-yawed wedge model

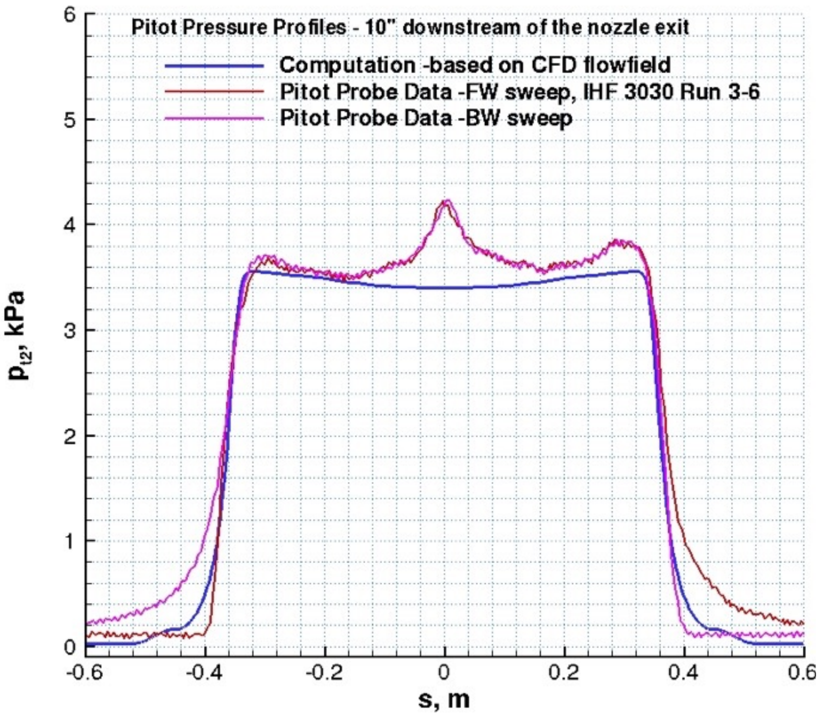
Existence of a flow disturbance in the IHF 30-inch nozzle was not known prior to this test series

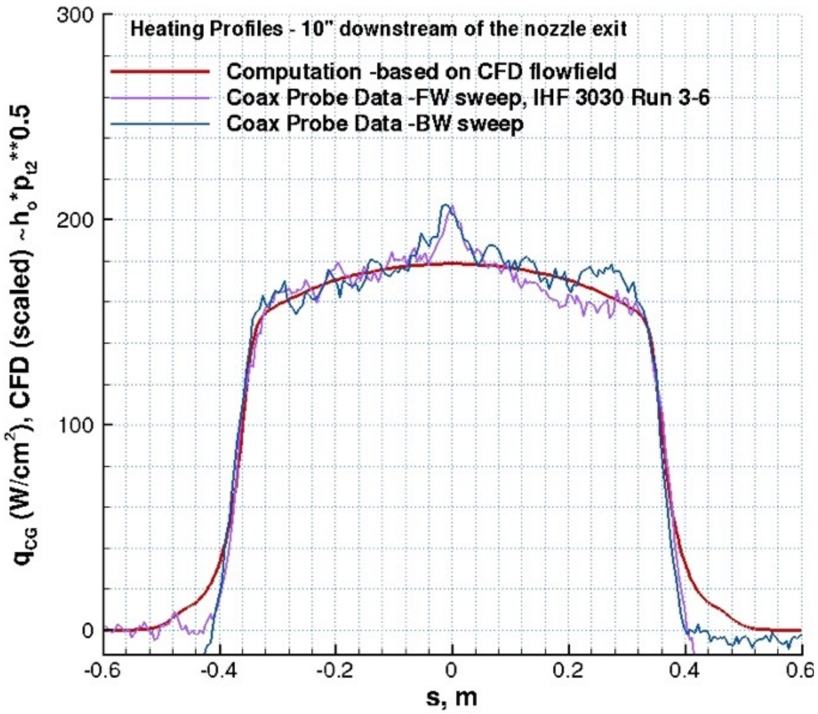
Probe Survey Data and Comparisons with Computations

IHF 30-inch nozzle flow: $\dot{m}$ = 410 g/s, h_{ob} = 15.9 MJ/kg, h_{ocl} = 17.8 MJ/kg, parabolic profile, 7.1% Ar



Trident fork for the IHF probe sweeps

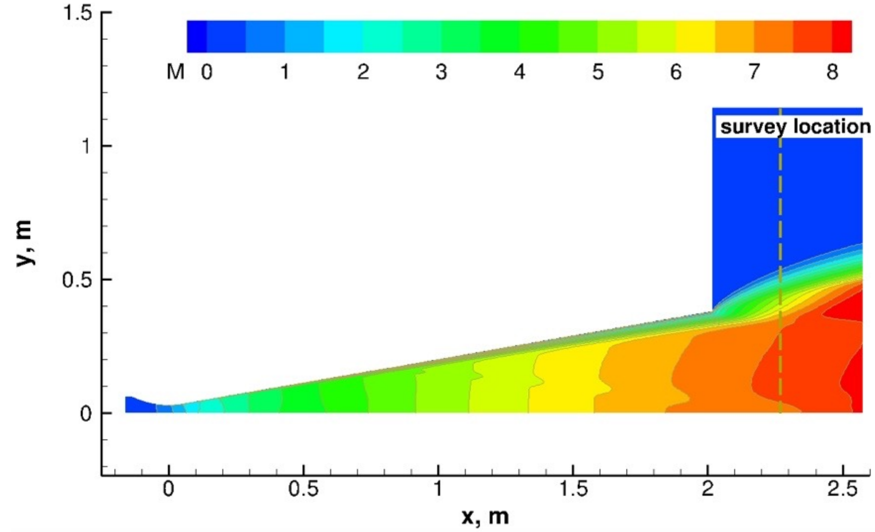




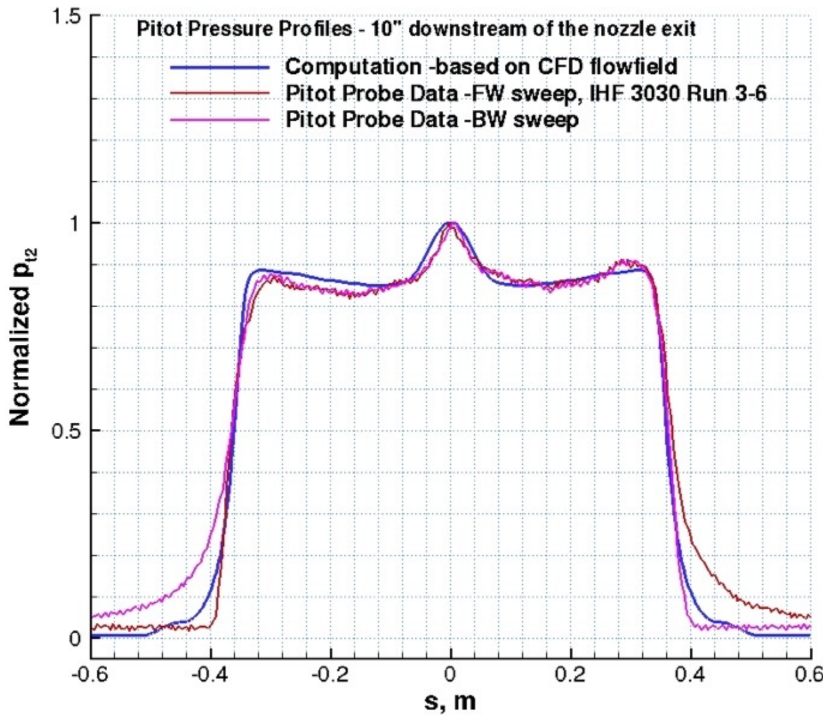
- Both pitot pressure and heat flux data show a feature near the nozzle centerline, showing higher pressure and heating levels
- Both pitot pressure and heat flux data are not exactly symmetric, but they are repeatable within the measurement fluctuations between forward and backward sweep directions (FW and BW)
- CFD-predicted pitot pressure and heat flux distributions are in reasonable agreement with the survey data except near the nozzle centerline
- This feature in the measured survey data is not ambiguous, so it can only be explained by the presence of a **flow disturbance** in the nozzle

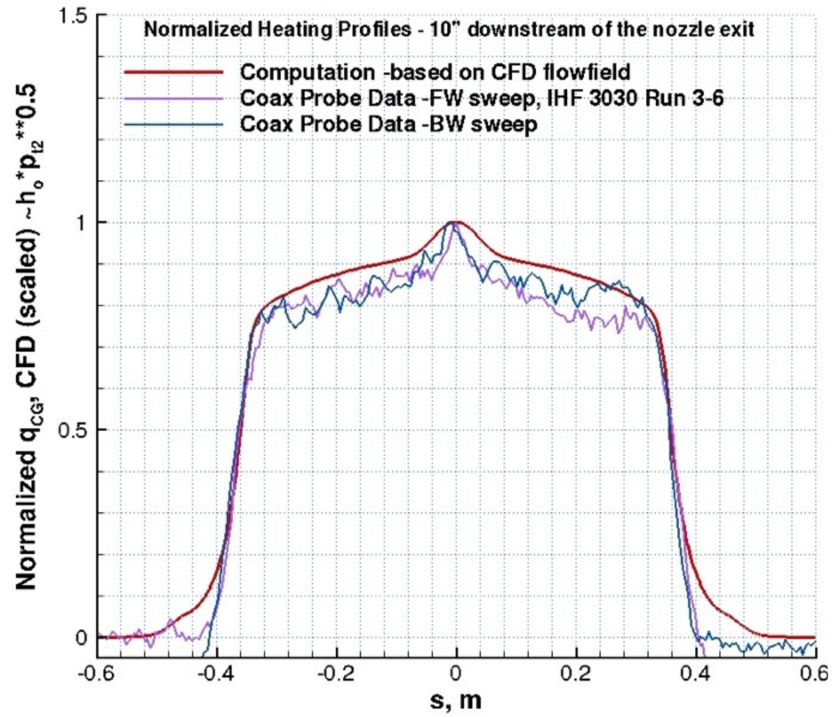
Probe Survey Data and Comparisons with Computations

IHF 30-inch nozzle flow: $\dot{m}$ = 410 g/s, h_{ob} = 15.9 MJ/kg, h_{ocl} = 17.8 MJ/kg, parabolic profile, 7.1% Ar



with the flow disturbance





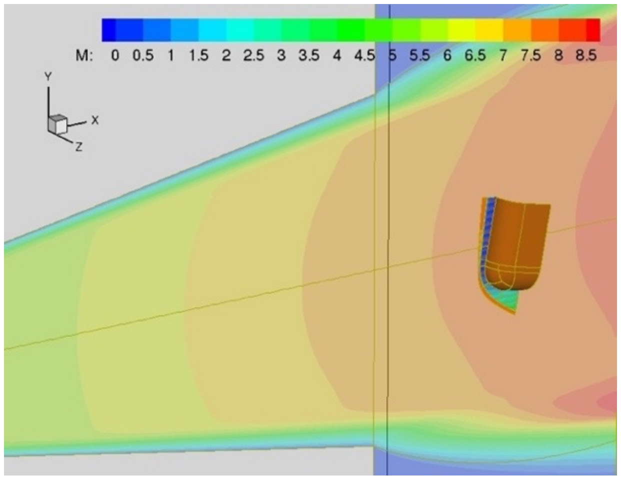
- To reproduce the measured survey data with CFD simulations, a flow disturbance in the nozzle (a small protuberance placed near one of the nozzle joints) is introduced. The objective here is, by reproducing the survey data with computations, to investigate the effects of this disturbance on the model surface quantities.

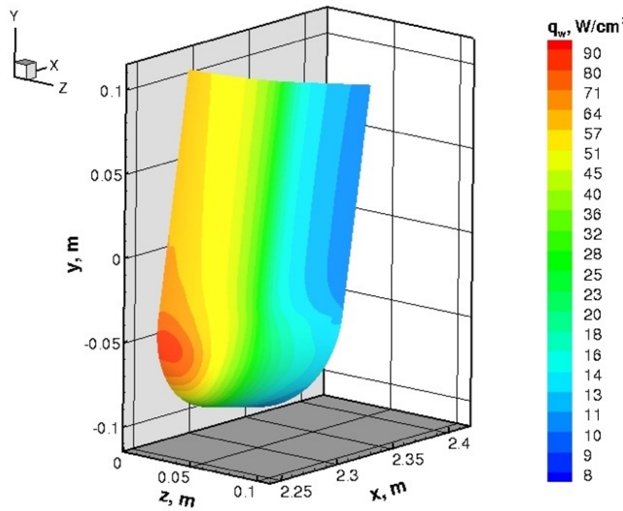
Effects of the Flow Disturbance on Model Surface Heat Flux

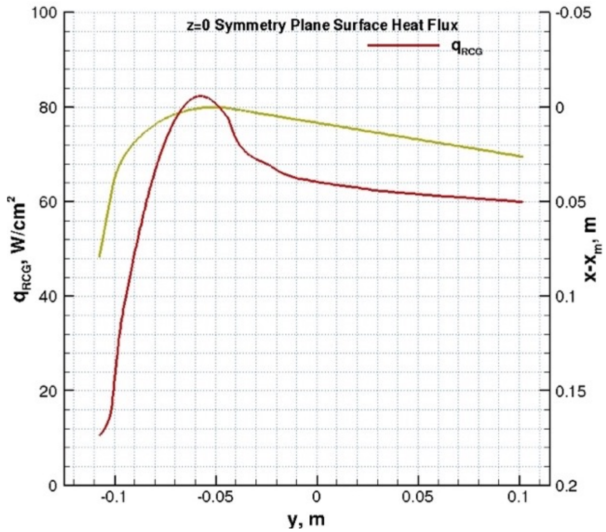
10°-yawed wedge model (x_{ml} = 25.4 cm, leading edge is 5.1 cm below the nozzle centerline)

IHF 30-inch nozzle flow: $\dot{m}$ = 410 g/s, h_{ob} = 15.9 MJ/kg, h_{ocl} = 17.8 MJ/kg, parabolic profile, 7.1% Ar

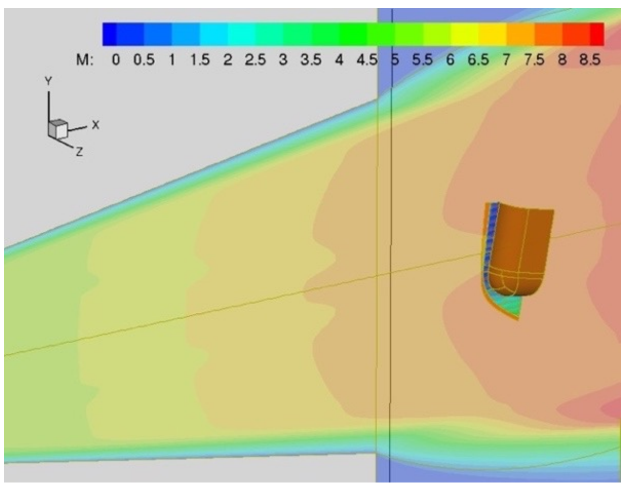
Mach number contours, nominal

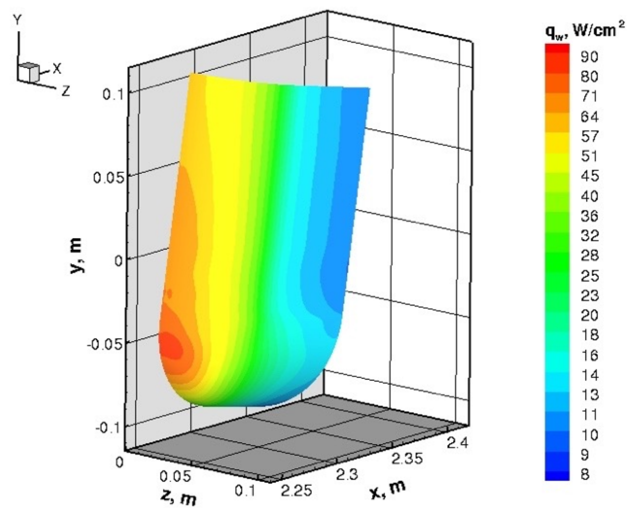


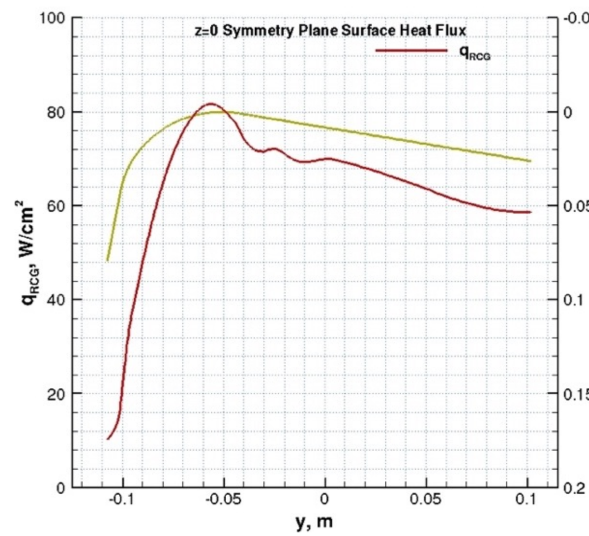




with the flow disturbance







- The predicted surface heat fluxes at the stagnation point are similar, ~82 W/cm² (reaction-cured glass coating)
- When the flow disturbance is included, the heat flux does not decrease monotonically, and the heat flux difference between the stagnation-point and y=0 location is smaller
- Both non-monotonic temperature distribution from the stagnation point to y=0 location and smaller temperature difference are observed (infrared camera)

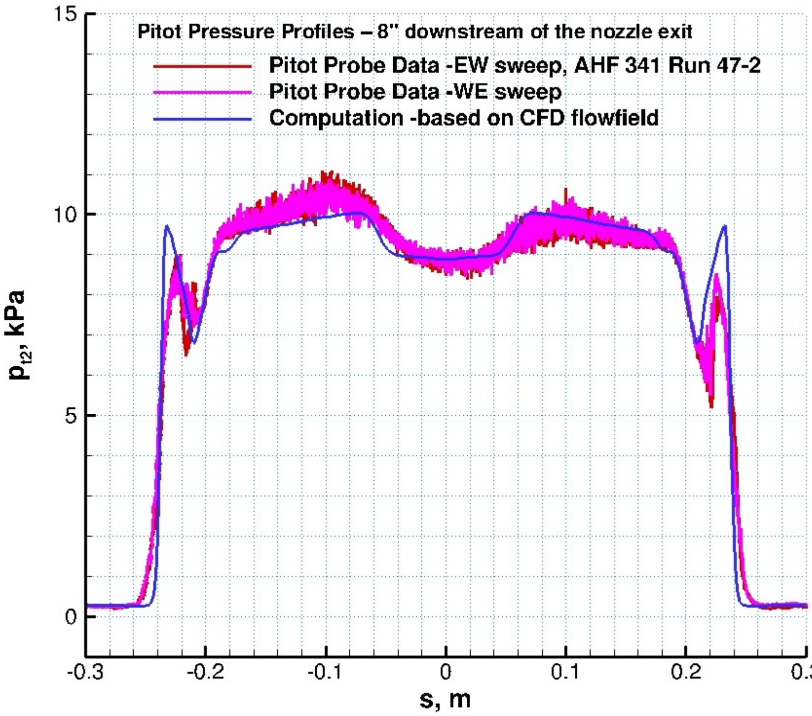
Case 2, AHF 341:
TP3 15-inch nozzle, 10.2-cm iso-q and 20.3-cm flat-faced models

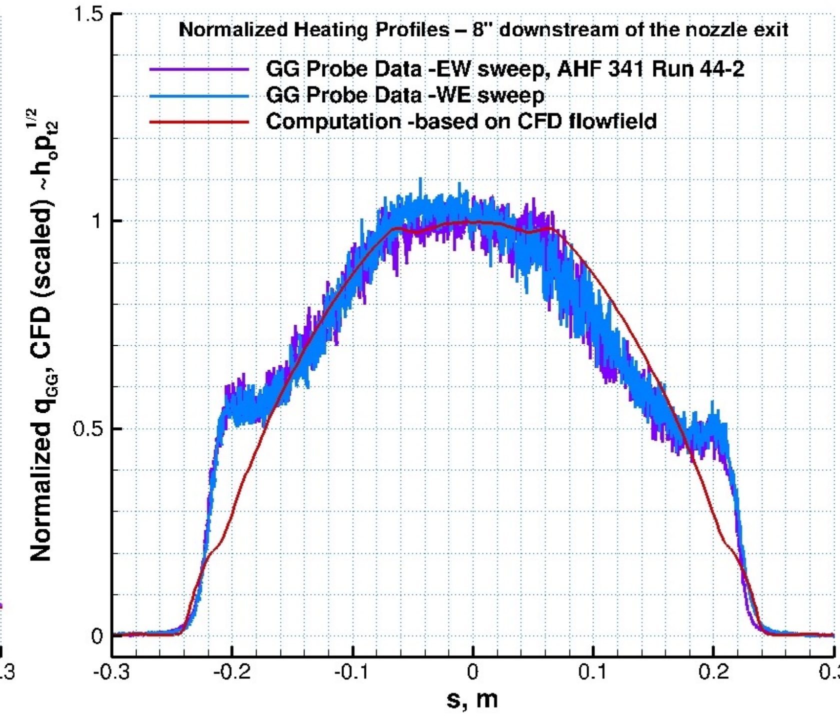
Existence of a flow disturbance originating from the nozzle throat in the TP3 15-inch nozzle was known prior to this test series (predicted from CFD simulations)

Probe Survey Data and Comparisons with Computations

TP3 15-inch nozzle flow: $\dot{m}$ = 500 g/s, h_{ob} = 12.9 MJ/kg, h_{ocl} = 28.8 MJ/kg, N_2/O_2 mixture, p_{box} = 2 torr

1.59-cm hemisphere probes used for TP3 flow surveys



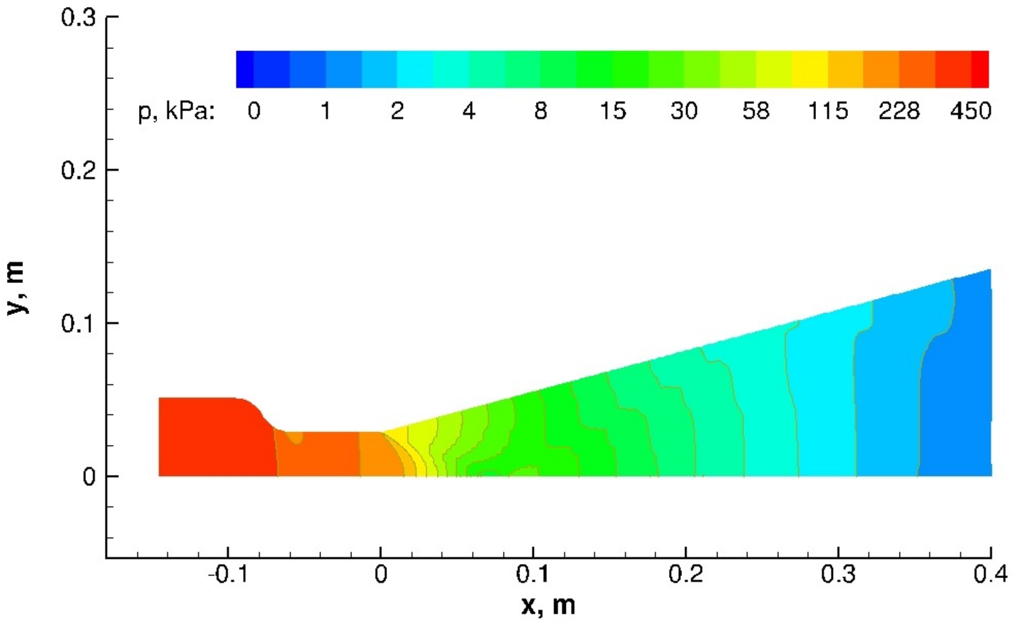


- Both pressure and heat flux data are repeatable between E-W and W-E sweep directions; slightly asymmetric
- The non-uniform feature (dip) is present in both pitot pressure data and computations
- CFD simulations reproduce the pitot pressure data well including the dip but they underpredict the heat flux distribution near the jet boundary
- Enthalpy distribution in the test flow is considered highly non-uniform (h_{ocl}/h_{ob} = 2.23)
- For this case, origin of the flow disturbance can be traced back to the nozzle throat

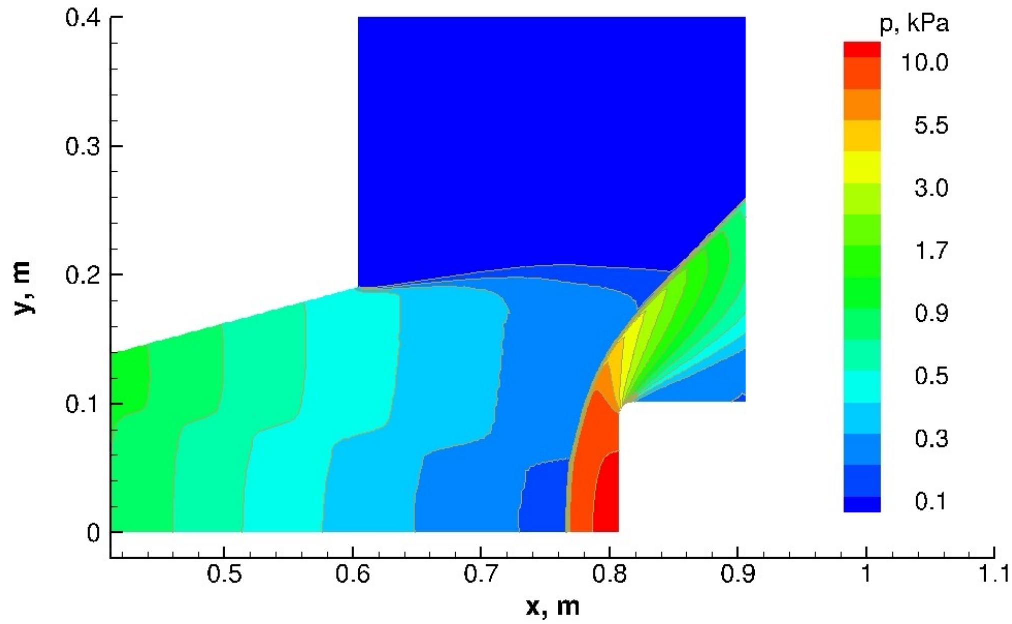
TP3 Nozzle Throat Design and Oblique Shock Wave Formation

TP3 15-inch nozzle flow: $\dot{m}$ = 500 g/s, h_{ob} = 12.9 MJ/kg, h_{ocl} = 28.8 MJ/kg, N_2/O_2 mixture, p_{box} = 2 torr

near the throat region



model flowfield



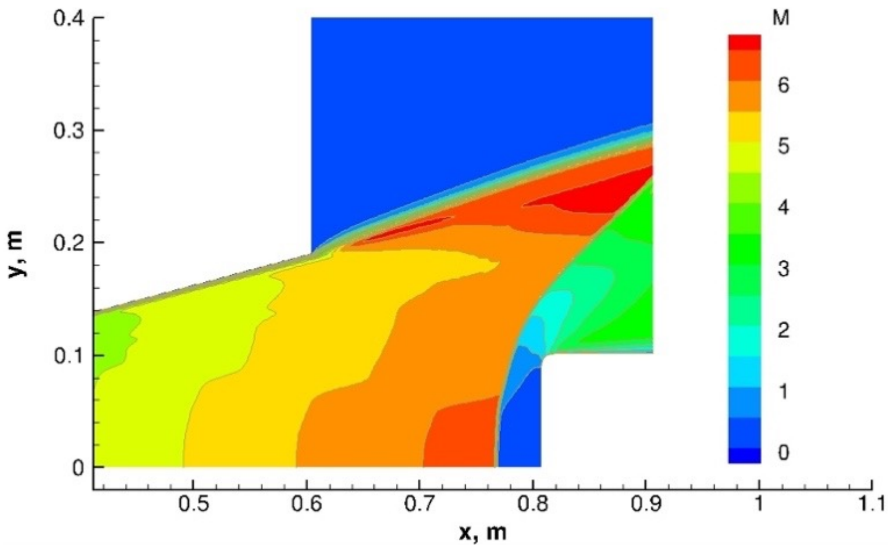
- For the TP3 elongated throat design, expansion waves are generated at the throat and diverging-nozzle cone intersection, and when these expansion waves reflect on the nozzle centerline as compression waves, and then eventual shock formation
- The reflected shock wave from the nozzle wall interacts with the model bow shock downstream; for some cases, this interaction adversely affects surface pressure and heating distributions on the model
- This issue is not unique to the TP3: formation of shock waves in conical supersonic nozzles has been known for a long time; a more gradual fairing of the throat section to the conical section would help (see AIAA Paper 2021-3149)

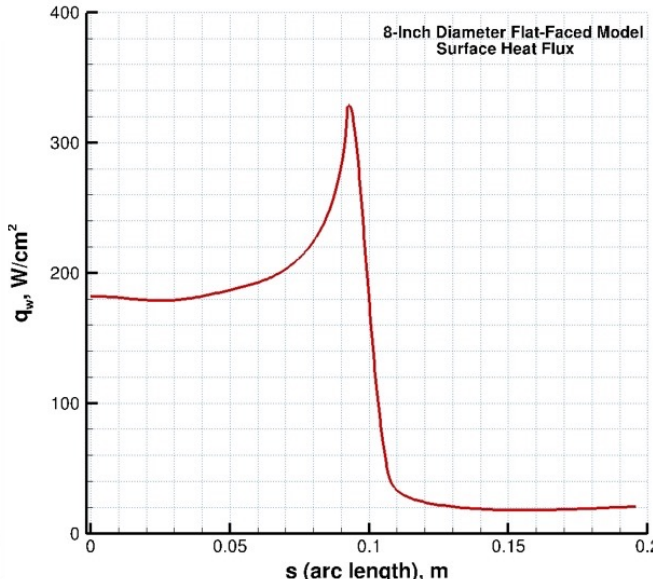
Effects of the Flow Disturbance on Model Surface Heat Flux

20.3-cm diameter flat-faced and 10.2-cm diameter iso-q models at x_{ml} = 20.3 cm

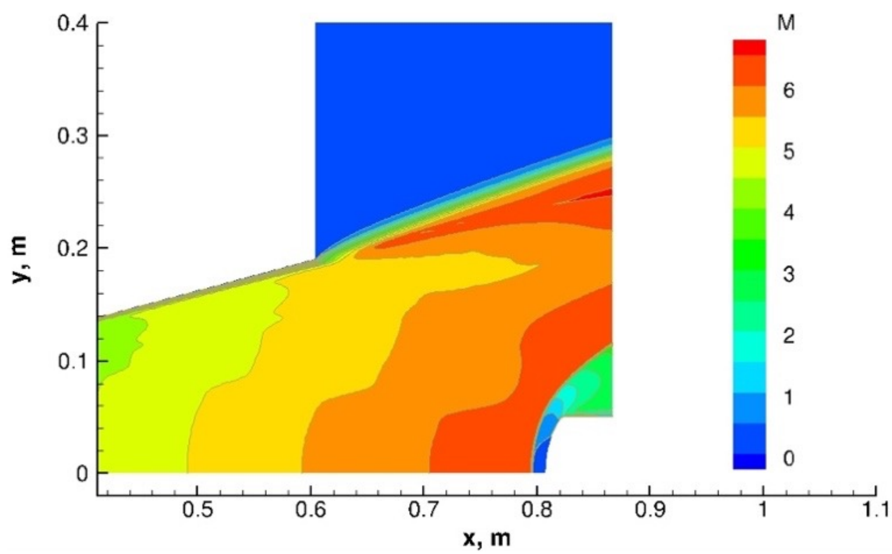
TP3 15-inch nozzle flow: $\dot{m}$ = 500 g/s, h_{ob} = 12.9 MJ/kg, h_{ocl} = 28.8 MJ/kg, N_2/O_2 mixture, p_{box} = 1 torr

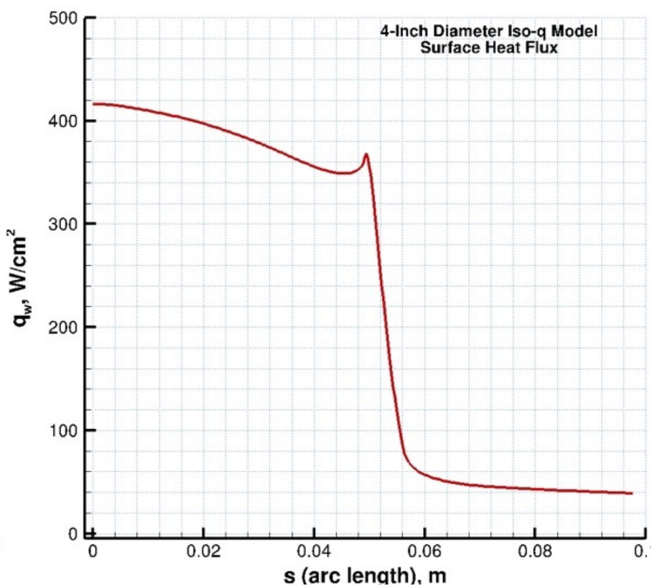
flat-faced model





iso-q model





- The fact that surface heating distributions for both models appear to be typical of these model geometries is somewhat misleading
- The ratio of stagnation-point heat fluxes, q_{isoq}/q_{ffc8}, should be about 1.7 with ideal uniform freestream conditions, but for this case the ratio is 2.27

Case 3, AHF 345:
AHF 12-inch nozzle, 10.2-cm iso-q and 15.2-cm flat-faced models

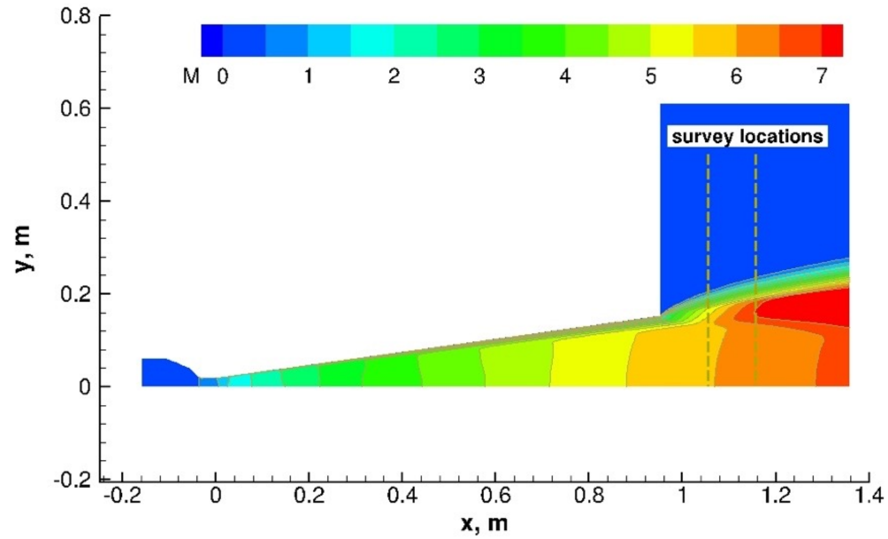
Existence of a flow disturbance in the AHF 12-inch nozzle was not known prior to this test series

- During calibration runs, several calorimeter anomalies were observed
  - Facility repeatability issues (calorimeter measurements were not repeatable and sensitive to small changes in the arc heater conditions)
  - Some of the measured calorimeter heat flux levels (both iso-q and flat-faced slugs) were much higher than expected for given arc current and mass flow rates
  - Ratios of the iso-q and flat-faced calorimeter heat fluxes were not consistent with analytical or CFD predictions
  - Measured heat fluxes did not follow an expected trend, a decreasing trend as the model moved further away from the nozzle exit because of the decrease in surface pressure

- Pitot pressure and Gardon gage probe sweeps were performed at two axial locations

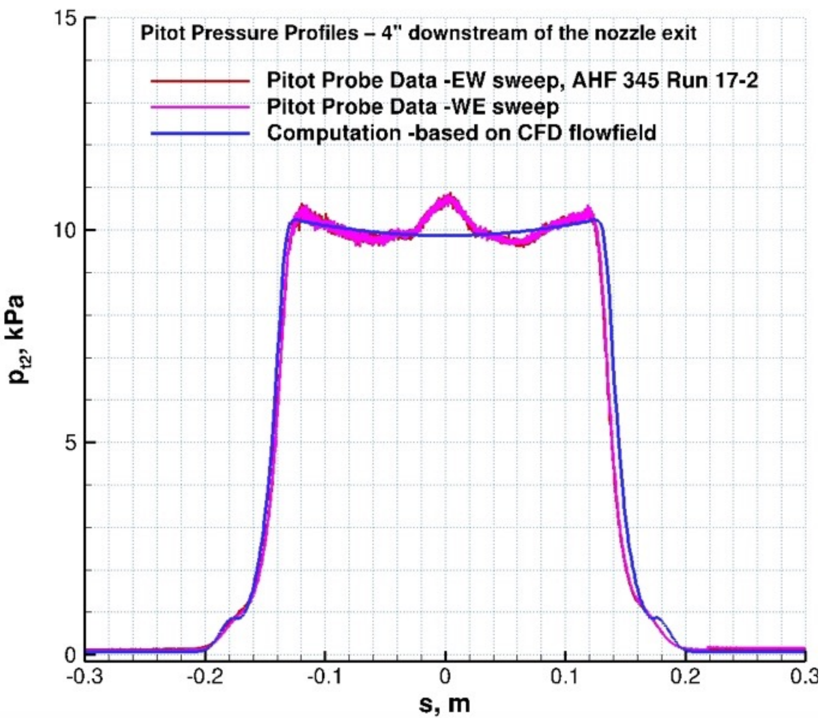
Probe Survey Data and Comparisons with Computations

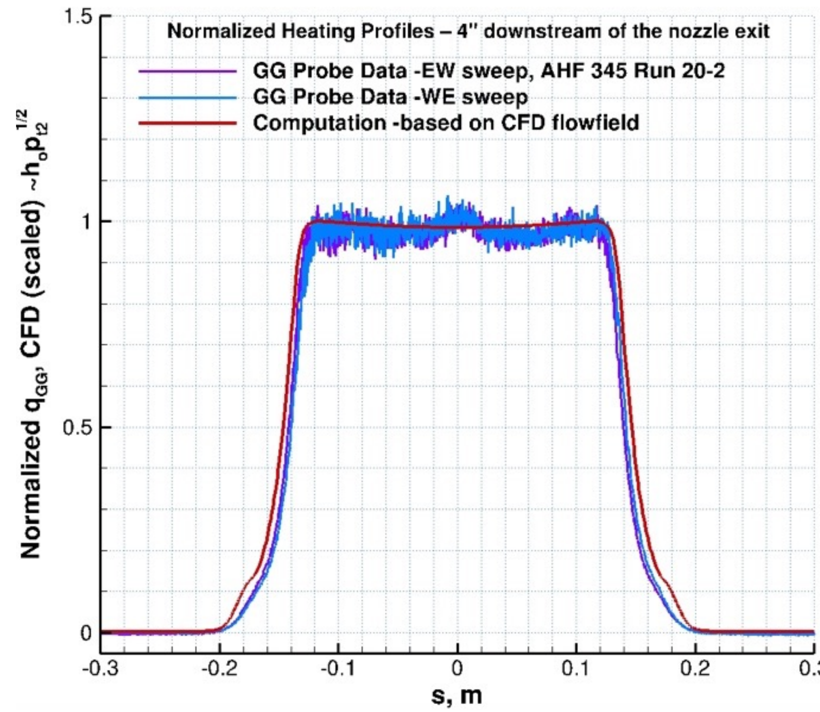
AHF 12-inch nozzle flow: $\dot{m}$ = 185 g/s, $h_{ob} = h_{ocl}$ = 16.9 MJ/kg, air with 8.1% Ar, p_{box} = 1 torr



probe sweeps were performed at x_{ml} = 10.2 cm and 20.3 cm (or 4 in and 8 in) locations from the nozzle exit

1.59-cm hemisphere probes used for AHF flow surveys

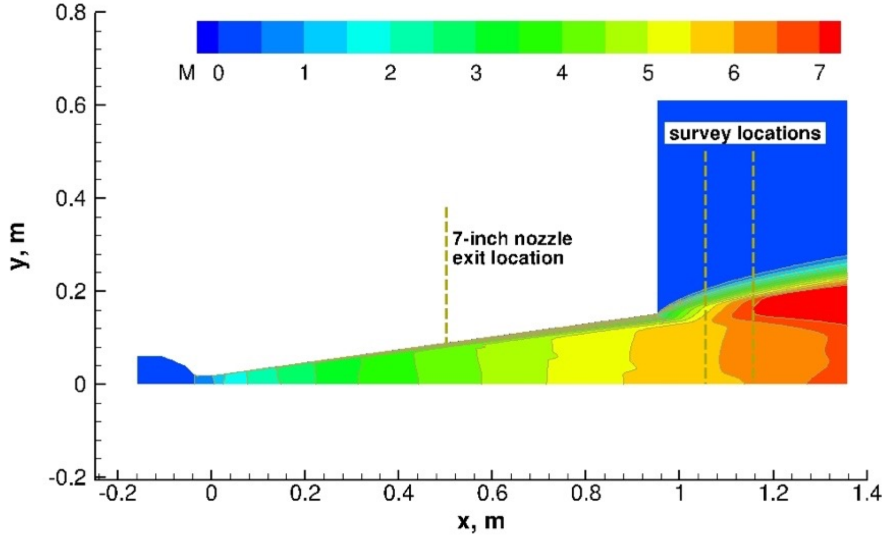




- Both pitot pressure and heat flux data show a feature near the nozzle centerline, showing higher pressure and heating levels (indication of a flow disturbance)
- *The probe sweep data at x_{ml} = 20.3 cm location and comparisons with CFD are given in the paper*

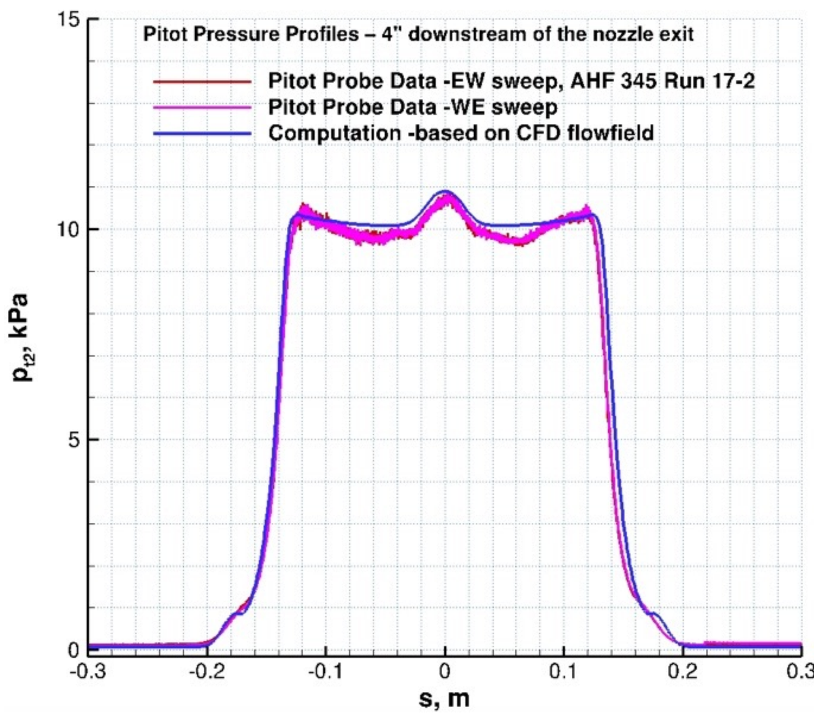
Probe Survey Data and Comparisons with Computations

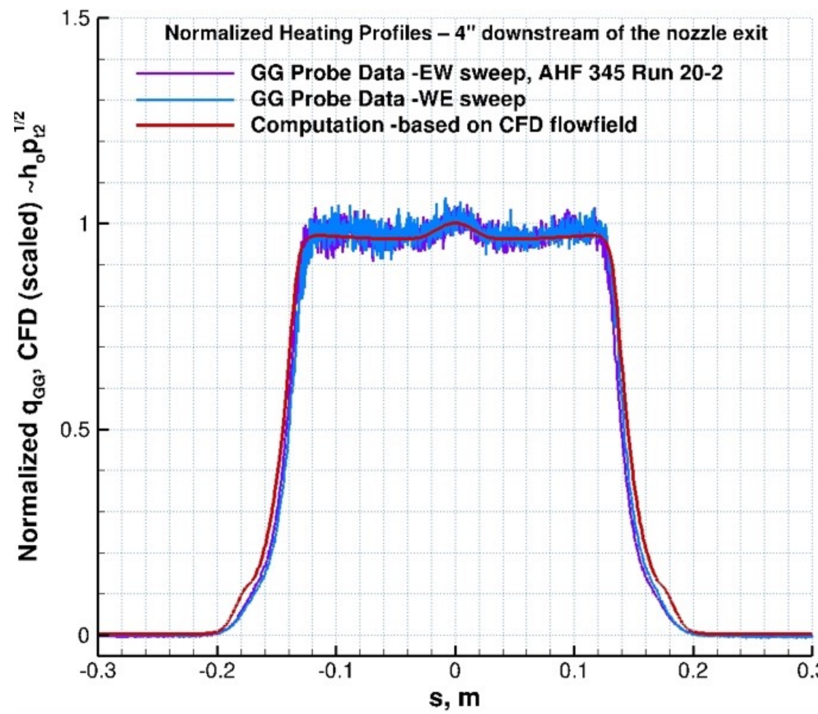
AHF 12-inch nozzle flow: $\dot{m}$ = 185 g/s, $h_{ob} = h_{ocl}$ = 16.9 MJ/kg, air with 8.1% Ar, p_{box} = 1 torr



probe sweeps were performed at x_{ml} = 10.2 cm and 20.3 cm (or 4 in and 8 in) locations from the nozzle exit

1.59-cm hemisphere probes used for AHF flow surveys





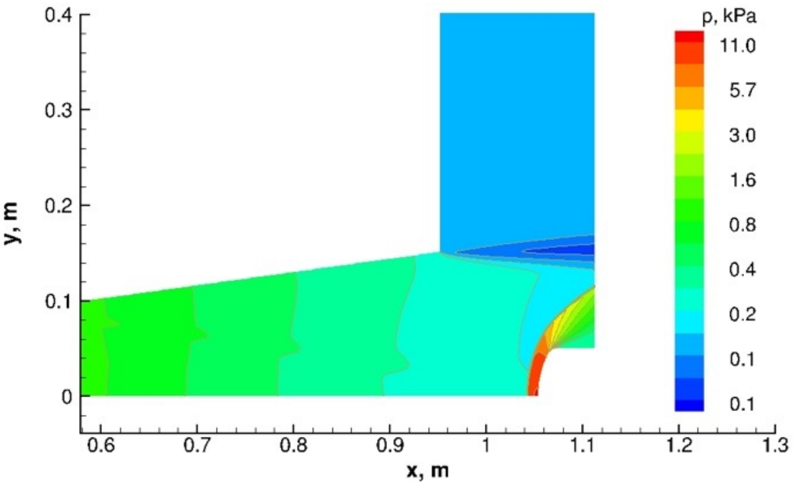
- To reproduce the survey data with CFD simulations, a flow disturbance in the nozzle (placed near the 7-inch nozzle exit, a 0.3 mm protuberance) is introduced
- The ultimate objective is to investigate effects of this disturbance on the model surface quantities, while reproducing the measured sweep data

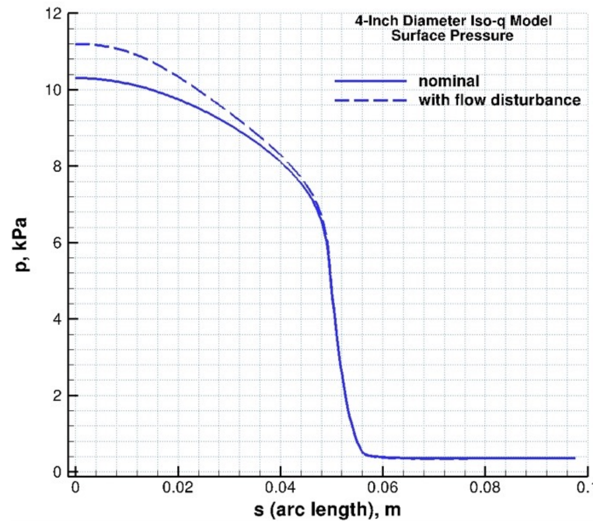
Effects of the Flow Disturbance on Model Surface Quantities

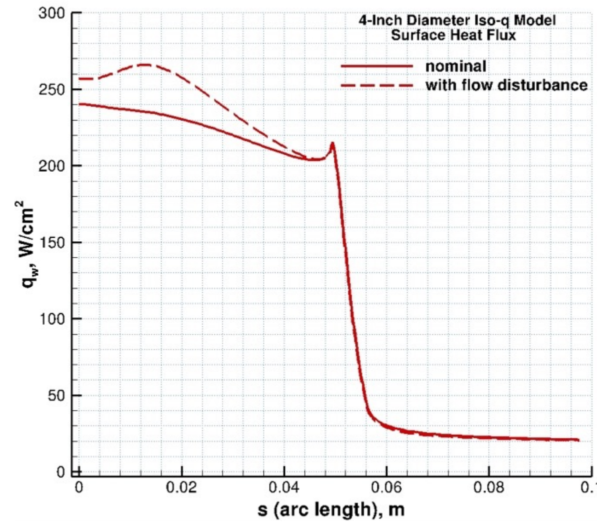
10.2-cm diameter iso-q model at two locations

AHF 12-inch nozzle flow: $\dot{m}$ = 185 g/s, $h_{ob} = h_{ocl}$ = 16.9 MJ/kg, air with 8.1% Ar, p_{box} = 1 torr

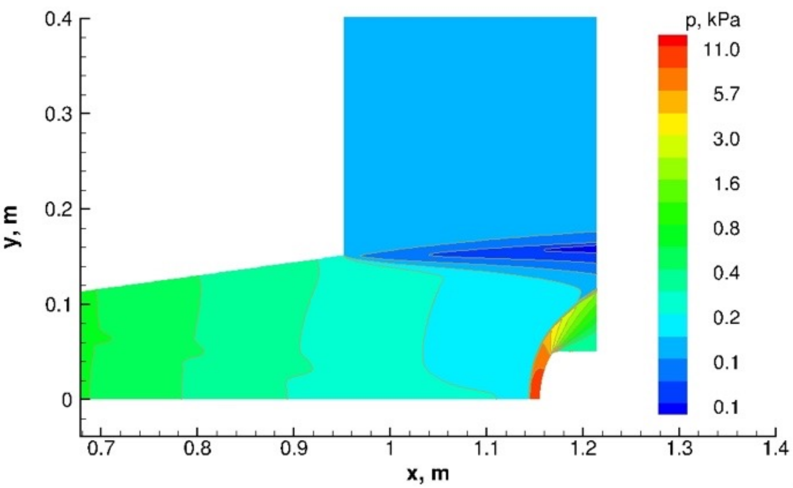
x_{ml} = 10.2 cm

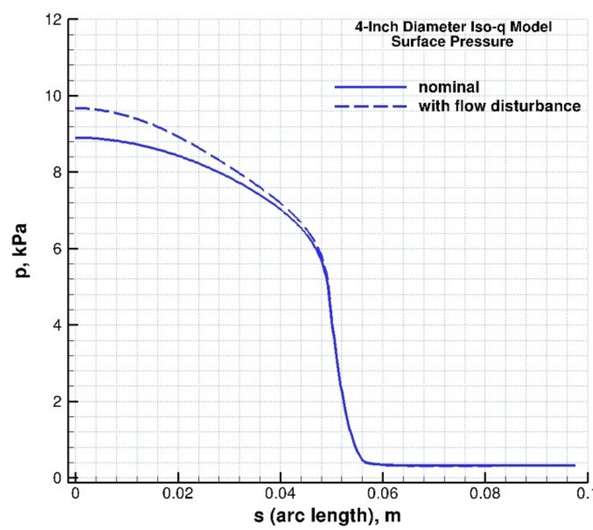


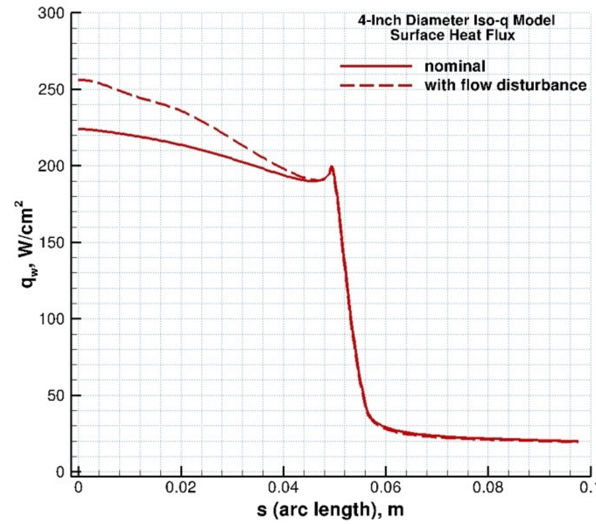




x_{ml} = 20.3 cm







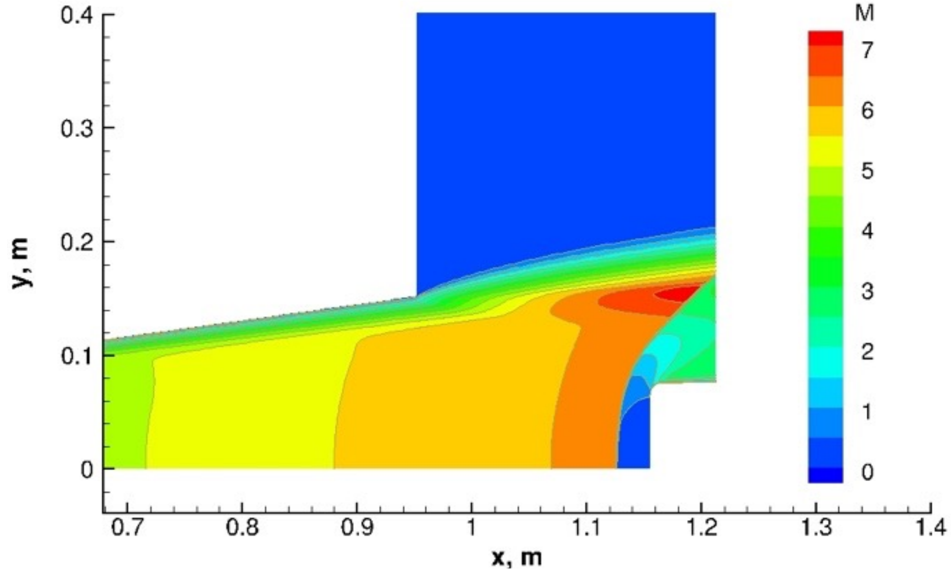
- The flow disturbance for each case interacts with the model bow shock wave at a different location, so effects of the interaction are naturally expected to be different
- When the flow disturbance is present, a decreasing trend in heat flux with the model location from the nozzle exit (because of the drop in surface pressure) is no longer predicted

Effects of the Flow Disturbance on Model Surface Quantities

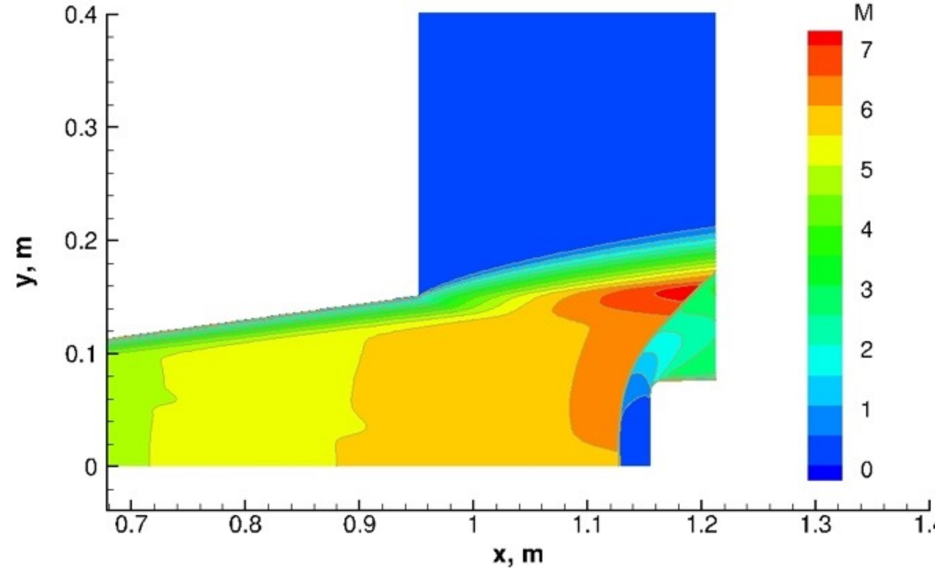
15.2-cm diameter flat-faced model at x_{ml} = 20.3 cm location

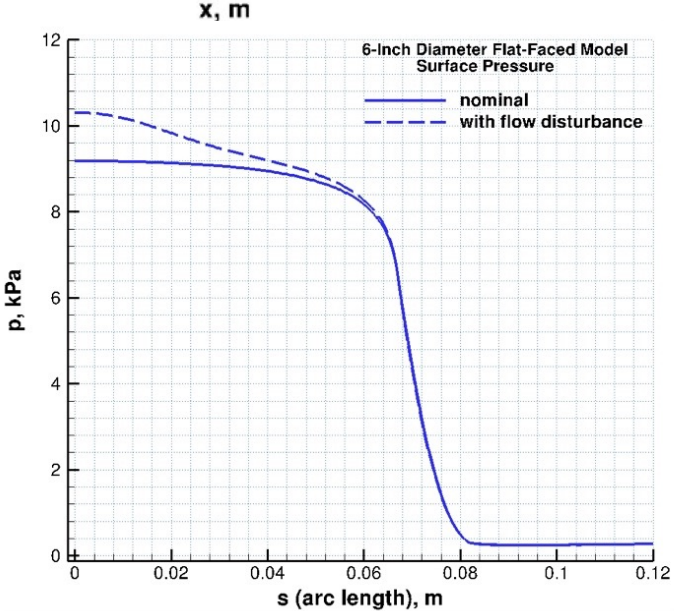
AHF 12-inch nozzle flow: $\dot{m}$ = 185 g/s, $h_{ob} = h_{ocl}$ = 16.9 MJ/kg, air with 8.1% Ar, p_{box} = 1 torr

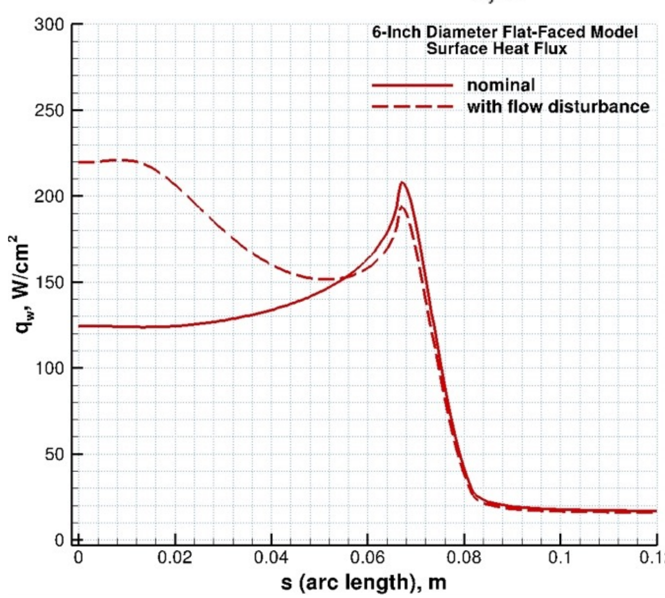
nominal



with the flow disturbance







- For this case, the flow disturbance interacts with the model bow shock wave at a location upstream of the sonic line in the shock layer
- Effects on the surface heating distribution is more dramatic

Summary and Concluding Remarks

- Computational simulations and analysis of flow characterization tests conducted in the NASA Ames arc-jet facilities are reported
  - The flow disturbances and their characterization are presented through three case studies: the 60-MW IHF 30-inch nozzle, the 10-MW TP3 15-inch nozzle, and the 20-MW AHF 12-inch nozzle
  - The test data included heat flux and pressure measurements with stagnation calorimeters, and surveys of arc-jet test flow with pitot pressure and heat flux probes
  - For each case, the survey probes are much smaller in size than the nozzle exit diameter, which is necessary to obtain spatial distributions of the pitot pressure and heat flux in the jet

- Comparisons of CFD results with the experimental measurements in three arc-jet nozzles with different arc heaters are presented
  - Computations that reproduce the probe sweep data approximately are used to explain experimental observations and calorimeter anomalies
  - Pitot pressure sweeps are especially important to detect any flow disturbance in the test flow
  - If there is a flow disturbance in the test flow and it is not detected, interpretation of both calorimeter and test data becomes difficult or inaccurate

- Probe sweeps are not routinely performed in arc-jet testing due to additional cost. These three case studies strongly suggest that they should be part of all arc-jet tests
  - Provide an assessment of the flow non-uniformity and are used to set the inlet boundary conditions in CFD simulations (total enthalpy distribution)
  - Detect any flow disturbance in the test flow

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