

Flow Characterization Studies of the 10-MW TP3 Arc-Jet Facility: Probe Sweeps

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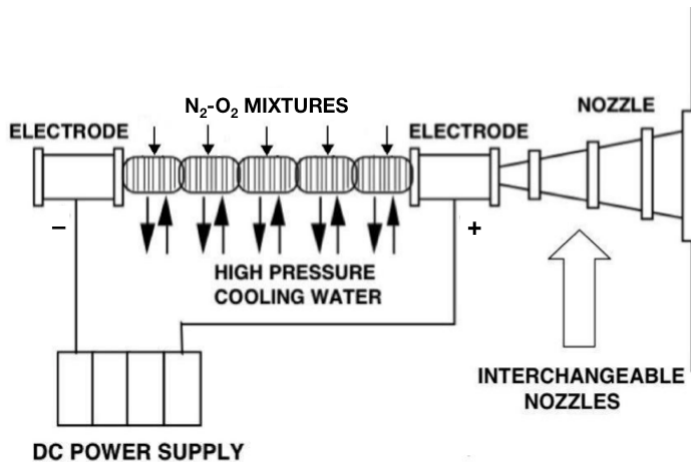
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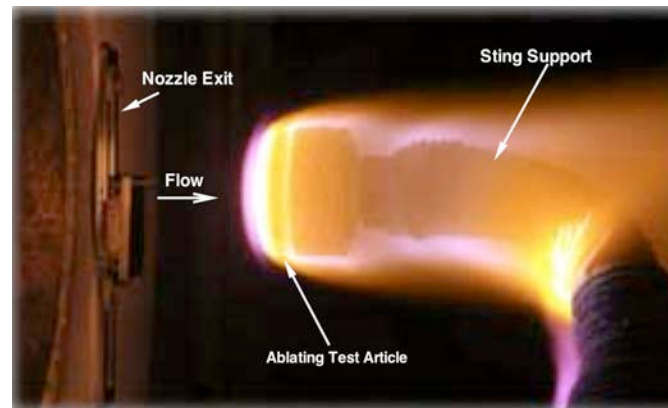
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Introduction: Arc-Jet Testing, 10-MW TP3 Facility



TP3 arc-heater/nozzle sketch



Stagnation coupon test



Wedge test

- Arc-jets provide the primary means to test the performance of various types of thermal protection systems (TPS) in an aerothermodynamic heating environment
- The Aerodynamic Heating Facility (AHF) at NASA Ames Research Center was recently upgraded to run an arc-heater, named TP3
 - 10-MW constricted arc-heater
 - Formerly known as TP2 when operated at NASA Johnson Space Center
 - Currently operates with a test gas mixture of nitrogen and oxygen
 - Testing capability with a N_2 - CO_2 mixture will be added in the near future (Fall 2016)
 - Able to simulate various heating profiles in time representative of hypersonic flight

Objectives and Scope

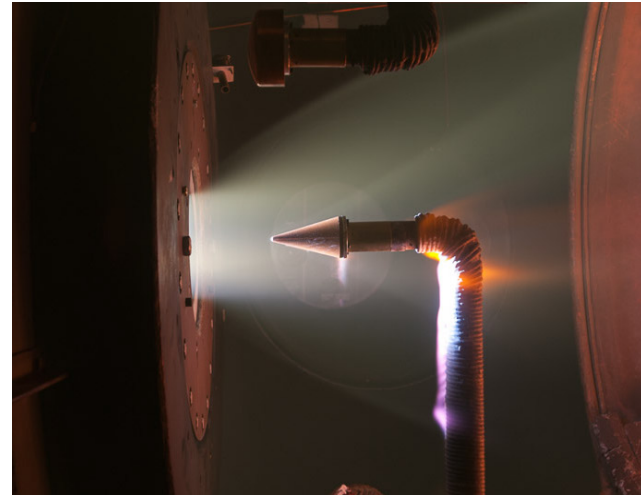
- Present arc-jet flow characterization data obtained in three test series in the TP3 7.5-inch conical nozzle
 - A flight heating profile was simulated in the arc-jet stream using 10.16-cm diameter flat-faced models (test articles and calorimeters), AHF 307
 - The heating profile was achieved through 7 steps (6 arc-heater conditions, with step 1 condition repeated as step 6 condition), AHF 307
 - Six conditions cover a wide range of facility parameters
 - For each step of the heating profile, surveys of the arc-jet test flow with the pitot and heat flux probes were performed for arc-jet flow characterization (AHF 307, AHF 318, AHF 320)
 - 9.1-mm diameter sphere-cone probes with null-point heat flux gages (AHF 307)
 - 15.9-mm diameter hemisphere probes with Gardon gages (AHF 318, AHF 320)
- Computational fluid dynamics simulations are performed to provide estimates of the arc-jet test environment parameters
 - Centerline total enthalpy
 - Comparisons with the pitot pressure and heat flux survey data

Pitot Pressure and Heat Flux Survey Probes

TP3 7.5-Inch Nozzle Flow



9.1-mm sphere-cone probe, null-point gage



AHF 307 test

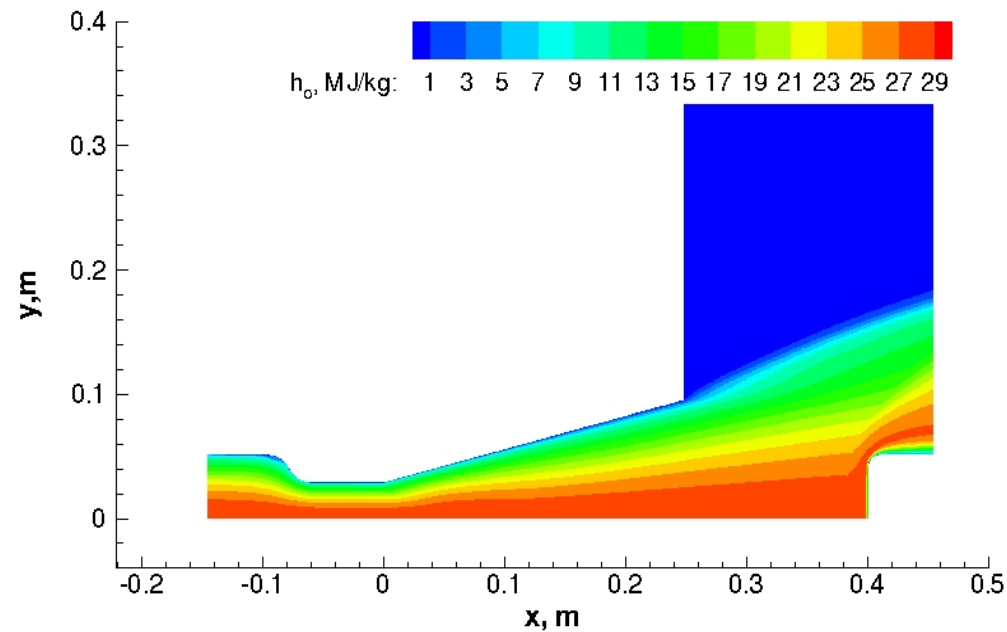
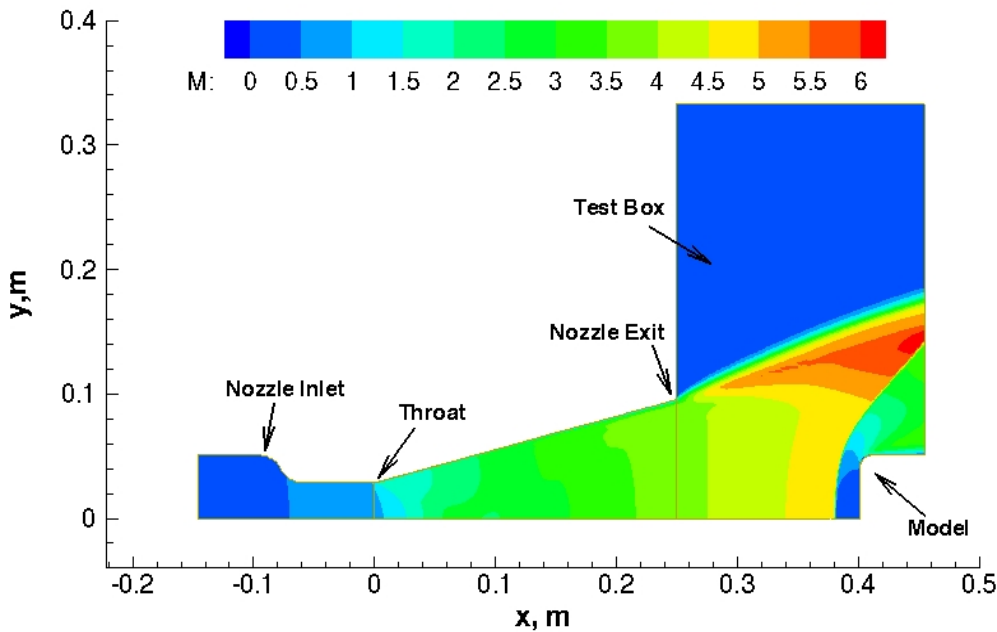


15.9-mm hemisphere probe, Gardon gage



AHF 320 test

Computational Approach



- CFD analysis includes simulation of nonequilibrium flow in the arc-jet facility (the nozzle, test box, over the model)
- Prescribe flow profiles with chemical equilibrium composition at the nozzle entrance; Centerline total enthalpy is set to match the measured slug calorimeter data
- 2-D axisymmetric 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

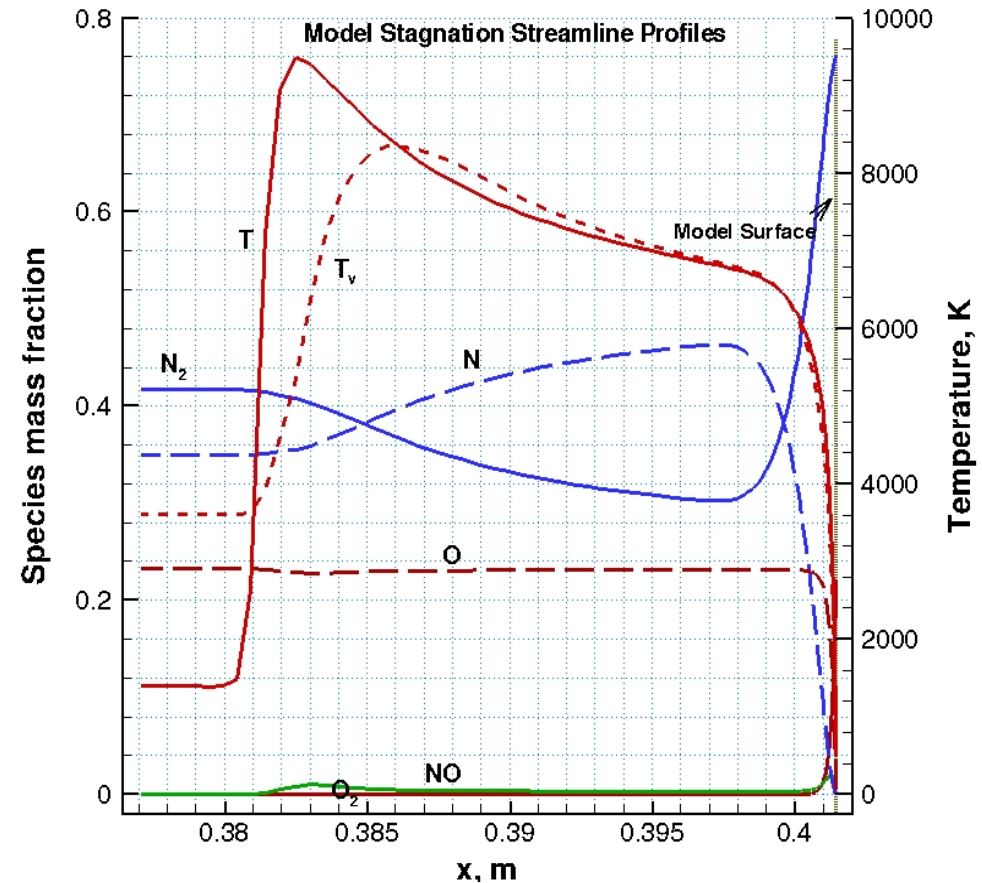
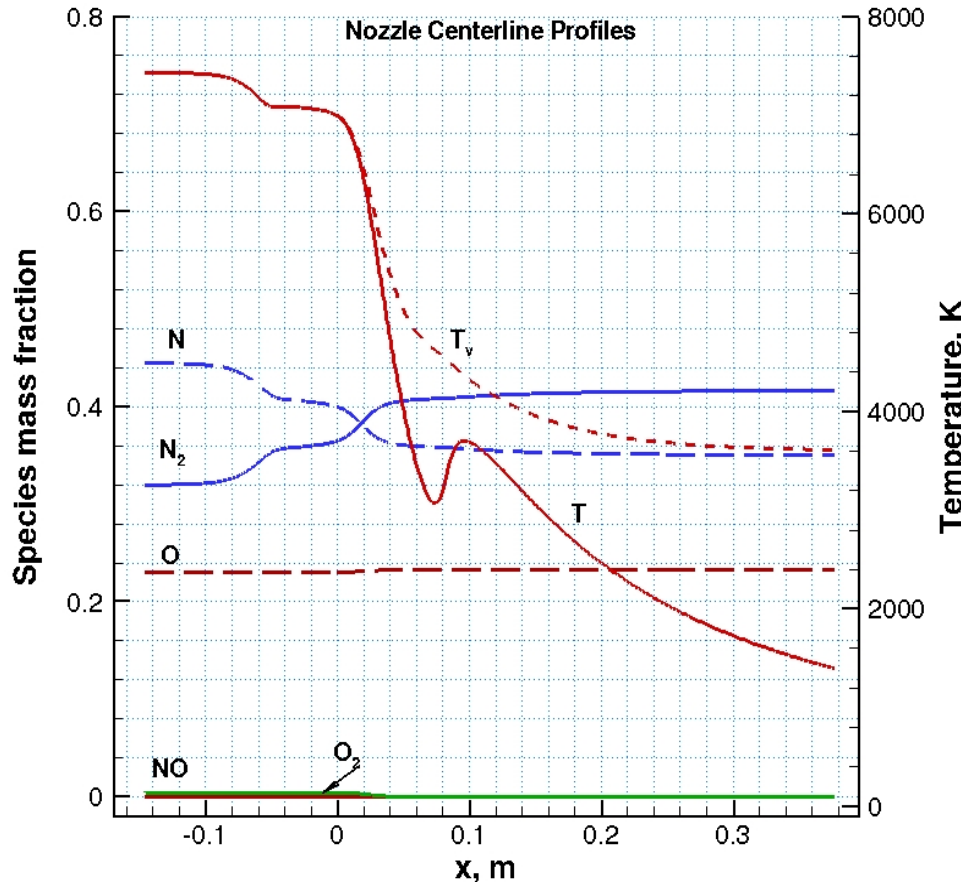
Presentation of Results

- One stagnation model simulation example
 - Estimate of centerline total enthalpy based on facility and calorimeter data
- Comparisons of computations with the pitot pressure and heat flux survey data
 - TP3-AHF 307, AHF 318 and AHF 320 survey data
 - Two different set of probes
 - The heating profile conditions: step 1 thru step 7 (six conditions covering a wide range of facility parameters)
 - Repeatability of the survey data are given in the paper

Example: Computed Nozzle Centerline and Stagnation Streamline Profiles

Flat-Faced Model ($D = 10.16 \text{ cm}$, $r_c/D = 3/32$), CWFC

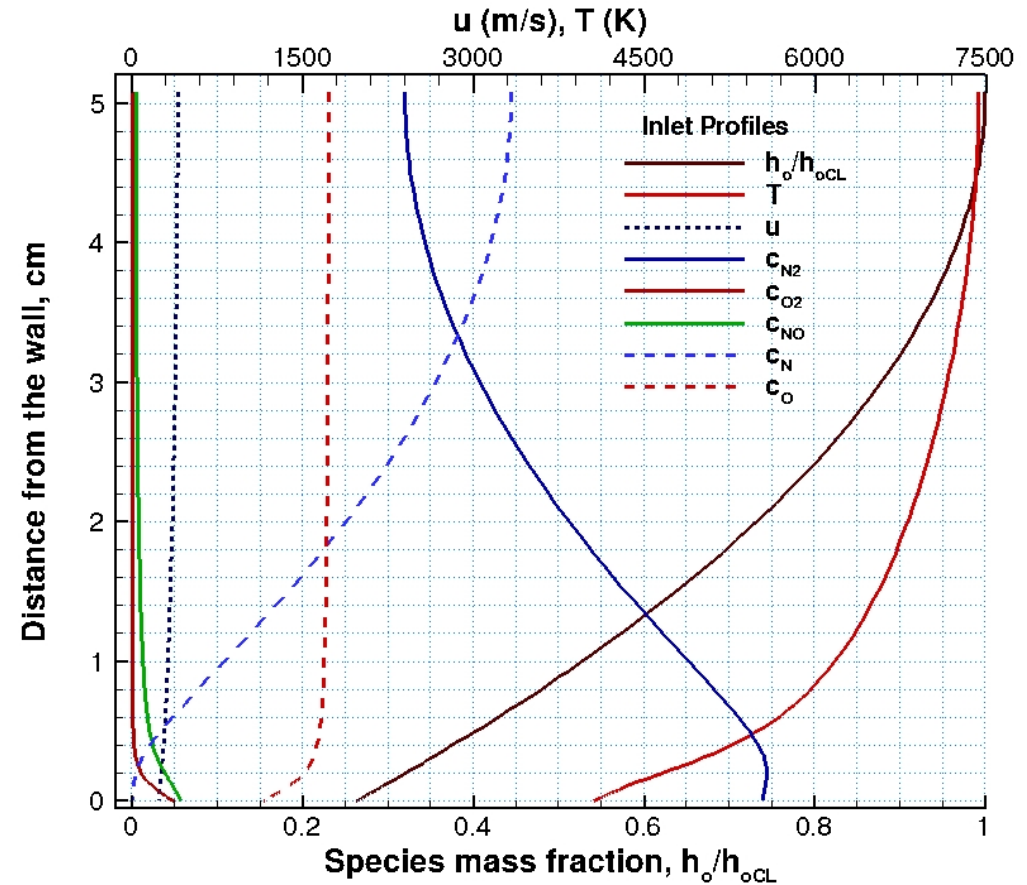
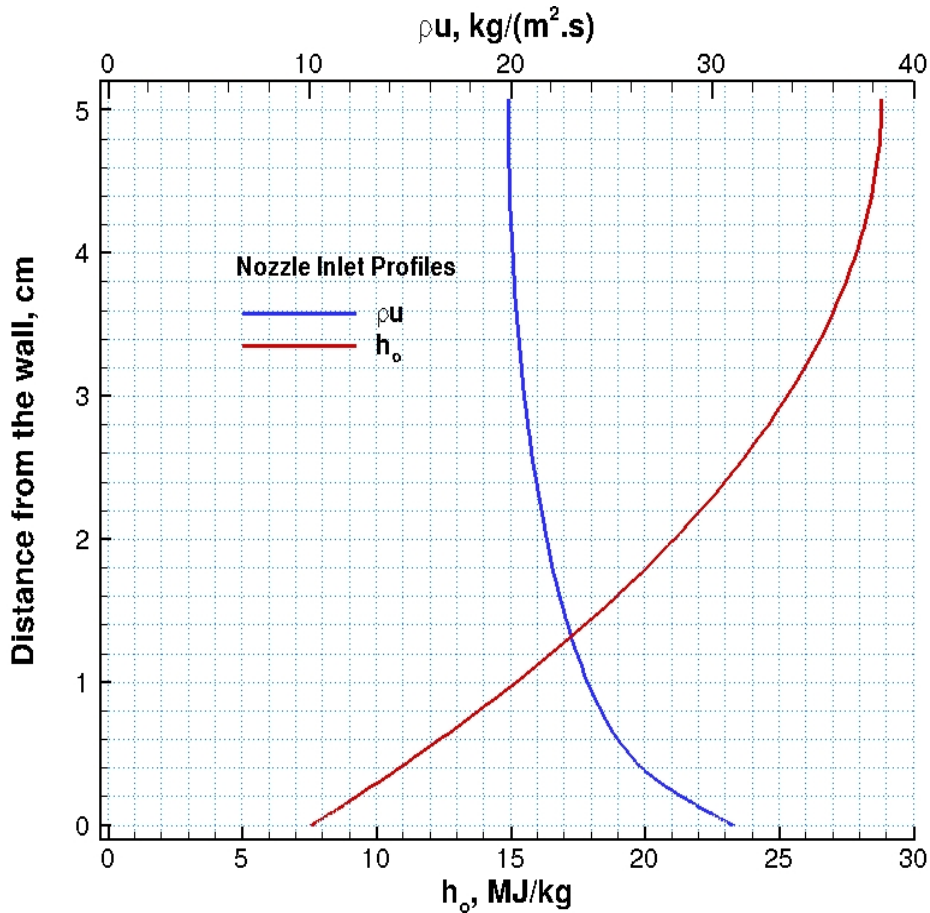
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 190 \text{ g/s}$, $h_{ob} = 17.6 \text{ MJ/kg}$, $h_{ocI} = 28.8 \text{ MJ/kg}$, nonuniform profiles



- Flow is in chemical and vibrational nonequilibrium
- Oxygen remains fully dissociated except in the boundary layer (and shear layer)
- Nitrogen is partially dissociated

Example Case: Prescribed Nozzle Inlet Profiles

TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 190 \text{ g/s}$, $h_{ob} = 17.6 \text{ MJ/kg}$, $h_{ocl} = 28.8 \text{ MJ/kg}$, nonuniform profiles

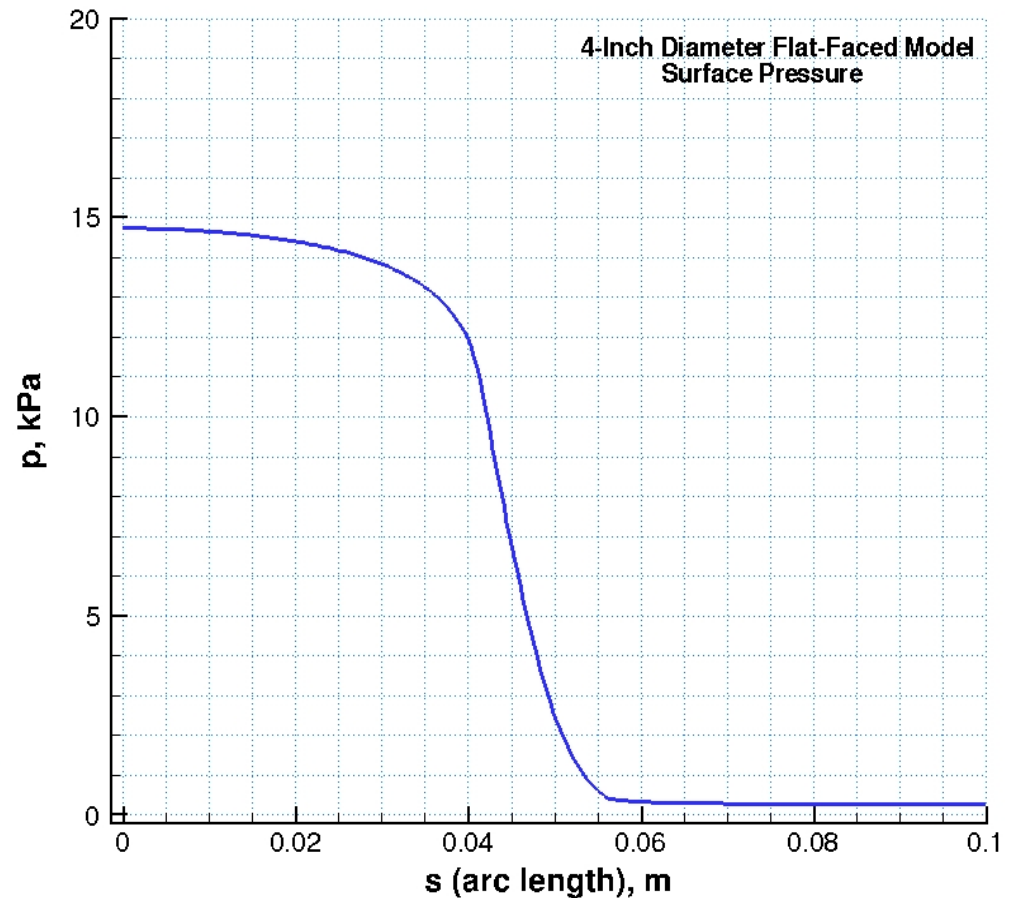
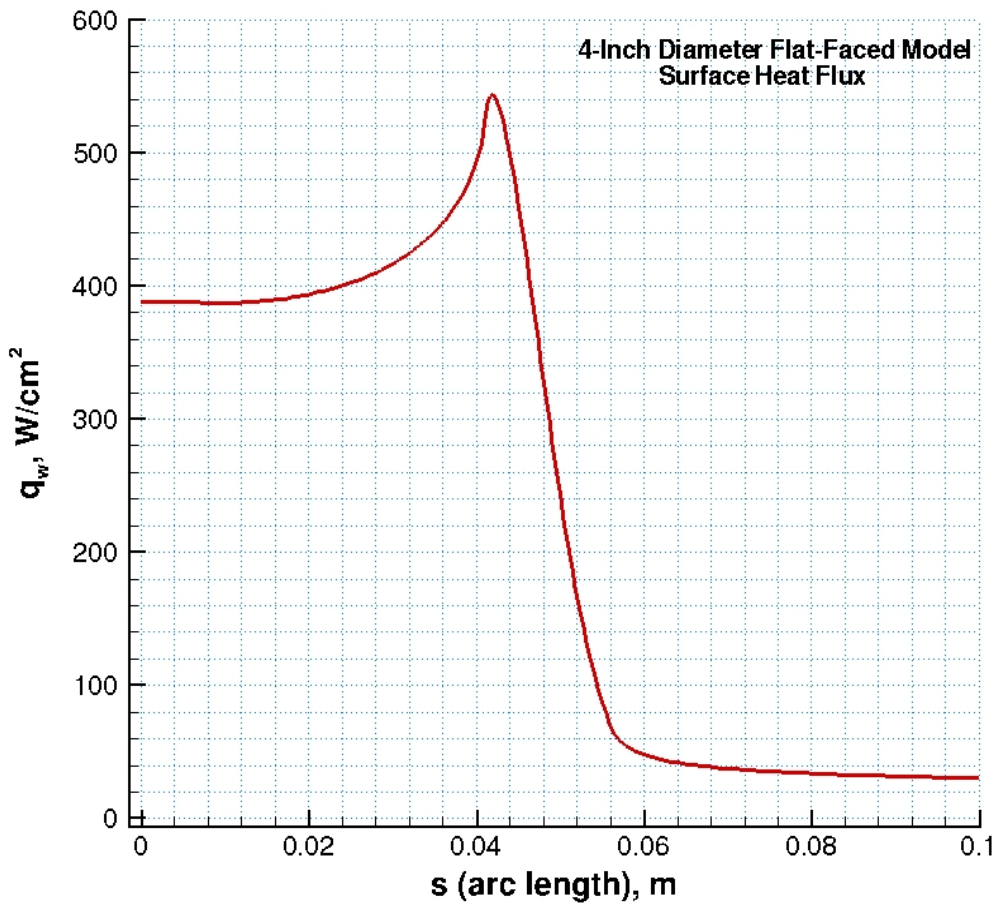


- Uniform pressure and parabolic enthalpy profiles are specified at the nozzle inlet
- Species concentrations and other flow properties are calculated from thermochemical equilibrium relations

Example: Computed Model Surface Heat Flux and Pressure

Flat-Faced Model ($D = 10.16 \text{ cm}$, $r_c/D = 3/32$), CWFC

TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 190 \text{ g/s}$, $h_{ob} = 17.6 \text{ MJ/kg}$, $h_{ocl} = 28.8 \text{ MJ/kg}$, nonuniform profiles



- Averaged calorimeter data from AHF 307 runs 11-2 and 12-2: 388 W/cm^2 and 14.75 kPa
- Centerline total enthalpy is determined to reproduce the measured slug calorimeter data
- At the nozzle inlet: parabolic enthalpy profile, and the mass flux profile is based on pressure and enthalpy

Comparisons of Computations with Pitot Pressure and Heat Flux Survey Data

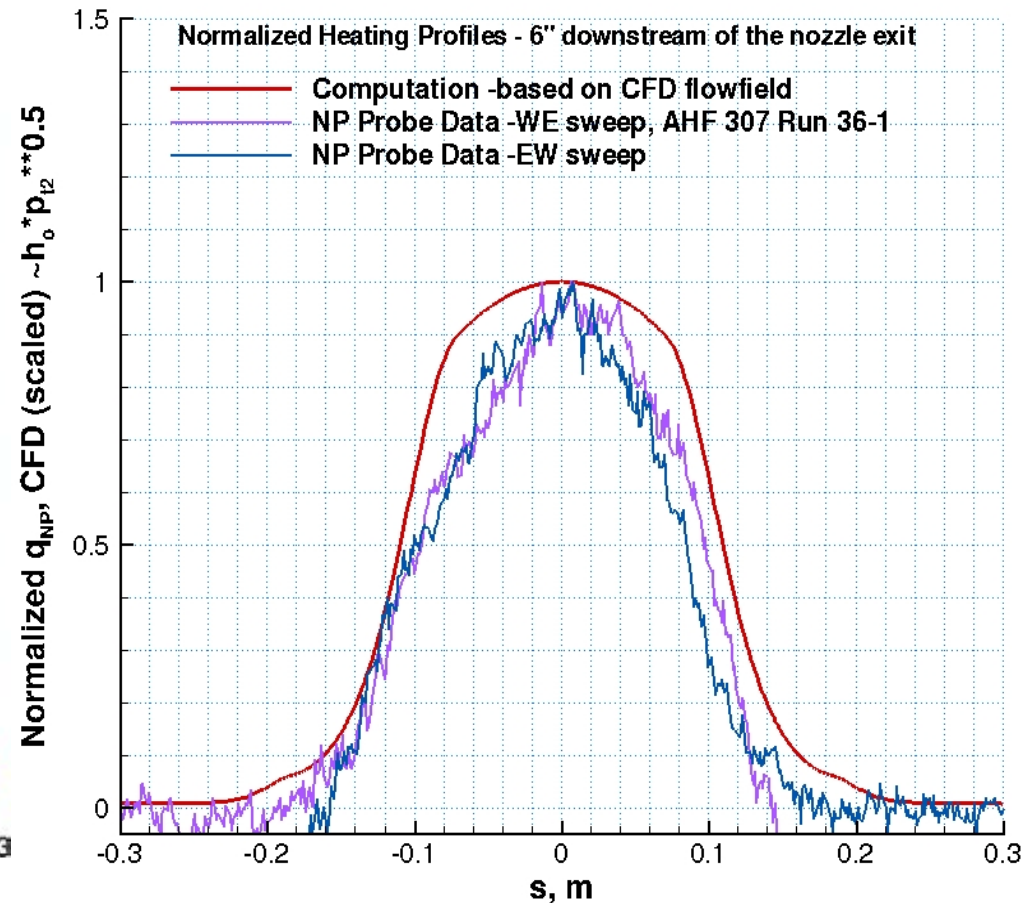
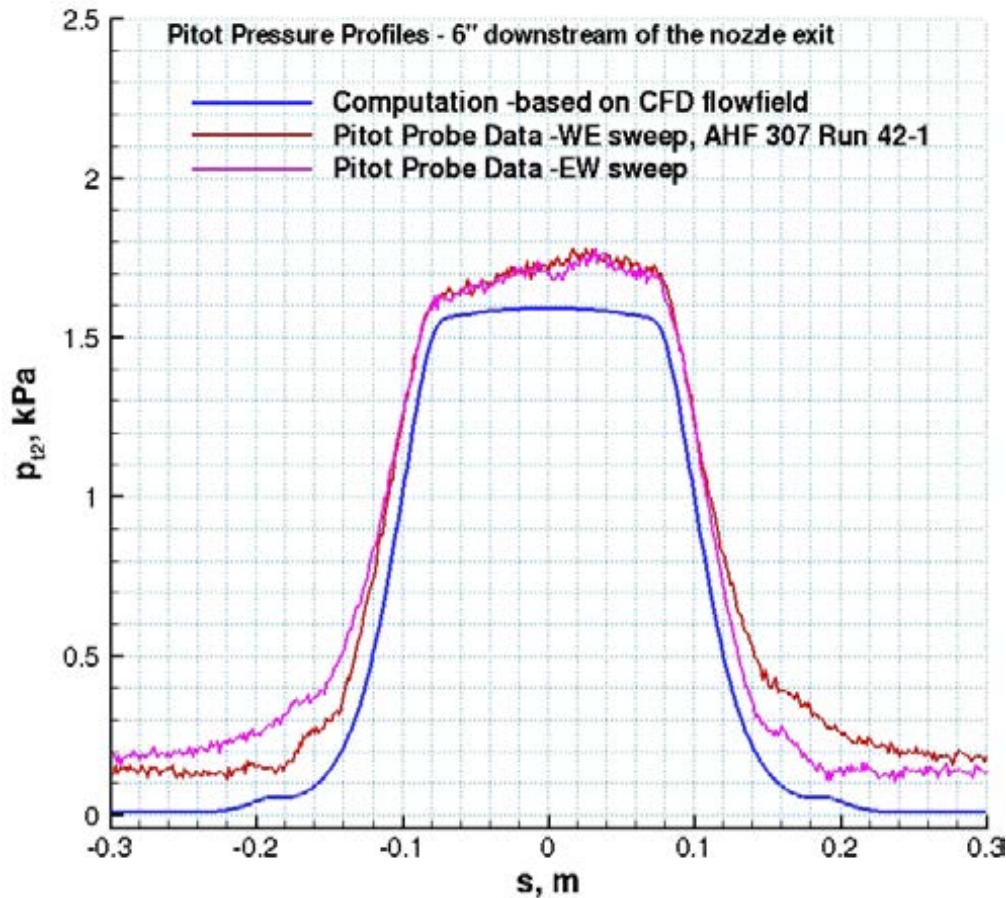
Test Series: AHF 307	I (A)	V (V)	\dot{m} (g/s)	p_{midc} (kPa)	q_s (W/cm ²)	p_s (kPa)	h_{ob} (MJ/kg) CFD	h_{ocl} (MJ/kg) CFD	q_{HWFC} (W/cm ²) CFD	Cond No.
Runs 14-1–35-1	262	1264	25	25.4	58.6	1.74	11.8	13.8	51.5	1
Runs 11-2, 12-2	1113	3401	190	220	388	14.8	17.6	28.8	349	2
Runs 8-1, 9-1	1762	5187	501	558	730	36.0	16.4	34.1	497	3
Runs 6-1, 7-1	1214	3946	310	311	335	21.5	13.6	21.9	292	4
Runs 3-2, 4-1	419	1683	40	43	118	3.3	15.4	19.6	104	5
Runs 3-3, 4-2	716	3681	310	251	114	17.0	7.5	9.4	89	6
AHF 320										
Runs 5-3, 6-3	1756	4861	500	516	593	33.5	13.9	29.9	N/A	3
Runs 3-4, 4-4	1204	3637	310	293	266	19.3	10.3	18.8	N/A	4

Conditions 4 and 6 include cold-gas injection at the plenum, 20% and 28% of the total mass flow rate, respectively.

- Pitot pressure and heat flux surveys were performed at separate arc-jet runs at the same nominal arc-heater conditions (current and mass flow rate)
- Six conditions cover a wide range of facility parameters: arc current varies from 262 A to 1762 A, and total mass flow rate from 24 g/s to 501 g/s
- Two conditions with cold-gas N₂ injection at the arc-heater plenum

Comparisons of Computations with Survey Data (step 1, AHF 307)

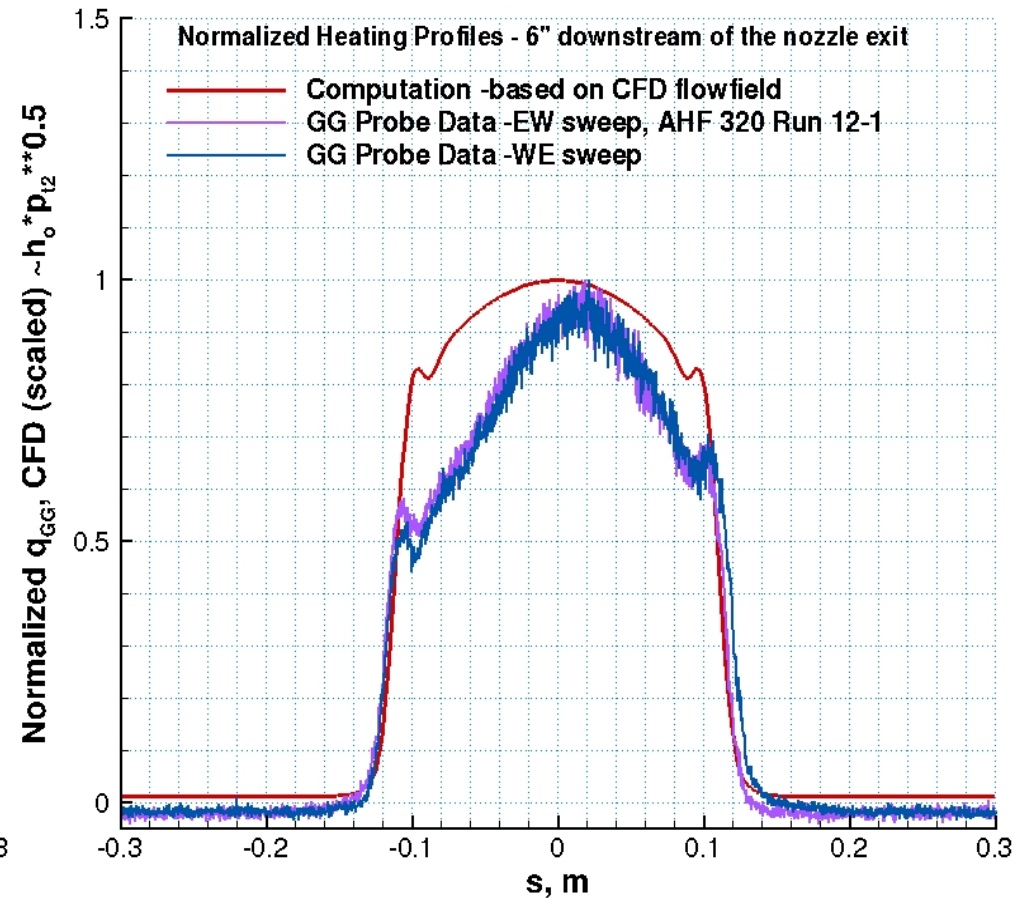
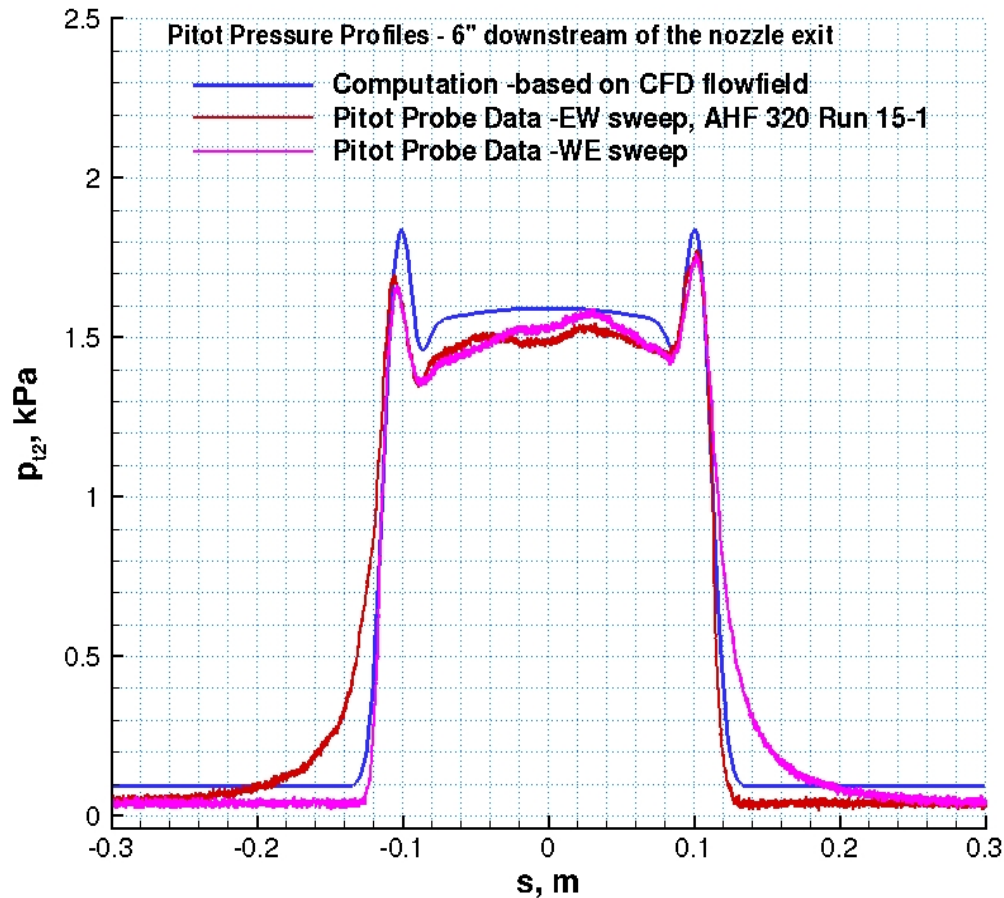
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 25$ g/s, $h_{ob} = 11.8$ MJ/kg, $h_{ocl} = 13.8$ MJ/kg, $p_{box} = 0.05$ torr



- This case represents a facility condition at an **extremely low mass flow rate, moderate enthalpy and without plenum gas injection**
- The pitot pressure data show an incomplete recovery to the test box pressure and a larger core than computations (probes were moving too fast to equilibrate at these lower pressures); and it is not symmetric
- Heat flux surveys show a more peaked distribution than computations

Comparisons of Computations with Survey Data (step 1, AHF 320)

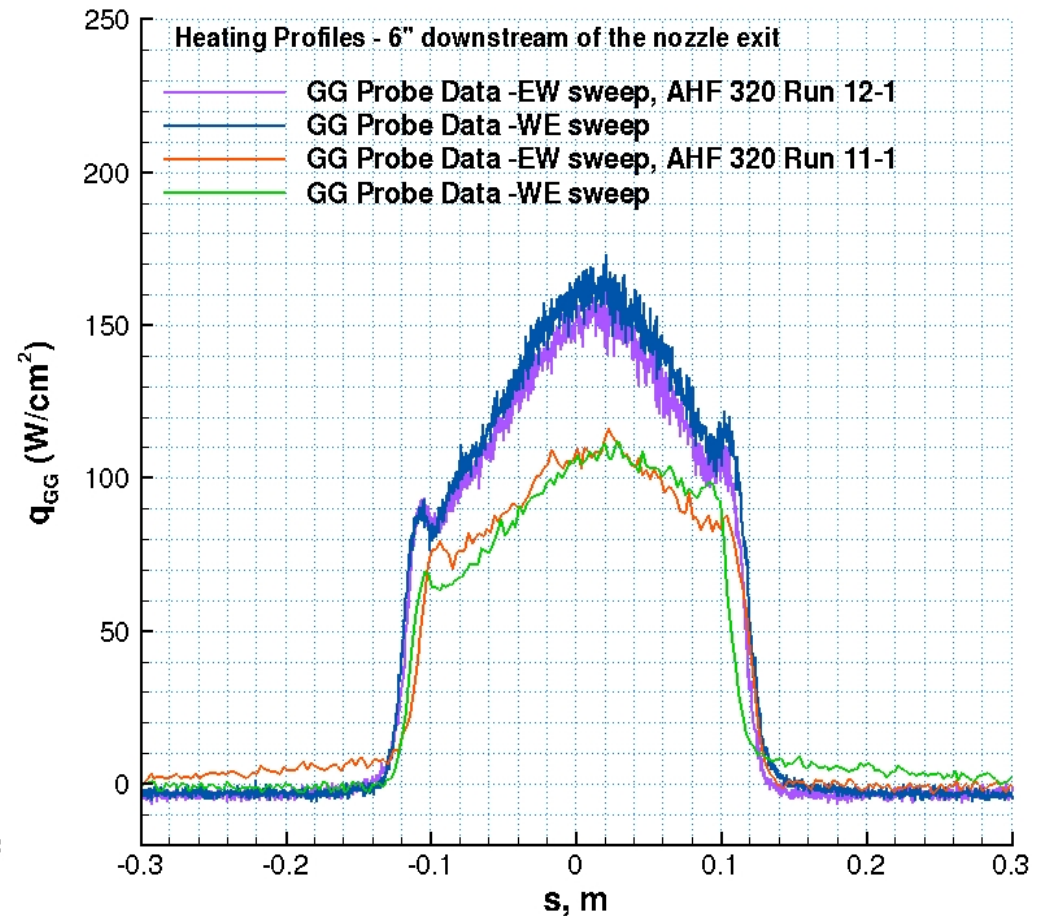
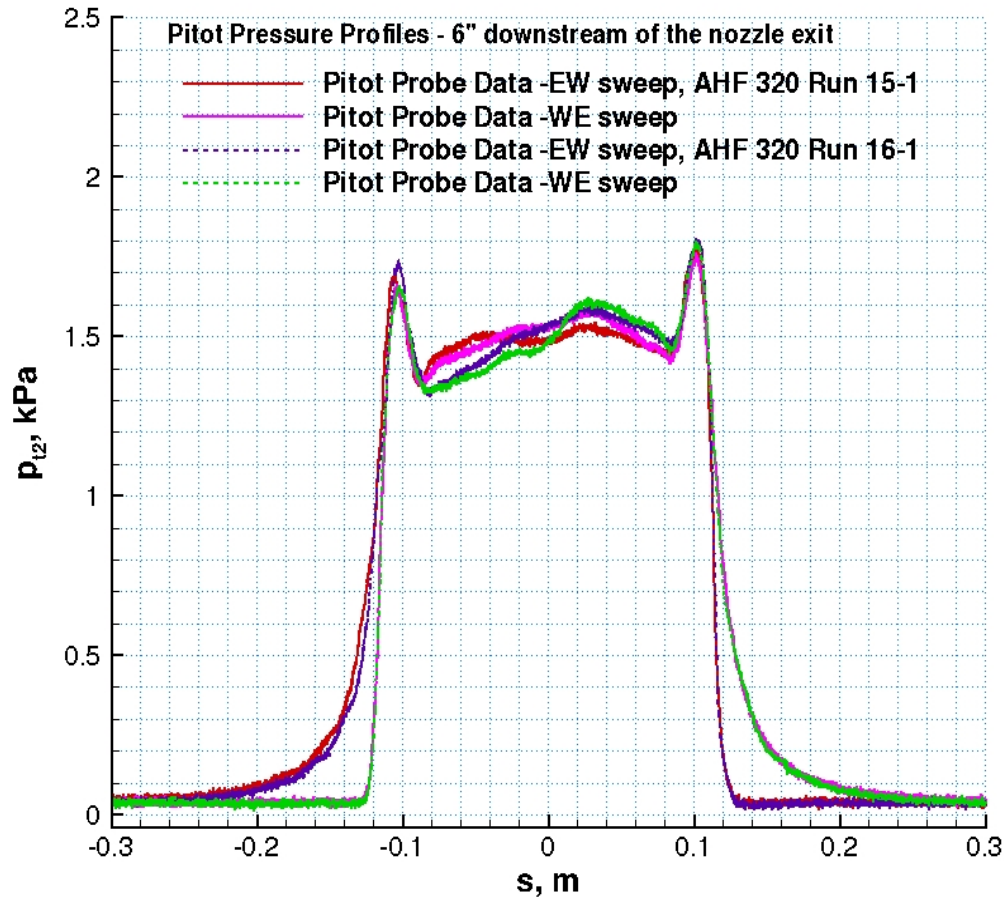
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 25$ g/s, $h_{ob} = 11.8$ MJ/kg, $h_{ocl} = 13.8$ MJ/kg, $p_{box} = 0.7$ torr



- Pitot probe speed is too high when probes are outside the core flow
- 15.9-mm probe measurements are sensitive to the probe speed, especially at lower pressures
- The heat flux data show an asymmetric distribution (also more peaked than computations)
- Note that the test box pressure for AHF 320 is higher than for AHF 307

Repeatability of 15.9-mm Probe Survey Data (step 1, AHF 320)

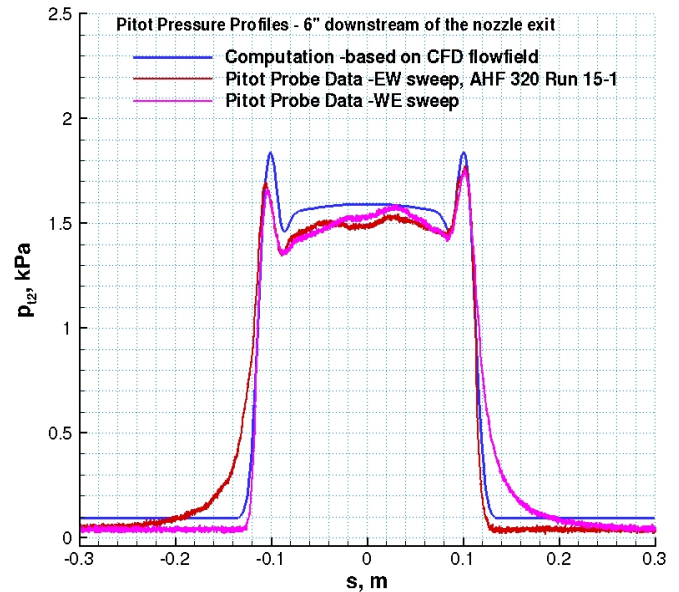
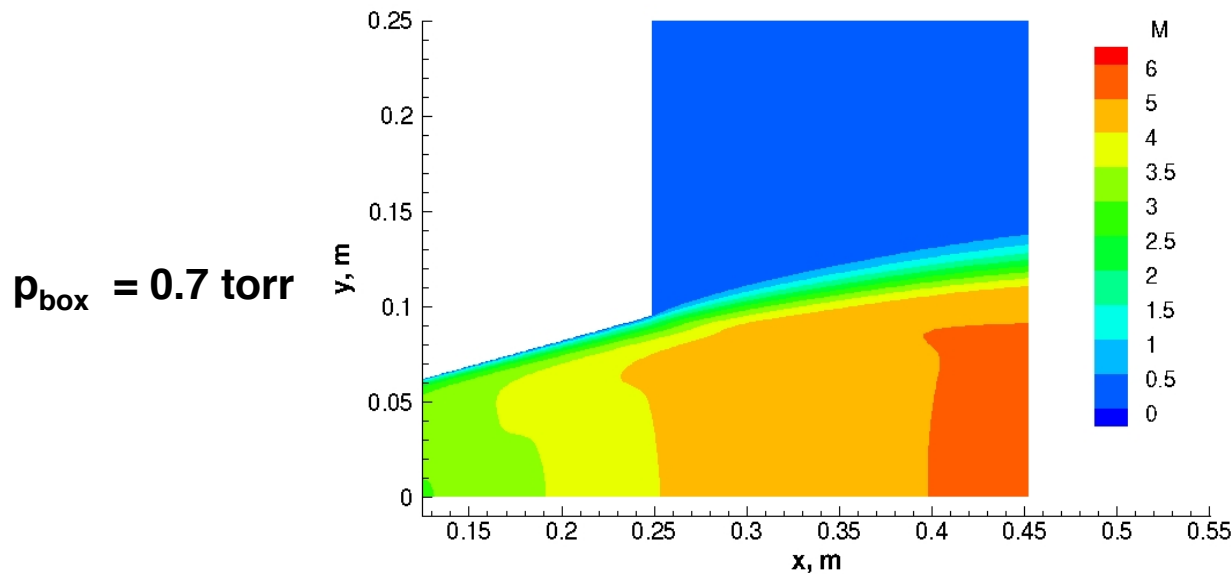
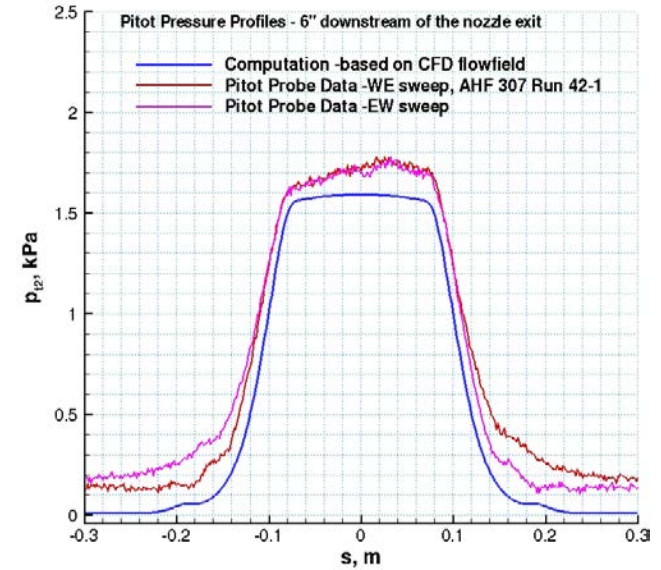
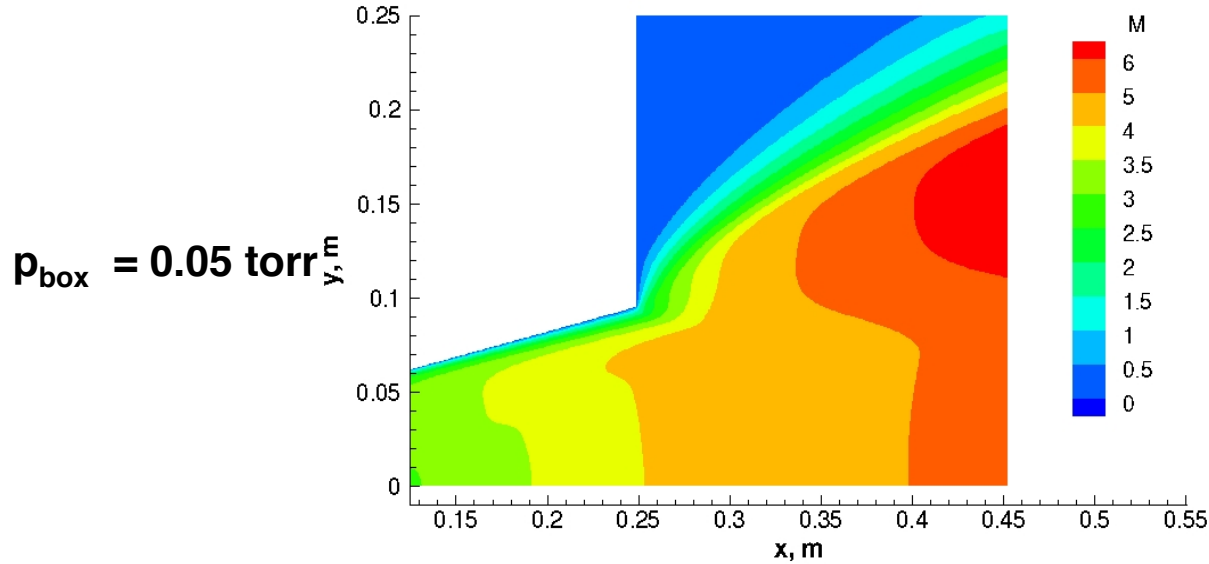
TP3 7.5-Inch Nozzle Flow: $\dot{m} = 25$ g/s, $I = 279$ A, $p_{midc} = 27.5$ kPa, $p_{box} = 0.7$ - 0.8 torr



- The pitot probe data are reasonably repeatable
- The heat flux data show an asymmetric distribution, not very repeatable
- Quantitative heat flux values from the Gardon gage probe are not used: normalized distribution is used for comparisons
- Approximate probe dwell times: 50 s for Runs 15-1 and 16-1, and 1.2 s for Run 11-1, 12 s for Run 12-1

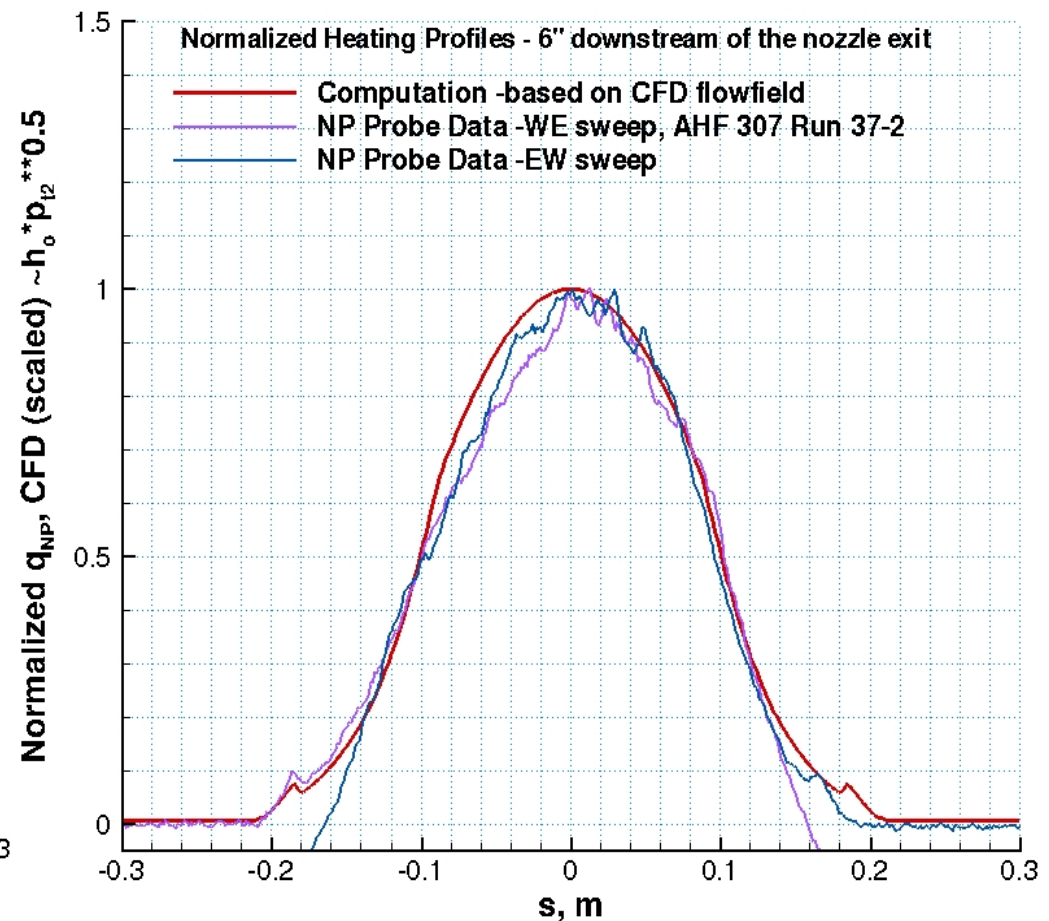
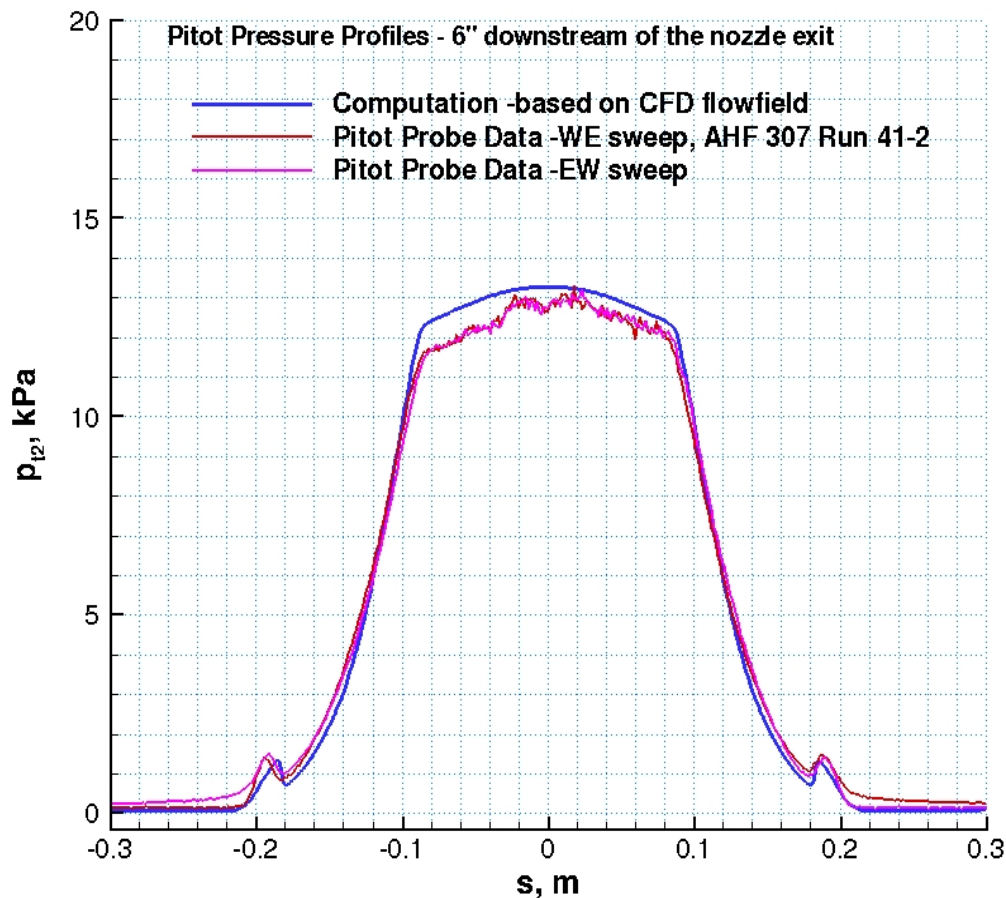
Effects of Test Box Pressure on Computed Flowfield and Survey Data

TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 25$ g/s, $h_{ob} = 11.8$ MJ/kg, $h_{ocl} = 13.8$ MJ/kg



Comparisons of Computations with Survey Data (step 2, AHF 307)

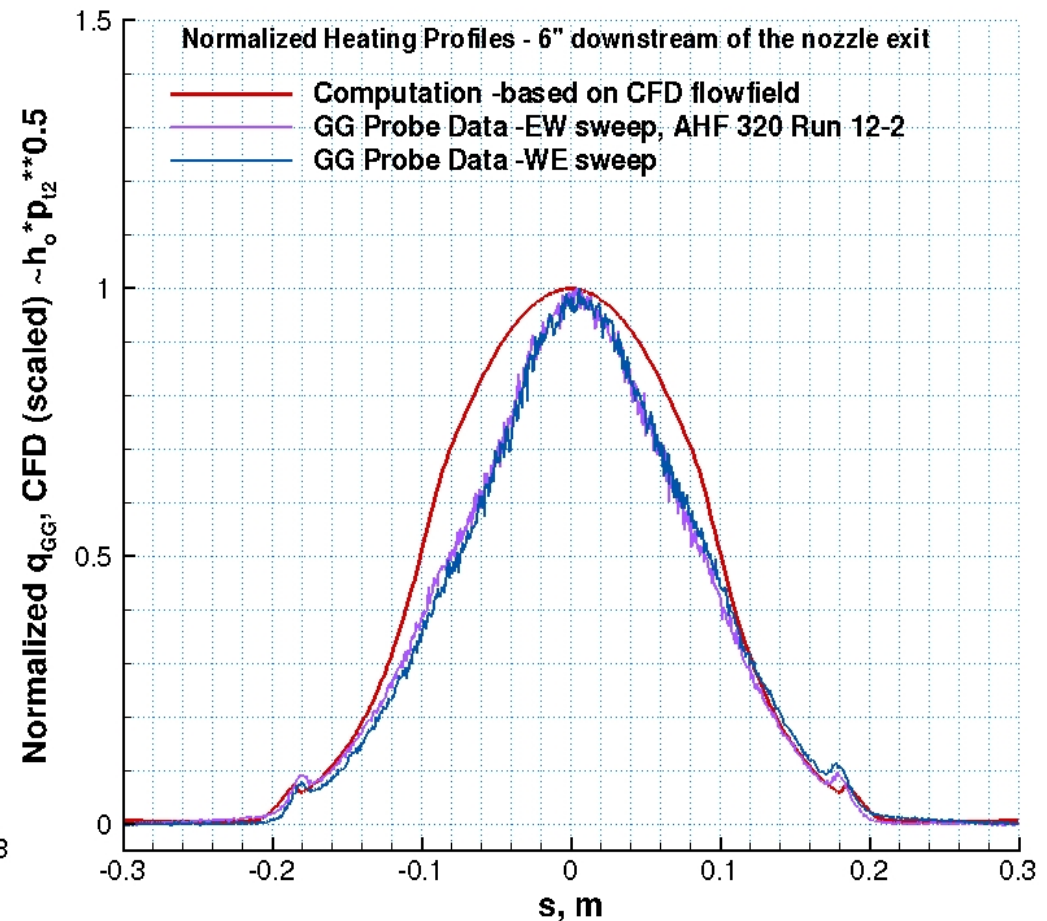
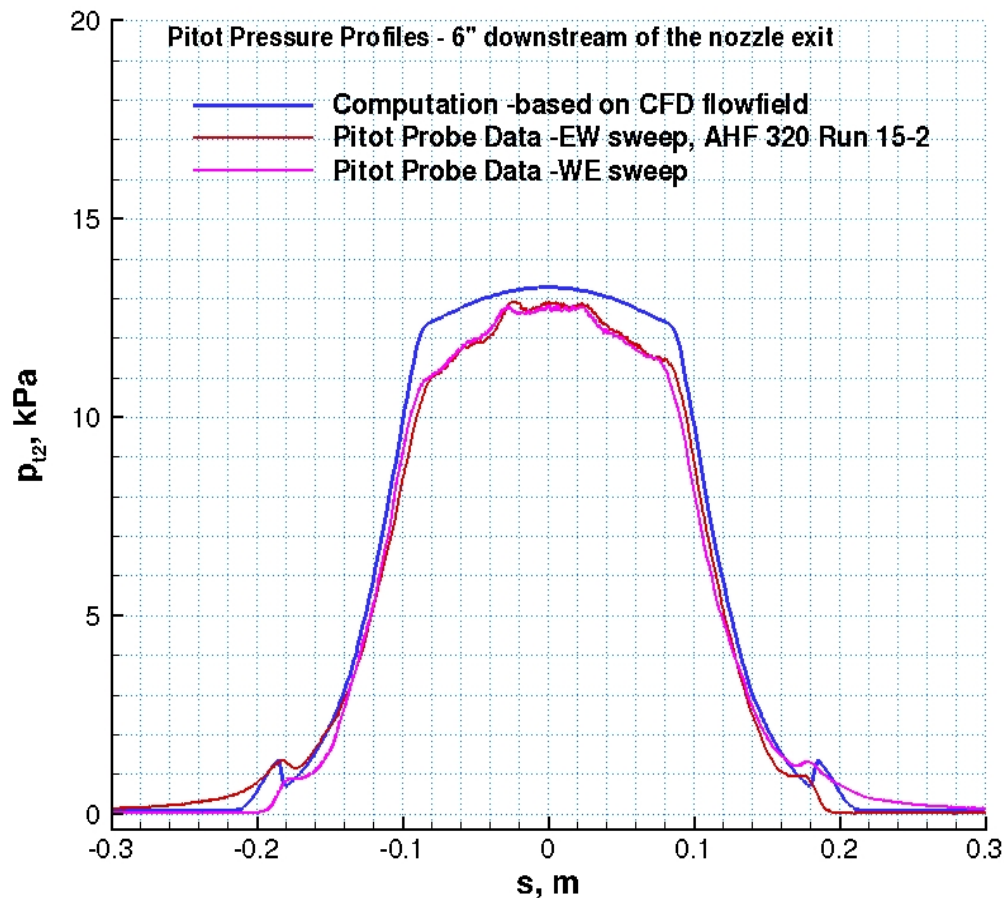
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 190$ g/s, $h_{ob} = 17.6$ MJ/kg, $h_{ocl} = 28.8$ MJ/kg, $p_{box} = 0.4$ torr



- This case represents a facility condition at an **intermediate mass flow rate, relatively high enthalpy** and **without plenum gas injection**
- CFD simulations reproduce the survey data quite well

Comparisons of Computations with Survey Data (step 2, AHF 320)

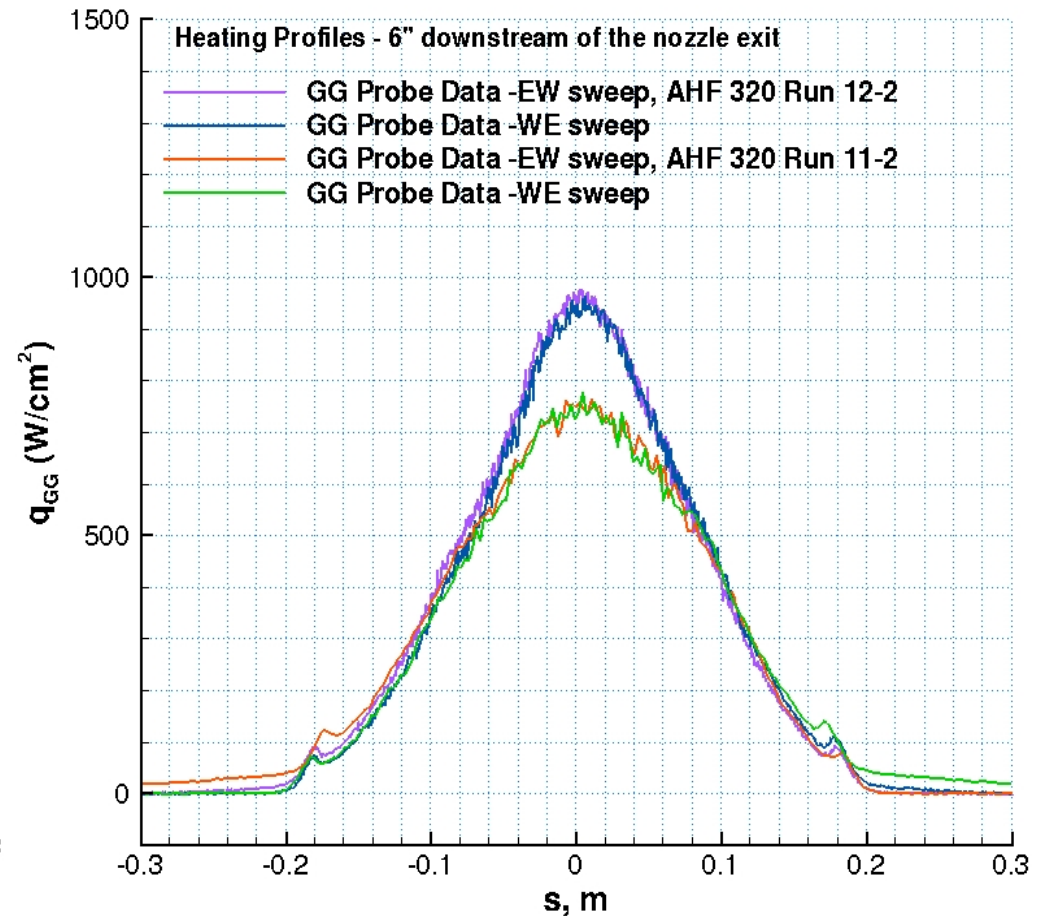
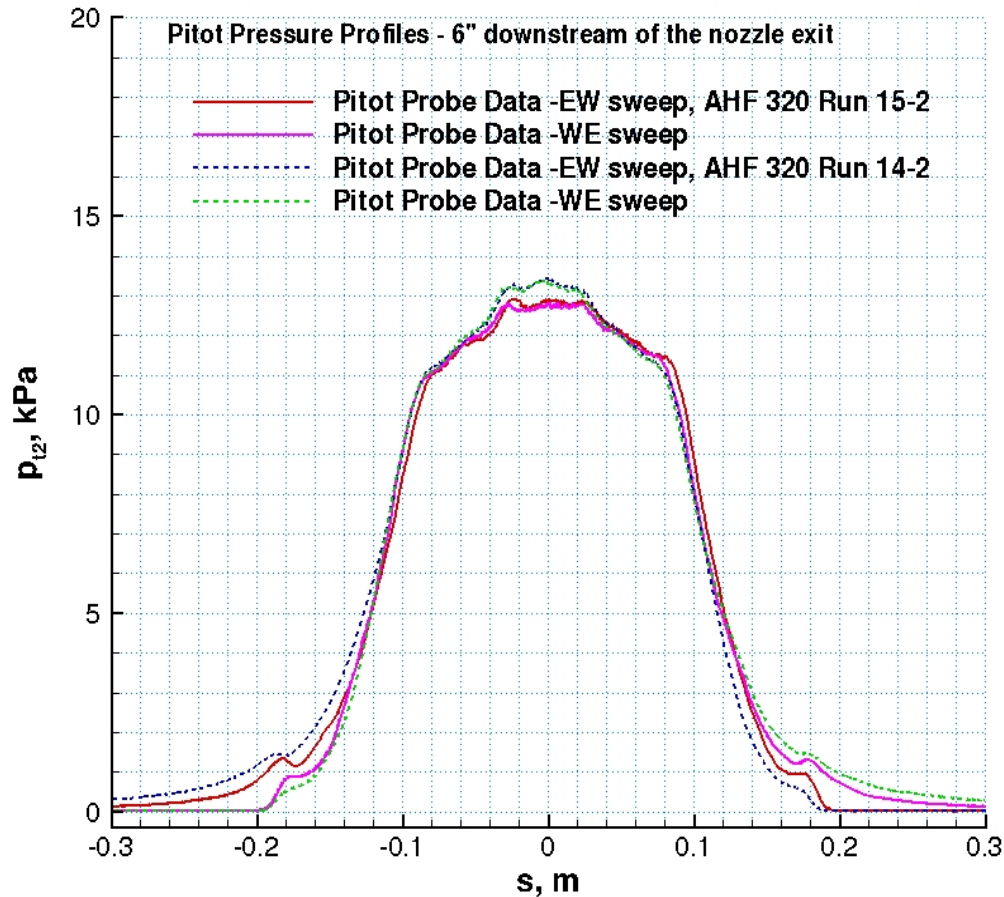
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 190$ g/s, $h_{ob} = 17.6$ MJ/kg, $h_{ocl} = 28.8$ MJ/kg, $p_{box} = 0.4$ torr



- The heat flux survey data show a highly peaked distribution (like a triangle), much more than computations
- Note the feature in the pitot pressure data near the nozzle centerline: possibly weak wave interactions

Repeatability of 15.9-mm Probe Survey Data (step 2, AHF 320)

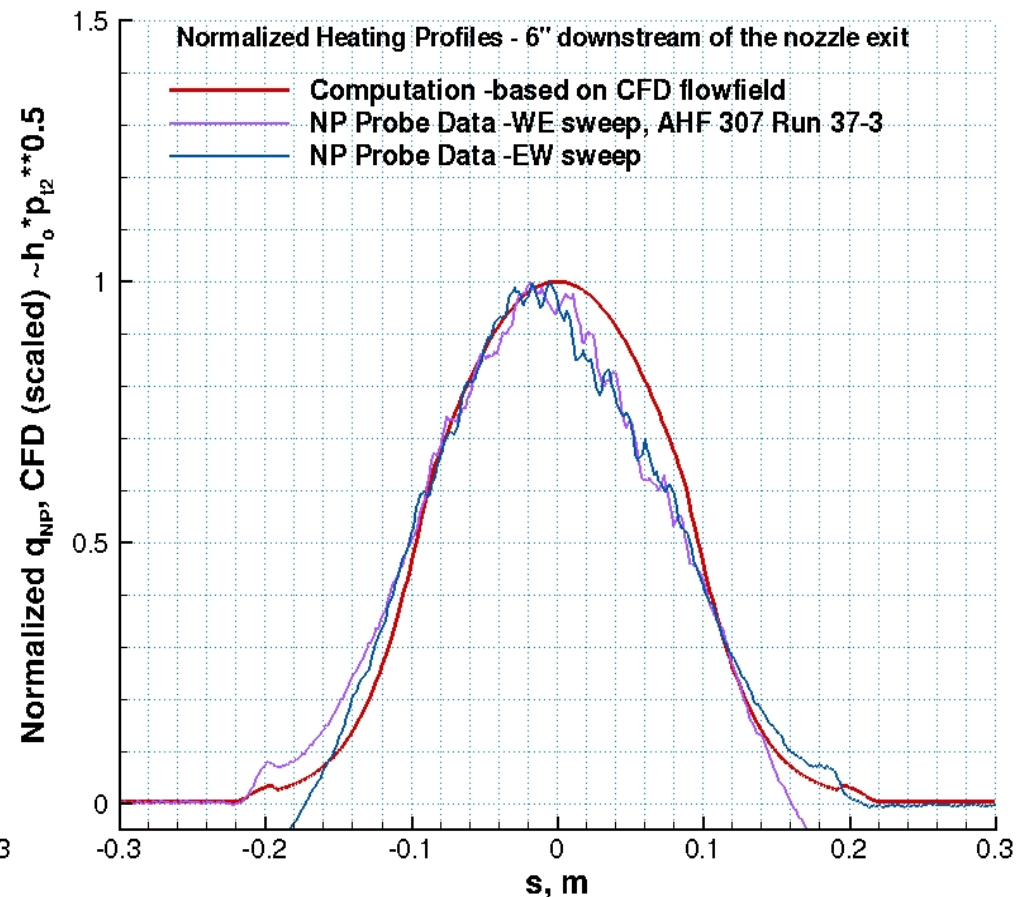
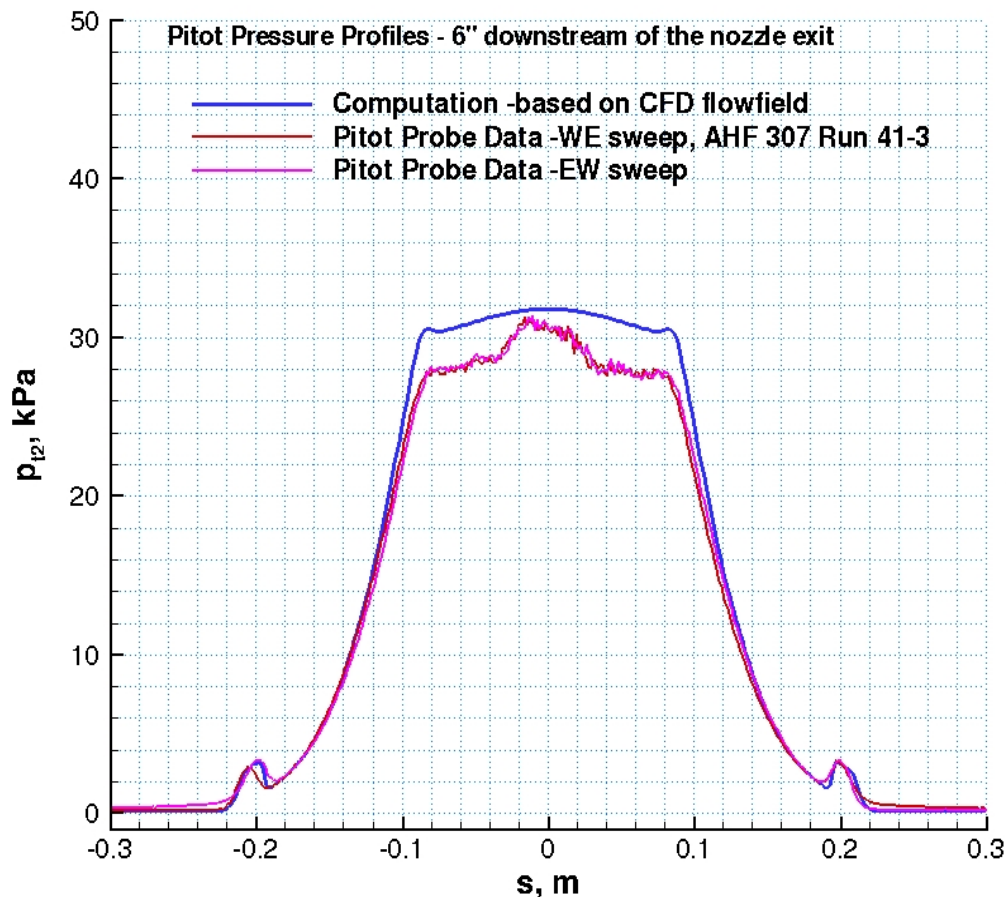
TP3 7.5-Inch Nozzle Flow: $\dot{m} = 190 \text{ g/s}$, $I = 1110 \text{ A}$, $p_{midc} = 205 \text{ kPa}$



- The pitot probe data are repeatable
- The heat flux data show a symmetric distribution (approximately), not repeatable
- Probe dwell times: 15 s and 30 s for Runs 14-2 and 15-2, and 1.6 s and 7 s for Runs 11-2 and 12-2

Comparisons of Computations with Survey Data (step 3, AHF 307)

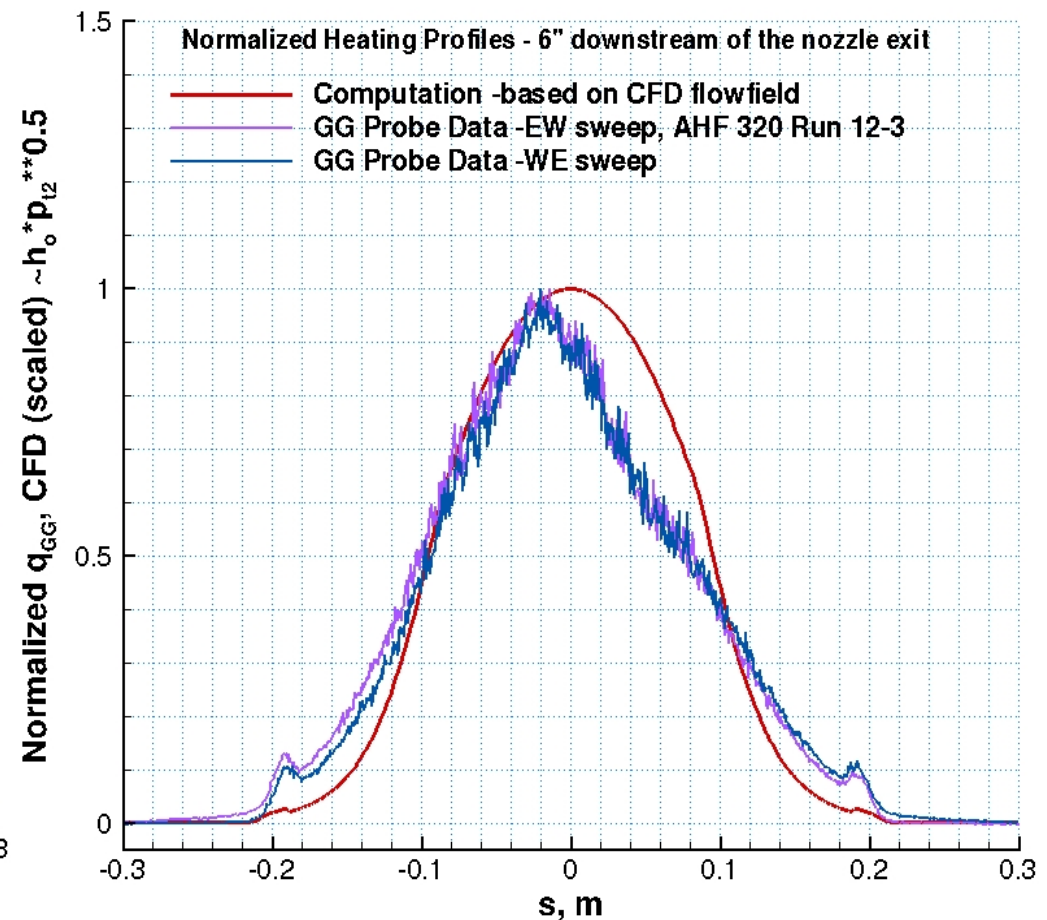
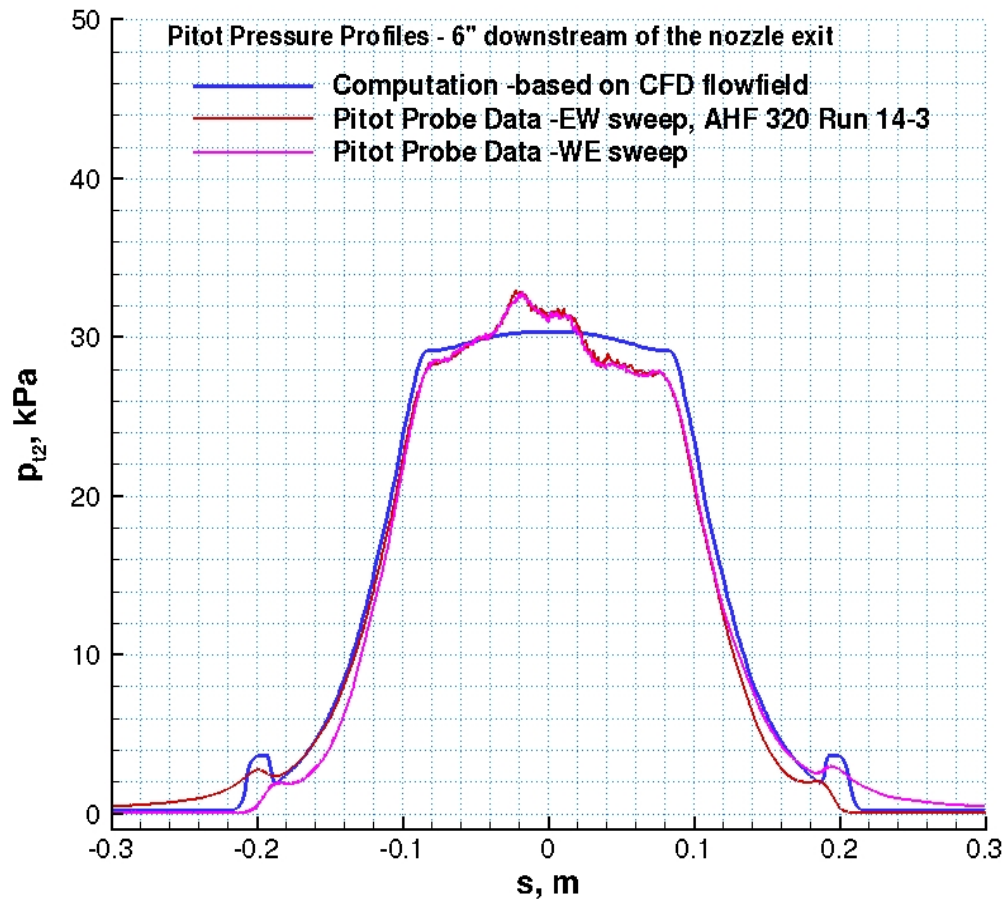
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 501$ g/s, $h_{ob} = 16.4$ MJ/kg, $h_{ocl} = 34.1$ MJ/kg, $p_{box} = 1$ torr



- This case represents a facility condition close to **the facility max (mass flow rate and current)** at high enthalpy and **without plenum gas injection**
- Pitot surveys show interesting features: somewhat higher pressure region near the nozzle centerline, possibly as a result of some disturbances in the nozzle flowfield; slightly asymmetric (skews to the west)
- Estimated total enthalpy is quite high for this facility

Comparisons of Computations with Survey Data (step 3, AHF 320)

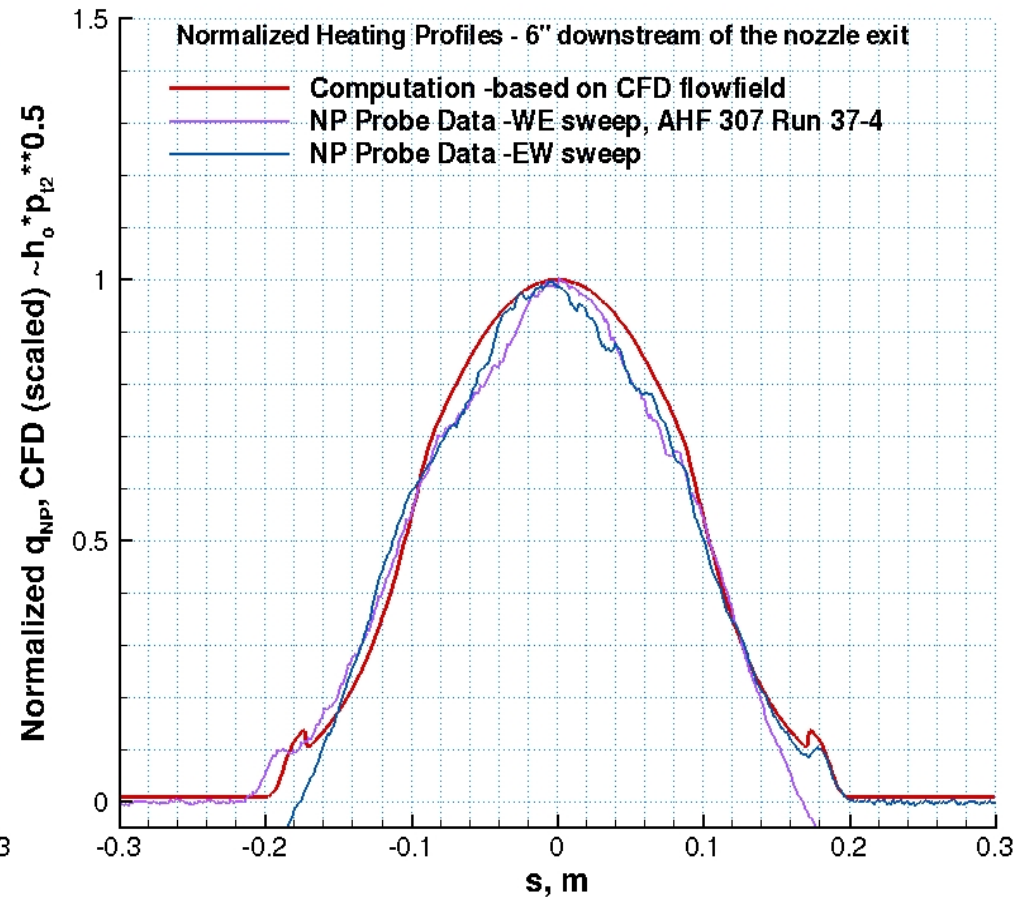
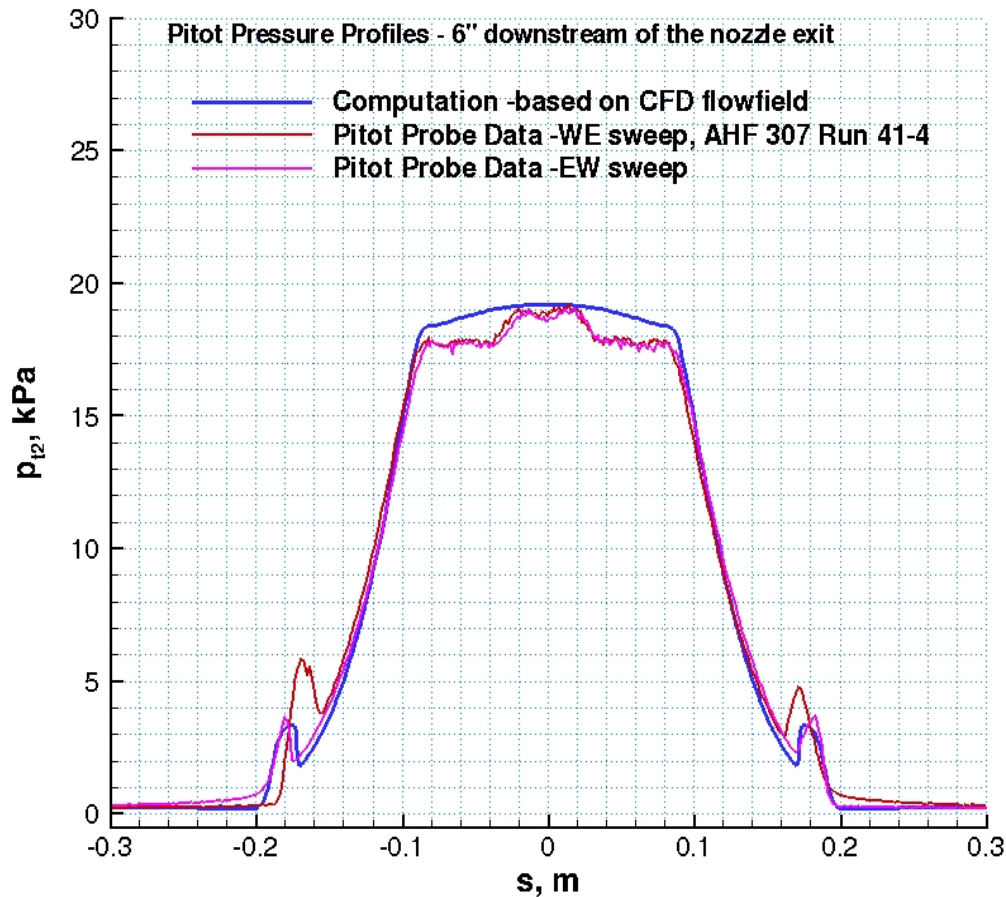
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 500$ g/s, $h_{ob} = 13.9$ MJ/kg, $h_{ocl} = 29.9$ MJ/kg, $p_{box} = 1$ torr



- CFD simulations are based on AHF 320 calibration data
- In the pitot surveys, there is a higher pressure region near the nozzle centerline (similar to the earlier surveys, but it is asymmetric); Although this feature could be explained by geometric imperfections in the nozzle walls, the fact that it does not appear in all surveys at other conditions requires further study
- Asymmetry in the heating profile is confirmed, skewed to the west side

Comparisons of Computations with Survey Data (step 4, AHF 307)

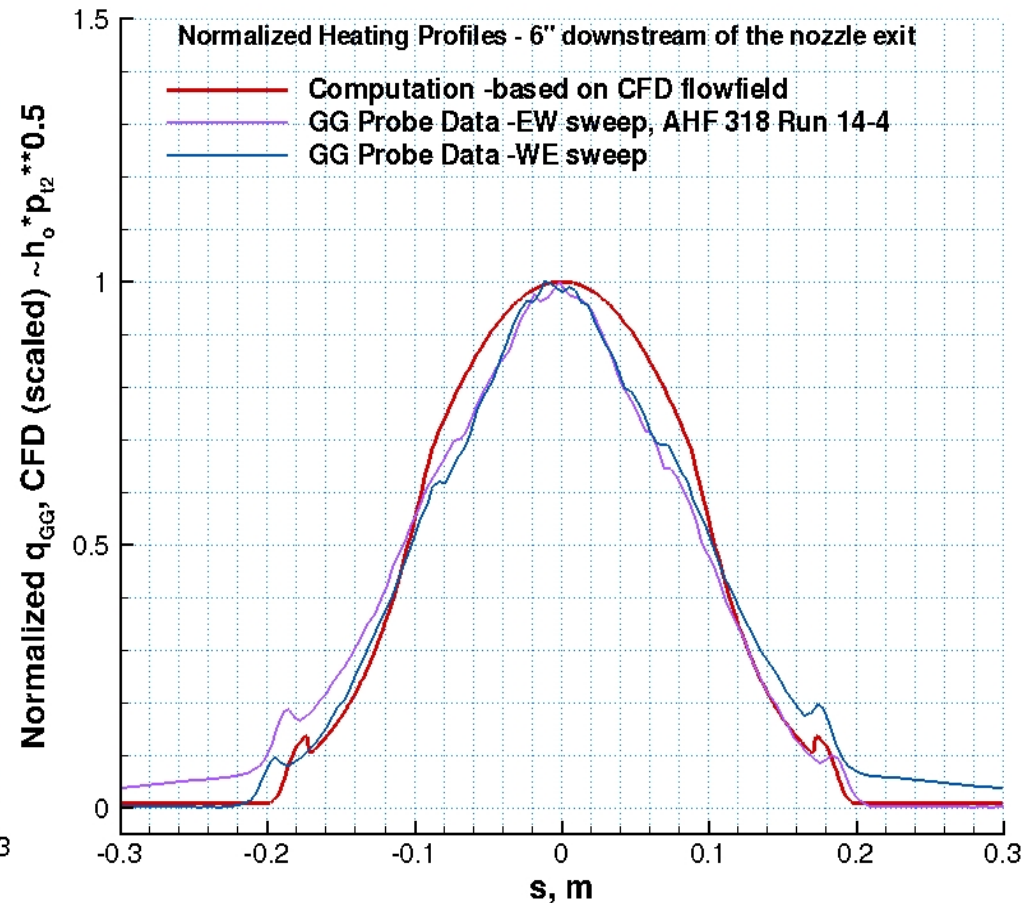
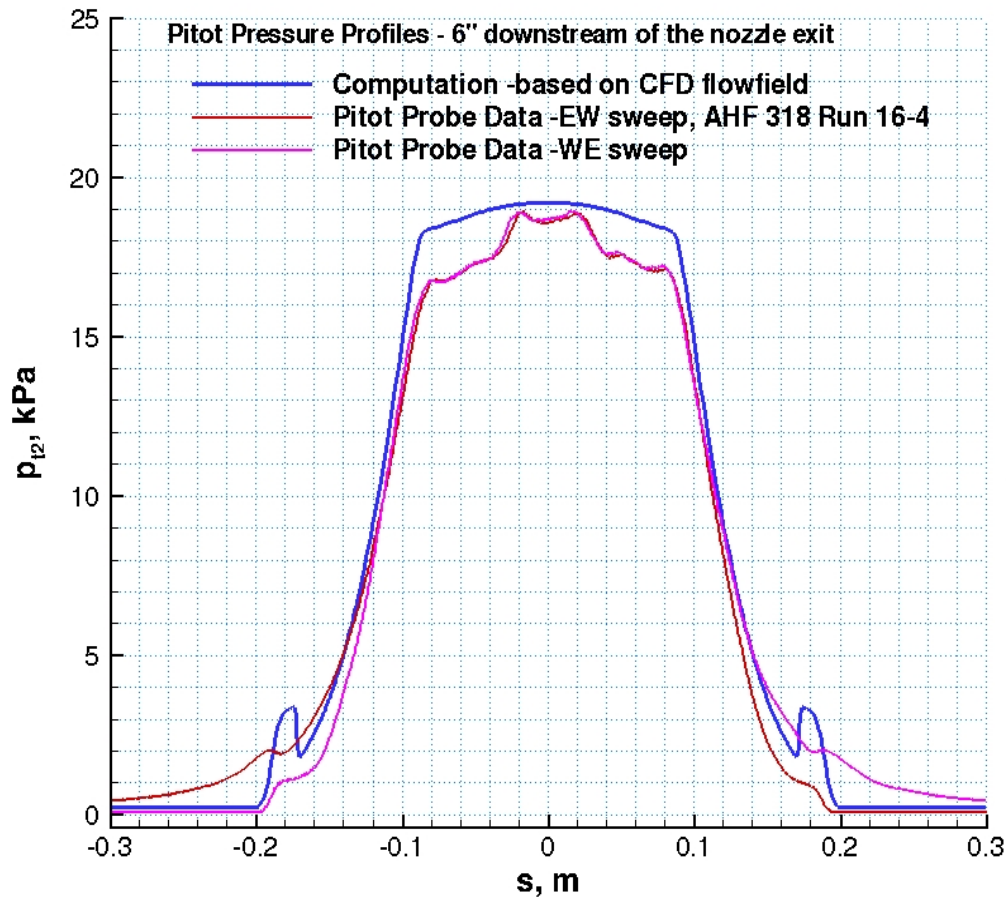
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 310$ g/s, $h_{ob} = 13.6$ MJ/kg, $h_{ocl} = 21.9$ MJ/kg, $p_{box} = 1$ torr



- This case represents a facility condition at **relatively high mass flow rate and moderately high enthalpy**, and **with cold gas injection** of N_2 at the plenum (20% of total mass flow rate)
- The pitot survey shows a somewhat higher pressure region near the nozzle centerline
- Both pitot and heat flux survey data are repeatable and approximately symmetric

Comparisons of Computations with Survey Data (step 4, AHF 318)

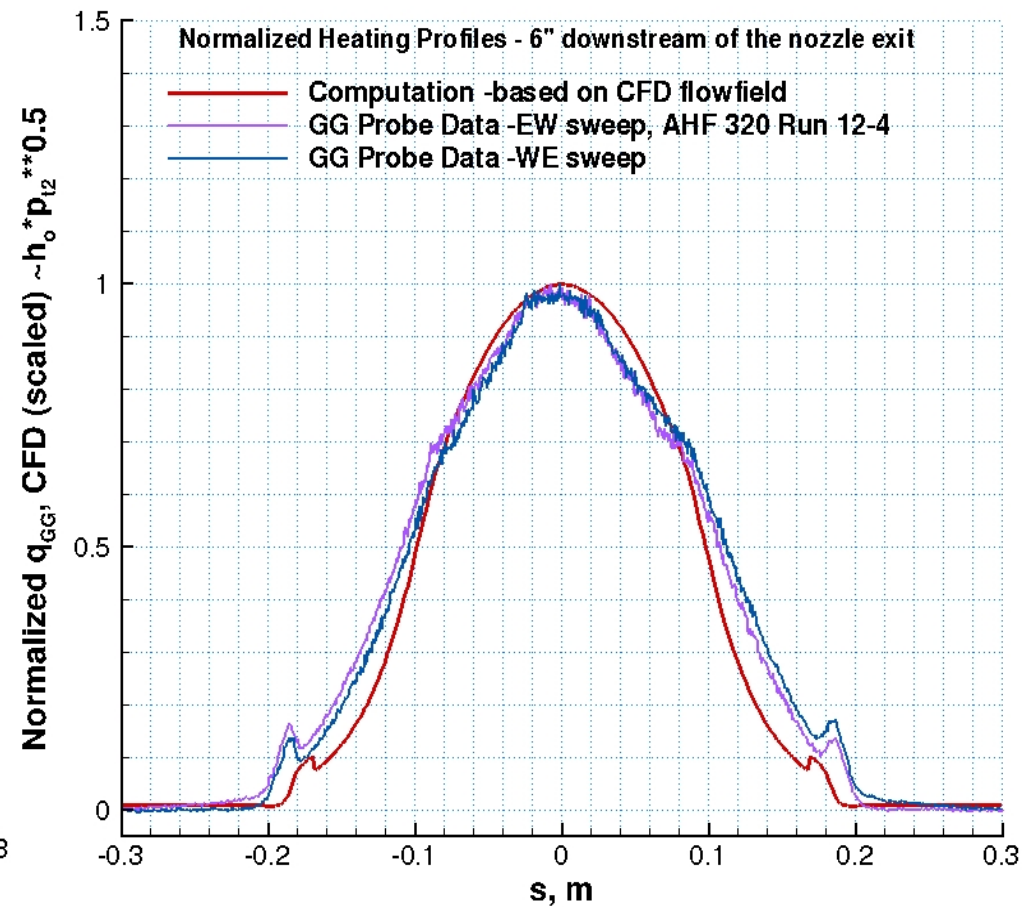
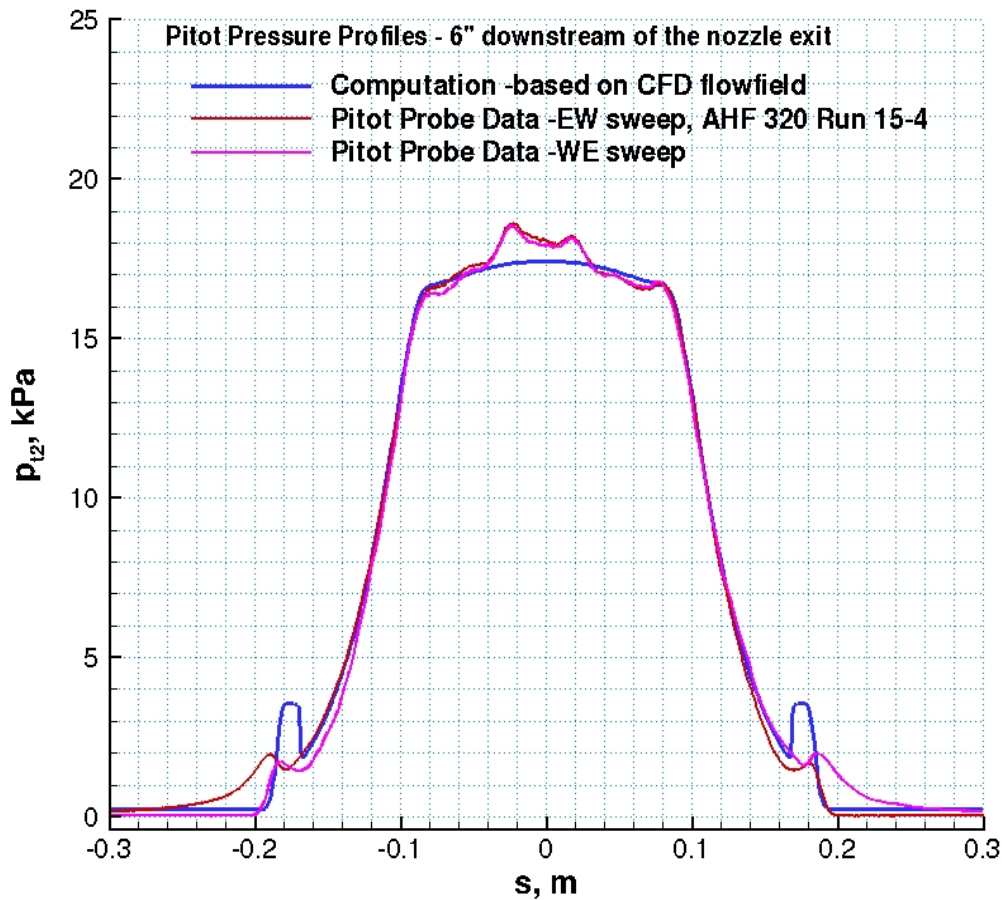
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 310$ g/s, $h_{ob} = 13.6$ MJ/kg, $h_{ocl} = 21.9$ MJ/kg, $p_{box} = 1$ torr



- The pitot survey shows a somewhat higher pressure region near the nozzle centerline (similar to AHF 307 survey data)
- Both pitot and heat flux survey data are repeatable and approximately symmetric

Comparisons of Computations with Survey Data (step 4, AHF 320)

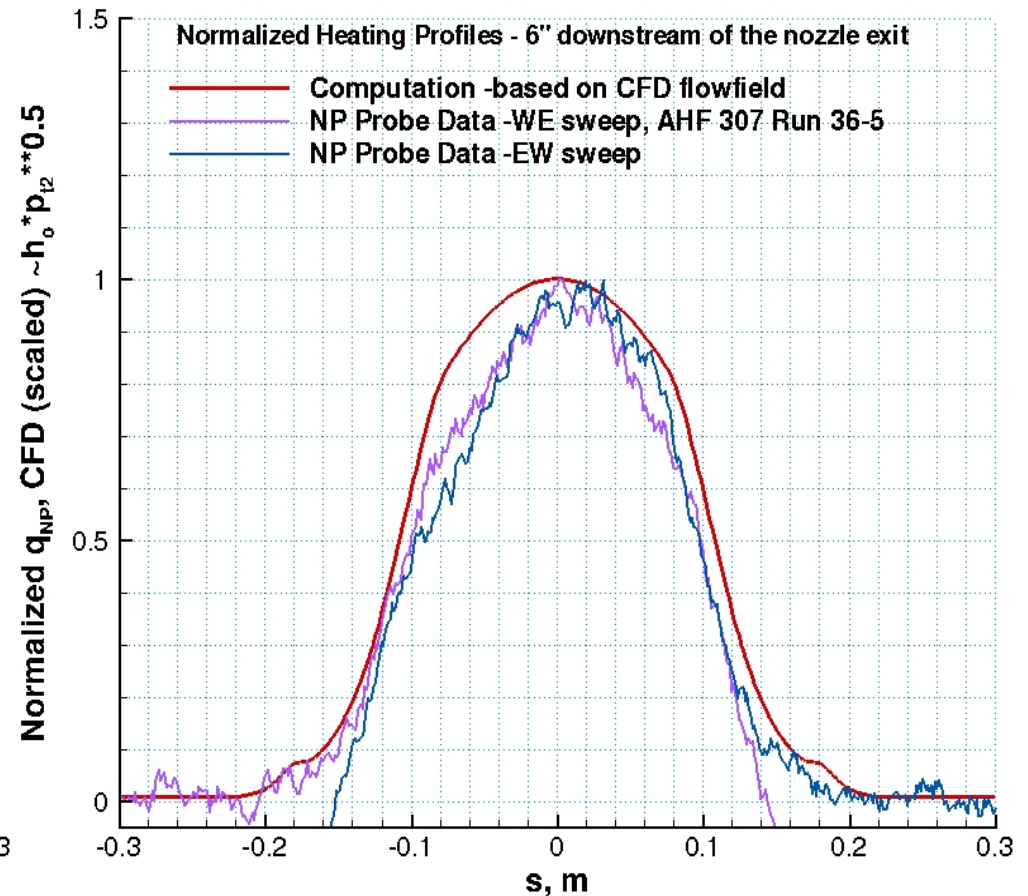
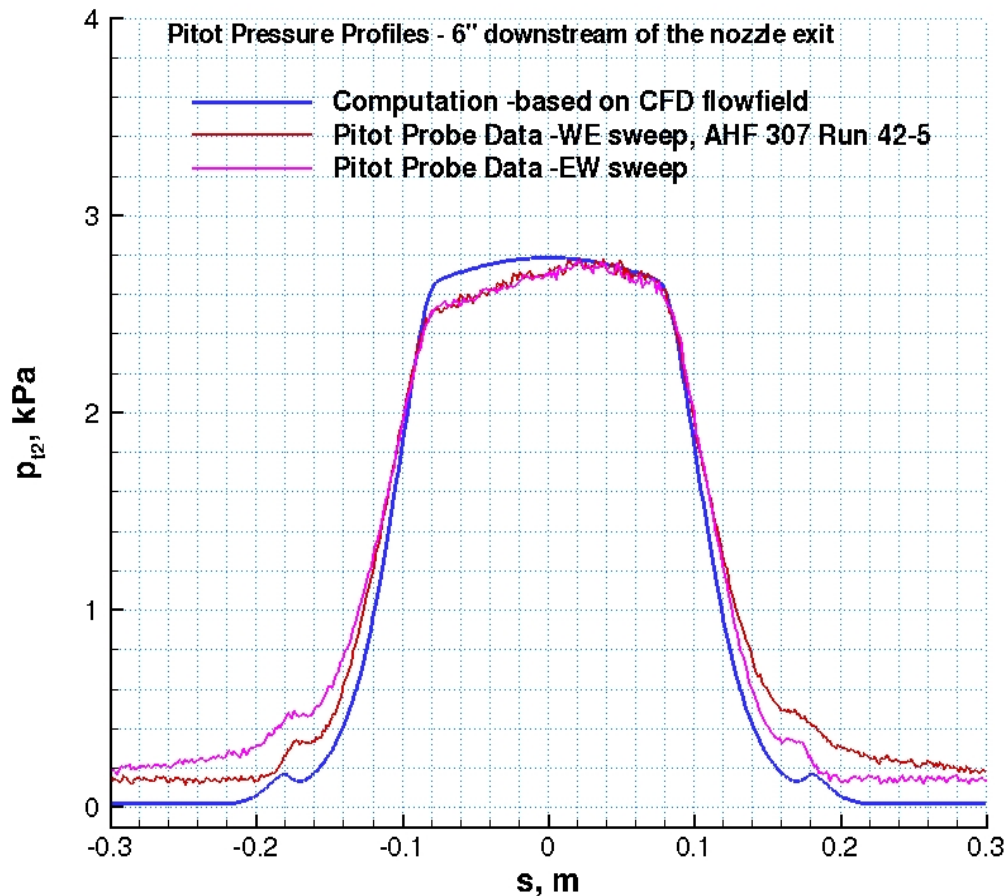
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 310$ g/s, $h_{ob} = 10.3$ MJ/kg, $h_{ocl} = 18.8$ MJ/kg, $p_{box} = 1$ torr



- CFD simulations are based on AHF 320 calibration data
- Both pitot and heat flow survey data are approximately symmetric

Comparisons of Computations with Survey Data (step 5, AHF 307)

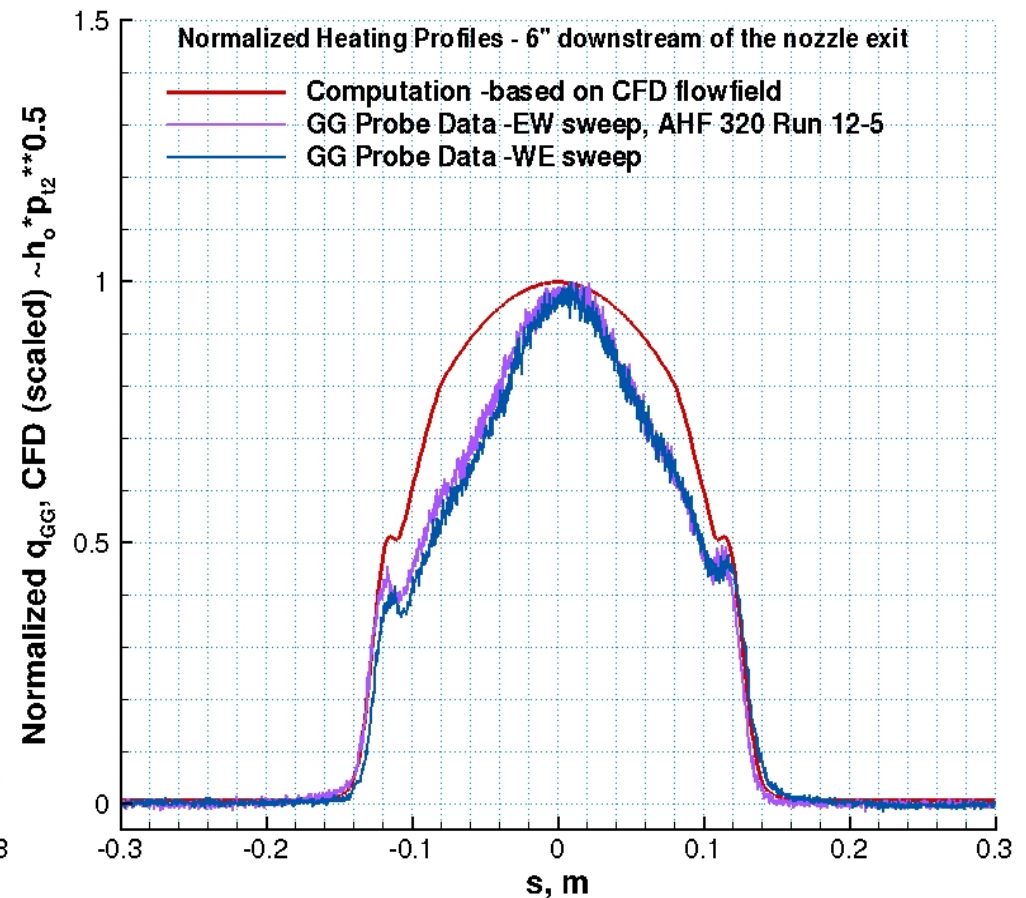
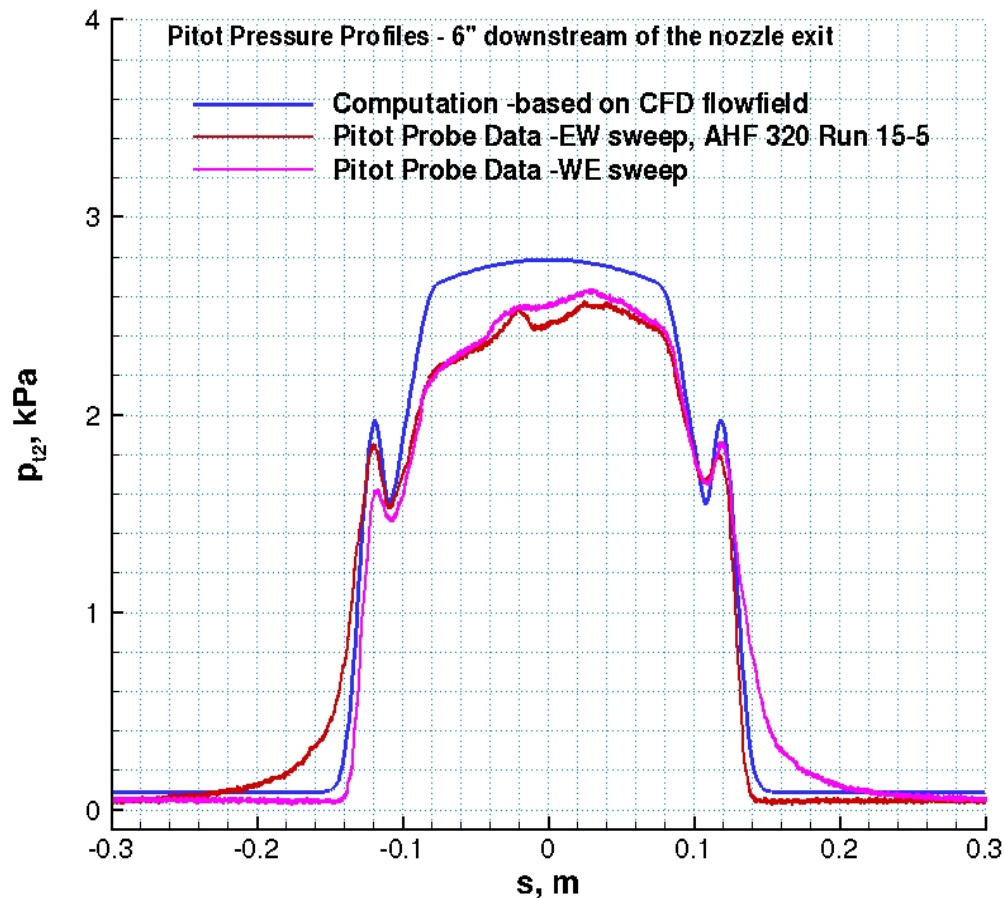
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 40$ g/s, $h_{ob} = 15.4$ MJ/kg, $h_{ocl} = 19.6$ MJ/kg, $p_{box} = 0.1$ torr



- This case represents a facility condition at relatively **low mass flow rate and moderately high enthalpy**, and **without cold gas injection** at the plenum
- Both pitot and heat flux survey data are not symmetric while the sweep data are repeatable in both sweep directions
- There is an incomplete recovery in the pitot pressure data to the test box pressure

Comparisons of Computations with Survey Data (step 5, AHF 320)

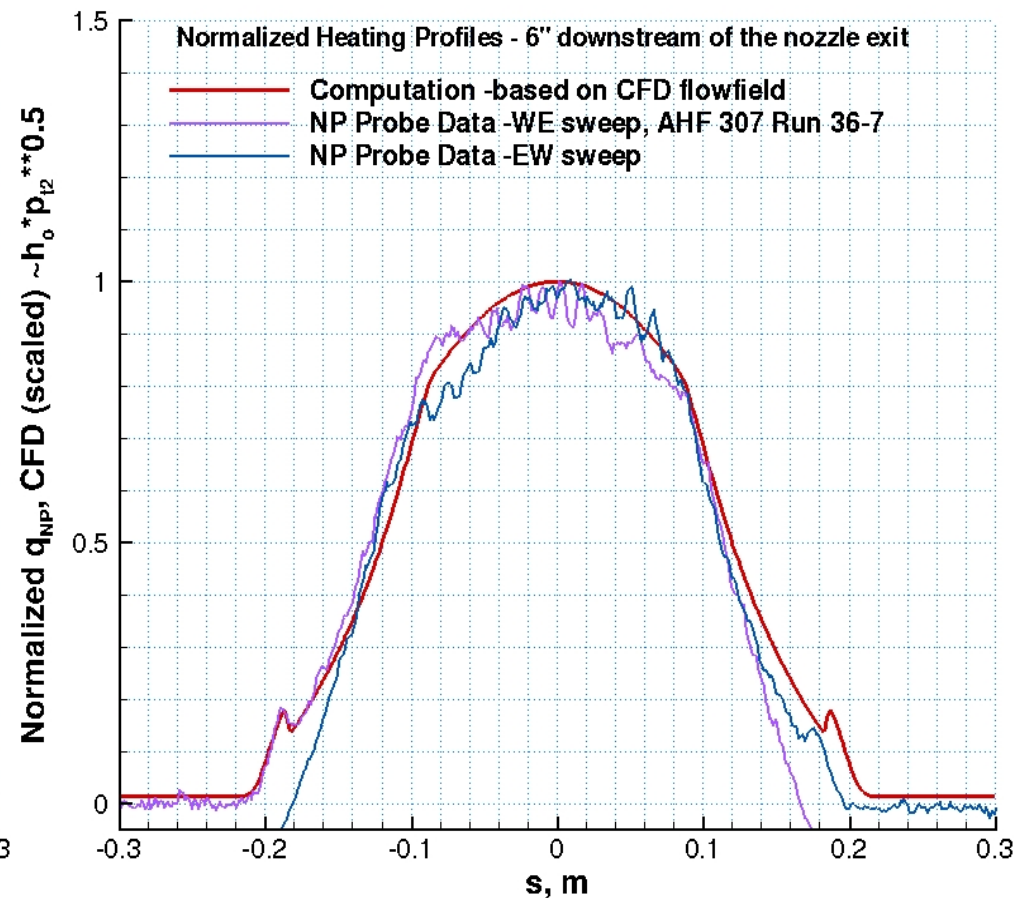
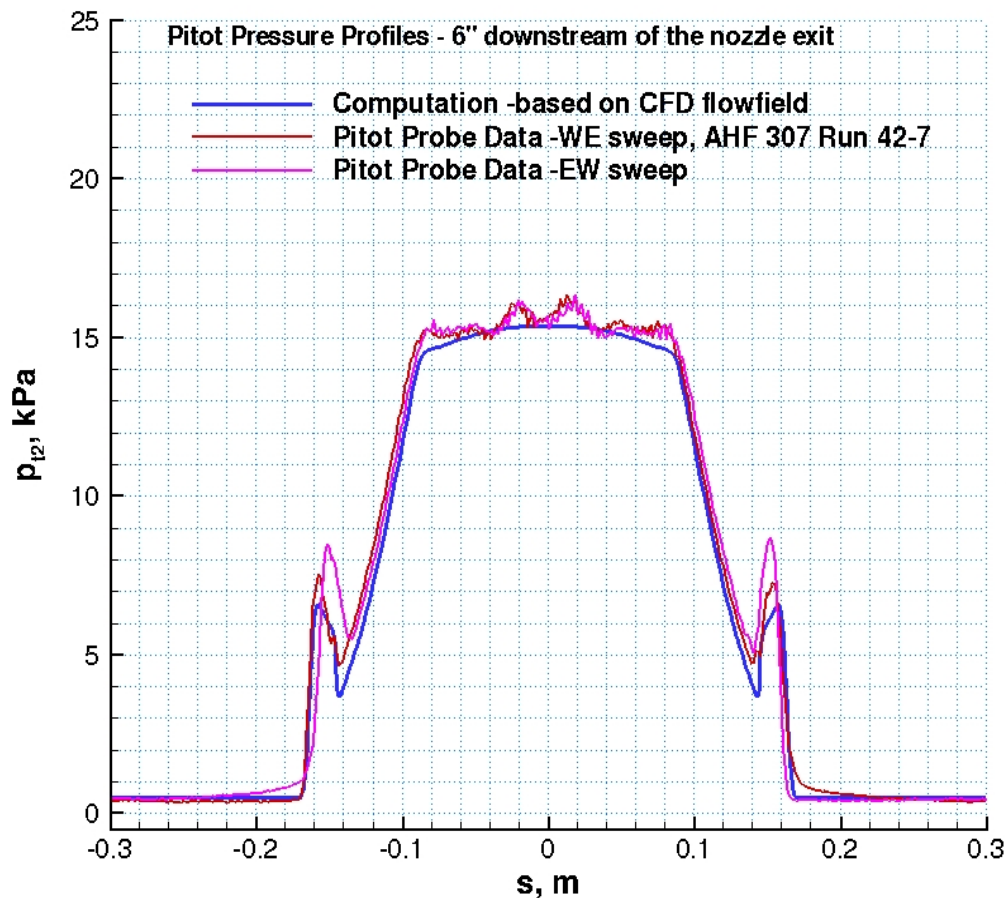
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 40$ g/s, $h_{ob} = 15.4$ MJ/kg, $h_{ocl} = 19.6$ MJ/kg, $p_{box} = 0.7$ torr



- Both pitot and heat flux survey data are not symmetric while the sweep data are reasonably repeatable in both sweep directions
- The asymmetric feature skewing to the east side is confirmed (west side in step 3 condition)
- The heat flux data show a more peaked distribution than computations
- Test box pressure for AHF 320 is much higher than for AHF 307

Comparisons of Computations with Survey Data (step 7, AHF 307)

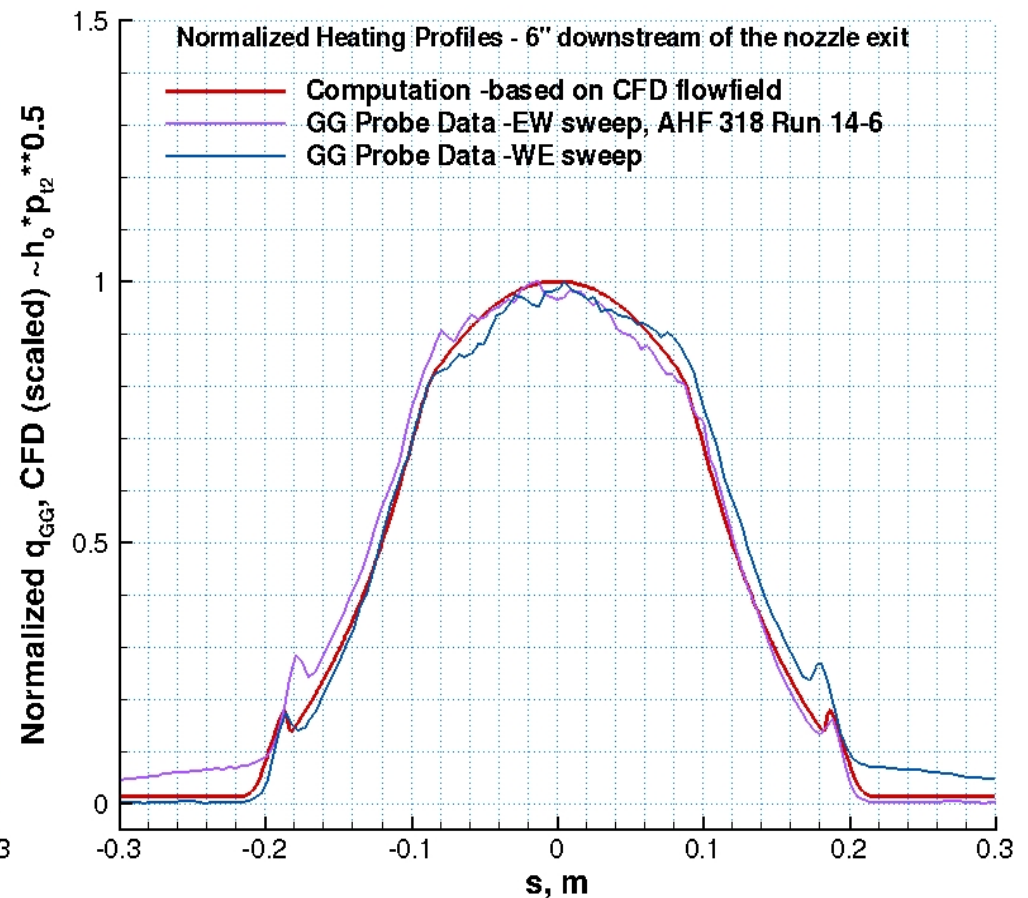
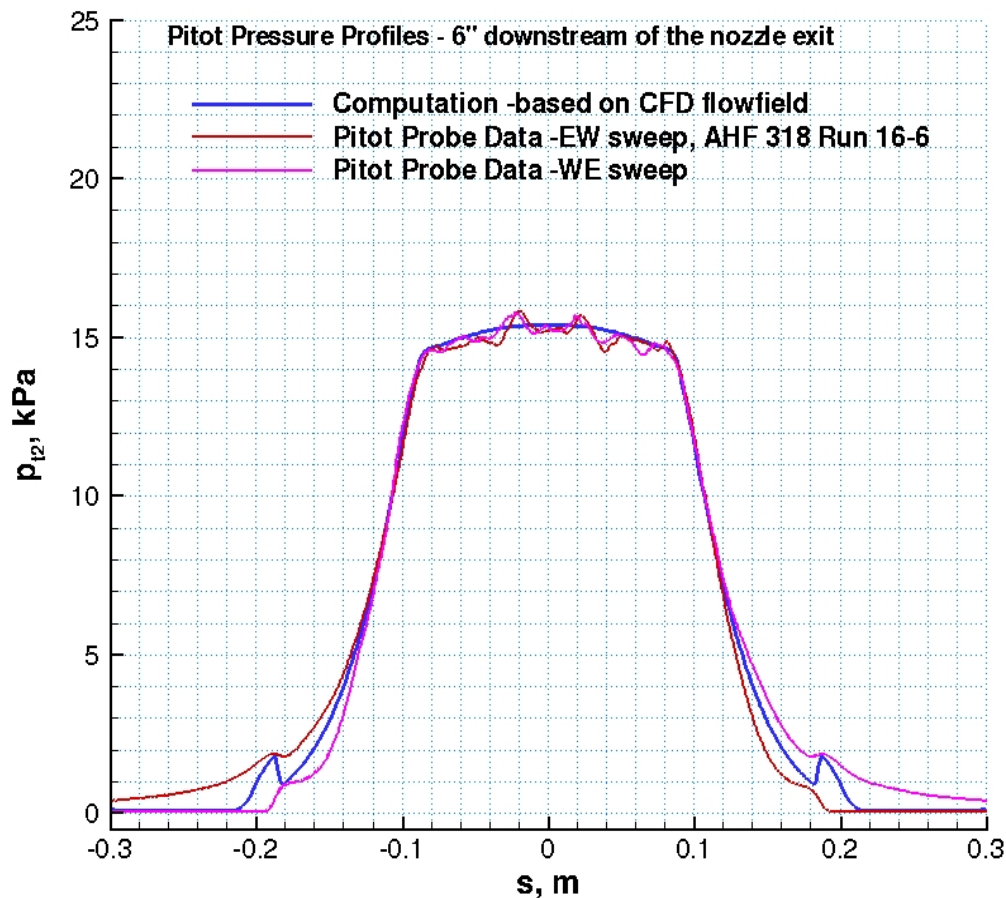
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 310$ g/s, $h_{ob} = 7.5$ MJ/kg, $h_{ocl} = 9.4$ MJ/kg, $p_{box} = 0.5$ -2 torr



- This case represents a facility condition at relatively **high mass flow rate and low enthalpy**, and **with cold gas injection** of N_2 at the plenum (28% of total mass flow rate)
- The pitot pressure data were obtained at $p_{box} = 2$ torr, and the NP heat flux data at $p_{box} = 0.5$ torr
- The pitot survey appears to indicate some wave interactions near the nozzle centerline

Comparisons of Computations with Survey Data (step 7, AHF 318)

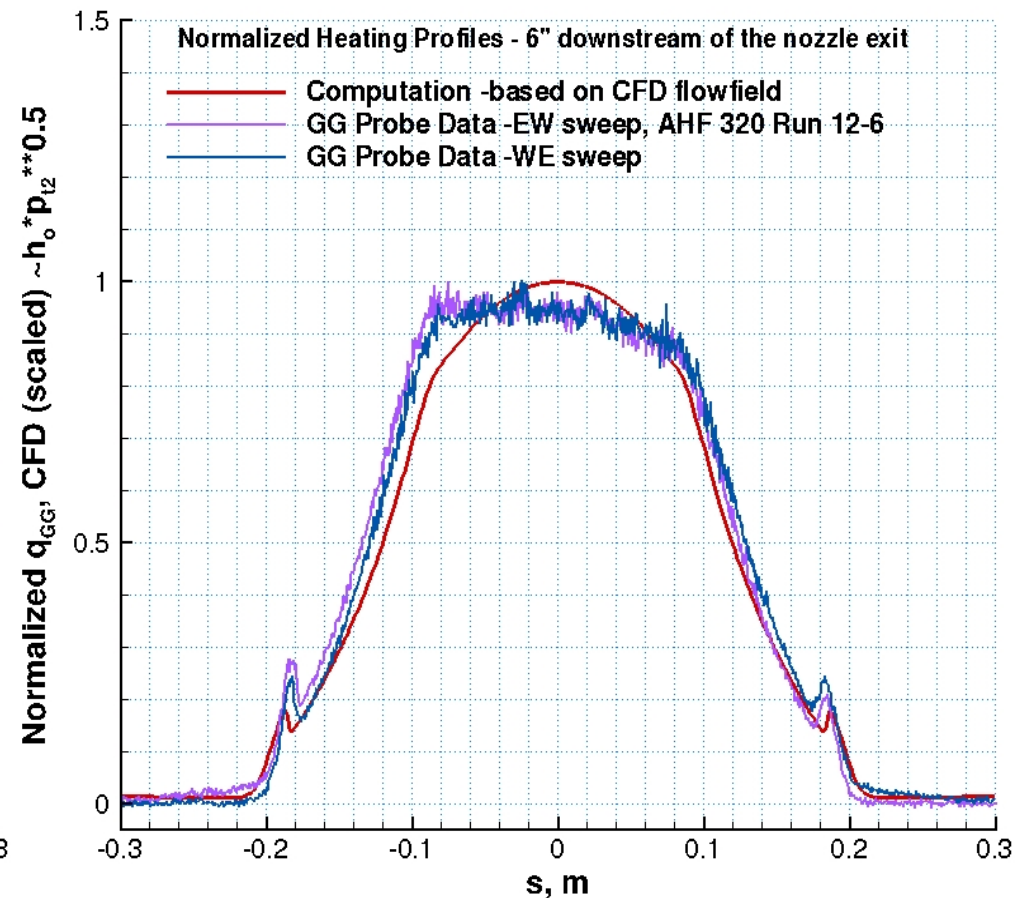
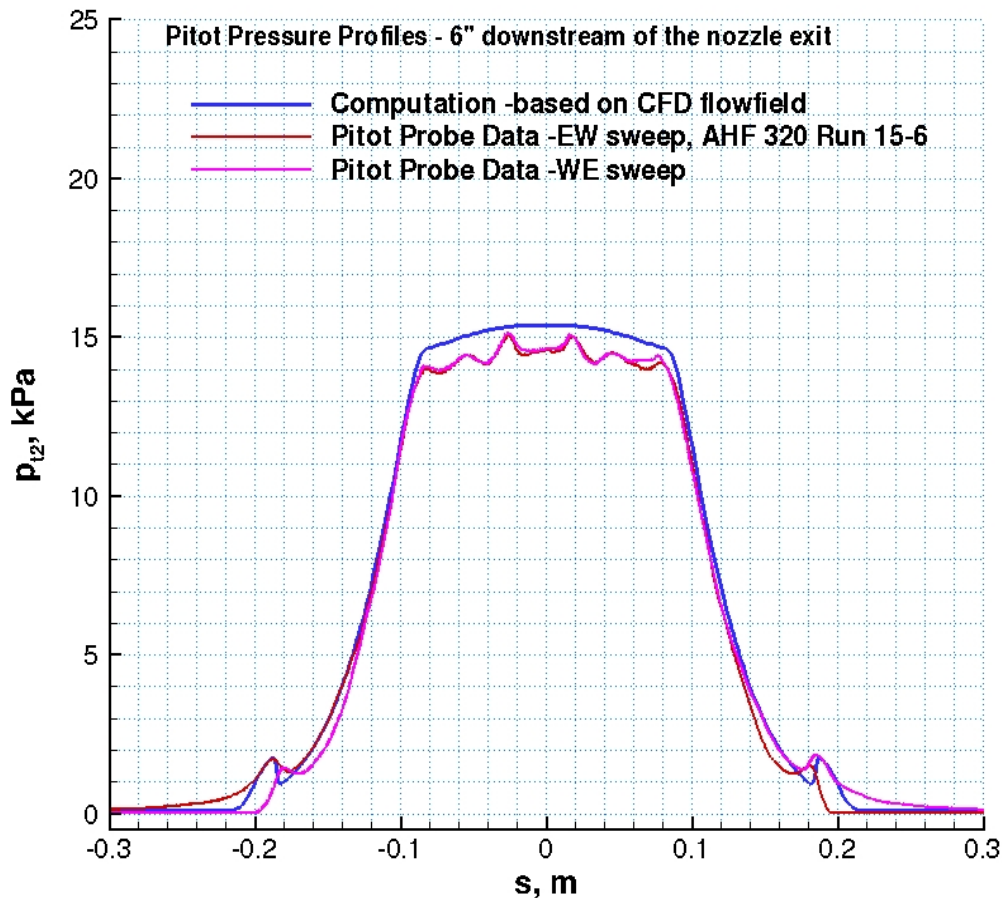
TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 310$ g/s, $h_{ob} = 7.5$ MJ/kg, $h_{ocl} = 9.4$ MJ/kg, $p_{box} = 0.5$ torr



- Both pitot and heat flux survey data are repeatable and approximately symmetric
- The pitot survey shows similar wave interactions near the nozzle centerline (observed in AHF 307)

Comparisons of Computations with Survey Data (step 7, AHF 320)

TP3 7.5-Inch Nozzle Flow Simulation: $\dot{m} = 310$ g/s, $h_{ob} = 7.5$ MJ/kg, $h_{ocl} = 9.4$ MJ/kg, $p_{box} = 0.5$ torr



- The heat flux data show a remarkably flat distribution, considering the cold gas injection at the plenum
- The pitot survey shows similar wave interactions near the nozzle centerline (observed in AHF 307 and AHF 318)
- Relatively uniform heating distribution is remarkable (in contrast to our experience with other arc-jet facilities)

Concluding Remarks and Future Work

- The survey data obtained using two different sets of probes at six arc-heater conditions in the TP3 7.5-inch nozzle provide assessment of the flow uniformity and valuable data for the arc-jet flow characterization
 - Six conditions cover a wide range of facility parameters: arc current varies from 262 A to 1762 A, and total mass flow rate from 24 g/s to 501 g/s
 - Two of these conditions include cold-gas N₂ injection at the arc-heater plenum
- The probe survey data clearly show that the arc-jet test flow in the TP3 facility is not uniform at most conditions, and the extent of non-uniformity is highly dependent on various arc-jet parameters such as arc current, mass flow rate (or arc heater pressure), and the amount of cold-gas injection at the plenum
 - Not even axisymmetric at the extremes of the facility operating envelope
 - Effects of the observed asymmetric flows on the calorimeter measurements and their interpretation (CFD-estimated centerline total enthalpy values) remain to be investigated
- CFD analysis is an essential part of arc-jet flow characterization studies
 - Computations show reasonably good agreement with the experimental measurements except at the extreme low pressure conditions of the facility envelope
 - Pitot pressure and normalized heating distributions from two sets of survey probes
- Several additional challenges remain in arc-jet flow calibration using multiple heat flux measuring devices to provide heat flux datasets consistent with each other: calibration of the null-point and Gardon gages, and reexamination of methodologies to infer the heat flux for these measurement devices

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