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

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

- 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 N₂-CO₂ 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

15.9-mm hemisphere probe, Gardon gage

AHF 307 test

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: N₂, O₂, NO, N, O, (Ar, if present)
  - Two-temperature model (Park): T -translational-rotational, Tᵥ -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 cm, r_c/D = 3/32), CWFC
TP3 7.5-Inch Nozzle Flow Simulation: \( \dot{m} = 190 \text{ g/s}, h_{\text{ob}} = 17.6 \text{ MJ/kg}, h_{\text{ocl}} = 28.8 \text{ MJ/kg} \), 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: $\dot{m} = 190$ g/s, $h_{ob} = 17.6$ MJ/kg, $h_{ocl} = 28.8$ 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 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

<table>
<thead>
<tr>
<th>Test Series: AHF 307</th>
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<tbody>
<tr>
<td></td>
<td>$I$ (A)</td>
<td>$V$ (V)</td>
<td>$\dot{m}$ (g/s)</td>
<td>$p_{\text{midc}}$ (kPa)</td>
<td>$q_s$ (W/cm$^2$)</td>
<td>$p_s$ (kPa)</td>
<td>$h_{\text{ob}}$ (MJ/kg) CFD</td>
<td>$h_{\text{ocl}}$ (MJ/kg) CFD</td>
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<td>Runs 14-1–35-1</td>
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<td>1264</td>
<td>25</td>
<td>25.4</td>
<td>58.6</td>
<td>1.74</td>
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<td>13.8</td>
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<td>3401</td>
<td>190</td>
<td>220</td>
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<td>5187</td>
<td>501</td>
<td>558</td>
<td>730</td>
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<td>311</td>
<td>335</td>
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<td>1683</td>
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<td>43</td>
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<td>15.4</td>
<td>19.6</td>
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<td>Runs 3-3, 4-2</td>
<td>716</td>
<td>3681</td>
<td>310</td>
<td>251</td>
<td>114</td>
<td>17.0</td>
<td>7.5</td>
<td>9.4</td>
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<td>AHF 320</td>
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<td>18.8</td>
<td>N/A</td>
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</table>

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 N$_2$ injection at the arc-heater plenum
Comparisons of Computations with Survey Data (step 1, AHF 307)

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

- 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: \( \dot{m} = 25 \text{ g/s}, \ i = 279 \text{ A}, \ p_{\text{mide}} = 27.5 \text{ kPa}, \ p_{\text{box}} = 0.7-0.8 \text{ torr} \)

- 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

$p_{box} = 0.05$ torr

$p_{box} = 0.7$ torr
Comparisons of Computations with Survey Data (step 2, AHF 307)

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

- 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: $\dot{m} = 190 \text{ g/s}, \ h_{ob} = 17.6 \text{ MJ/kg}, \ h_{ocl} = 28.8 \text{ MJ/kg}, \ p_{box} = 0.4 \text{ torr}$

- 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.
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: \( \dot{m} = 501 \text{ g/s}, h_{ob} = 16.4 \text{ MJ/kg}, h_{ocl} = 34.1 \text{ MJ/kg}, p_{box} = 1 \text{ torr} \)

- 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: \( \dot{m} = 500 \text{ g/s}, h_{ob} = 13.9 \text{ MJ/kg}, h_{ocl} = 29.9 \text{ MJ/kg}, p_{box} = 1 \text{ torr} \)

- 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: \( \dot{m} = 310 \text{ g/s}, h_{ob} = 13.6 \text{ MJ/kg}, h_{ocl} = 21.9 \text{ MJ/kg}, p_{box} = 1 \text{ torr} \)

- This case represents a facility condition at relatively high mass flow rate and moderately high enthalpy, and with cold gas injection of \( \text{N}_2 \) 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: \( \dot{m} = 40 \, \text{g/s}, \quad h_{ob} = 15.4 \, \text{MJ/kg}, \quad h_{ocl} = 19.6 \, \text{MJ/kg}, \quad p_{\text{box}} = 0.1 \, \text{torr} \)

- 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: \( \dot{n}_0 = 40 \text{ g/s}, h_{ob} = 15.4 \text{ MJ/kg}, h_{ocl} = 19.6 \text{ MJ/kg}, p_{box} = 0.7 \text{ torr} \)

- 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
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 $p_{\text{box}} = 2$ torr, and the NP heat flux data at $p_{\text{box}} = 0.5$ 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: \( \dot{m} = 310 \text{ g/s}, \ h_{ob} = 7.5 \text{ MJ/kg}, \ h_{ocl} = 9.4 \text{ MJ/kg}, \ p_{box} = 0.5 \text{ torr} \)

- 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 $\text{N}_2$ 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
Acknowledgments

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