Planning for a Supersonic Retropropulsion Test in the NASA Langley Unitary Plan Wind Tunnel

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Background

• Retropropulsion starting at supersonic conditions, or SRP, is enabling for the descent phase of high-mass Mars EDL systems
  – NASA has used supersonic parachutes and subsonic retropropulsion multiple times for Mars robotic landers
  – Tens of metric ton payloads (Curiosity rover = 0.9 t)

• NASA ran high-fidelity aerosciences models against Falcon 9 SRP data (AIAA 2017-5296)

• NASA is preparing for a SRP test in the Langley Unitary Plan Wind Tunnel (UPWT) in 2019

Outline:
• Flight Reference Vehicles
• Test Motivation & Objectives
• Status of Scaling Analysis
• Summary
Current Flight Reference Vehicles

- The planned wind tunnel test will have sub-scale models of one or both current NASA reference Mars vehicles
  - Aerodynamic surfaces will be geometrically scaled, engine nozzles will not
- 8 LO$_2$/LCH$_4$ engines, ~100 kN each, multiple arrangements have been proposed
- The attitude control approach still is TBD, using the main engines and/or separate thrusters

The current trajectory analysis approach is to turn off all AI F&M during propulsive descent. More fidelity is needed going forward.
Sample Flight CFD Results (Low-L/D)

- Time-averaged Loci-CHEM solutions at Mach 2.7 are shown
  - Hundreds of thousands of CPU-hours per powered case
- Pressure coefficient ($C_p$) > 0 produces an aerodynamic axial force ($C_A$), which typically is set to 0 for trajectory analysis
- Are the results realistic? What about moments? Non-zero angle-of-attack? Differential throttling?

**Unpowered**

$C_A = 1.7$ (100% of total)

$C_p$

-2.20
-1.60
-1.00
-0.40
-0.20

**“Single”**

$C_A = 0.58$ (14%)

**“Doublet-B”**

$C_A = 0.93$ (21%)

F. Canabal, NASA MSFC

"Planning for a Supersonic Retropropulsion Test in the NASA Langley UPWT," IPPW-15, Boulder, CO, USA, 11-15 June 2018
Motivation for Wind Tunnel Test

- Predicting aerodynamic interference (AI) forces & moments (F&M) poses a significant challenge for Mars EDL
- Computational fluid dynamics (CFD) is the high-fidelity method for predicting AI F&M, but relevant ground test data to anchor the CFD are scarce

Wind tunnel testing on an appropriately-scaled model would provide valuable data for calibrating CFD tools that currently are used for flight calculations
Scaling for a SRP Wind Tunnel Test

• Most aerodynamic facilities require using an inert gas (typically unheated air) to simulate rocket engine plumes
• Geometric scaling is used on the aerodynamic surfaces
• Jet scaling is used to adjust the nozzle design to account for differences between the flight engine combustion products and the plume simulant gas
• Jet scaling parameters from historical literature (missiles) include:
  - Thrust coefficient, \( \frac{\text{thrust}}{\frac{1}{2} \rho \infty V_{\infty}^2 S_{\text{ref}}} \)
  - Ratio of nozzle exit pressure to freestream stagnation pressure, \( \frac{p_e}{p_{0,2}} \)
  - Ratio of nozzle-to-freestream momentum
  - Ratio of nozzle-to-freestream mass flow rate
  - Many others not listed

\[
p_{0,2} = f(M_{\infty}, \rho_{\infty}, \gamma_{\infty}) \quad \rightarrow \quad p_{0,2} \quad p_e \quad p_c
\]

\( p_c = f(\text{engine design}) \)
\( p_e = f(\text{nozzle design}) \)
Nominal Flight vs. Tunnel Conditions

- The only dimensional flight parameter that overlaps with the UPWT, and only for the Low-L/D vehicle, is freestream Mach number.
- Differences in dynamic pressure can be accounted for in the test design.
- We have recent experience (2010) in the UPWT testing at thrust coefficients that are similar to current flight values.
Scaling of Flight Nozzle (Low-L/D)

- Compare geometric and jet scaling of the 177:1 flight engine on the Low-L/D vehicle to a 5-in diameter wind tunnel model (unheated air plumes)
  - Tunnel test section is approximately 4-feet square

- Results:
  - Geometric scaling gives a small nozzle throat and very low temperature (multi-phase flow)
  - Reducing the tunnel nozzle area ratio is required to eliminate the effects of low gas temperatures at the nozzle exit

- The inability to heat the air significantly (only up to ~350 K) will most likely lead to a nozzle area ratio that is close to what was tested in 2010 (4:1)

<table>
<thead>
<tr>
<th>Nozzle Parameter</th>
<th>Flight</th>
<th>Tunnel Geometric</th>
<th>Tunnel Match $C_T$ and $p_e/p_{0,2}$</th>
<th>Tunnel Match $C_T$ or $p_e/p_{0,2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area Ratio ($A_e/A^*$)</td>
<td>177</td>
<td>177</td>
<td>35.6</td>
<td>4</td>
</tr>
<tr>
<td>Specific Heat Ratio</td>
<td>1.28</td>
<td></td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Throat Diameter (in)</td>
<td>3.01</td>
<td>0.024</td>
<td>0.053</td>
<td>0.159</td>
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<tr>
<td>Exit Mach Number</td>
<td>5.55</td>
<td>7.87</td>
<td>5.45</td>
<td>2.94</td>
</tr>
<tr>
<td>Exit Temperature (K)</td>
<td>841</td>
<td>26</td>
<td>50</td>
<td>128</td>
</tr>
</tbody>
</table>

Differences between inert gases and flight engine combustion products prevent full simulation of hot gas rocket plumes, and require compromises in testing
Sample Tunnel Nozzle Profiles

- There is little experience scaling a flight engine nozzle to wind tunnel model scale where an inert gas is used as the plume simulant
  - It is not yet known if the "standard" jet scaling parameters apply to SRP
- Pre-test analysis is underway to compare single-engine CFD at flight conditions to single-engine CFD at tunnel conditions, to support tunnel nozzle design
  - $A_e/A^* = 4$ was tested in 2010

Matches flight $C_T$ and $p_e/p_{0,2}$
Not an option due to nozzle temperatures

$A_e/A^* = 35.6$

Matches flight $C_T$ or $p_e/p_{0,2}$
Avoids lower temperatures, but only matches one parameter

$A_e/A^* = 4$
Summary

- A SRP test in the NASA Langley Unitary Plan Wind Tunnel will be completed to investigate scaled versions of current human Mars EDL flight reference vehicles

- The test will be conducted in 2019 and will:
  - Investigate the applicability of historical jet scaling laws to SRP
  - Attempt to match CFD-predicted flight AI F&M
  - Provide valuable data on relevant configurations against which current CFD codes will be compared
Backup
**Tunnel Parametrics**

- **Freestream conditions**
  - Mach, dynamic pressure, angle of attack
- **Nozzle parameters**
  - Chamber pressure (up to ~1500 psi)
  - Radial location (1)
  - Throat area (2)
  - Area ratio (2)
  - Cant angle (2)

*Flight Vehicle (A_e/A* = 177)*

*Tunnel Model (Air, A_e/A* = 35.6)*
General Schedule

• The SRP test is one of 5 tests in planning for the UPWT

• Model design (Q3/Q4 of 2018)
  – CFD analysis just started and will be used to investigate flight-to-tunnel nozzle scaling
  – Consider multiple (2?) nozzle area ratios and cant angles for each model

• Test matrix design (Q4 of 2018)

• Model fabrication (Q1 of 2019)

• Testing (Q1/Q2 of 2019)

• CFD analysis and uncertainty quantification (Q3/Q4 of 2019)