Experimental Characterization of Gas/Gas Injector Flowfields

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OUTLINE

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  ➢ Fuel & Oxidizer Preburners
  ➢ Shear Coaxial Injector
  ➢ Rocketdyne Injector
• Experimental Setup
  ➢ Flow Conditions
  ➢ Raman Setup
• Measurements
  ➢ Fuel & Oxidizer Preburner Characterization
  ➢ Raman Measurements to Date
• Summary
OBJECTIVES

- Study Flowfield Characteristics of Gas/Gas Injectors
- Provide Experimental Data to Aid CFD Modeling at NASA Marshall Space Flight Center (MSFC)
APPROACH

• Design/Fabricate Optically-Accessible Rocket Chamber for Uni-element Flowfield Characterization Utilizing Laser-based Diagnostic Techniques

• Fuel and Oxidizer Preburners Provide Realistic Hot-gas Operating Conditions Based On Full-scale Conditions For a Full-flow Engine Cycle
FUEL & OXIDIZER PREBURNER DESIGN

• Preburners Designed to Integrate Directly With Study Injector and Main Chamber
• Each Preburner Has Two Injection Stages:
  ➢ Main O$_2$/H$_2$ Impinging Injector For ‘Hot Core”
  ➢ Downstream Dilution Injectors
• Oxidizer and Fuel Preburners Made With Monel and OFHC Copper, Respectively
• O$_2$/H$_2$ Torch Ignitor For Each Preburner
GAS-GAS INJECTORS

SHEAR COAXIAL INJECTOR

ROCKETDYNE INJECTOR
THE BOEING COMPANY
US PATENT NO. 6,253,539

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ROCKET SETUP

OXIDIZER PREBURNER

MAIN CHAMBER

FUEL PREBURNER
MAIN ROCKET CHAMBER

WINDOW SECTION
MAIN CHAMBER DESIGN

• Heat-sink Design Main Chamber Fabricated with OFHC Copper With 1.5 in. Diameter Internal Cross-section

• Main Chamber Designed for 1000 psia Operation

• Optical Access Provided By Quartz Window

• Modular Design Allows Easy Configuration Changes for Optical Measurements in 0.5 in. Axial Increments

• Water-cooled Nozzle For $O_2/H_2$ Operation At Near Stoichiometric Conditions (~ 6500 R)
# Target Flow Conditions

<table>
<thead>
<tr>
<th></th>
<th>Full Scale Design</th>
<th>Uni-element Experiment*</th>
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</thead>
<tbody>
<tr>
<td>Preburner Propellants</td>
<td>LOX/GH₂</td>
<td>GO₂/GH₂</td>
</tr>
<tr>
<td>Main Chamber Pressure (psia)</td>
<td>3000</td>
<td>750</td>
</tr>
<tr>
<td># of Injection Elements</td>
<td>91</td>
<td>1</td>
</tr>
<tr>
<td>Injector Element Geometry</td>
<td>FULL-SCALE</td>
<td>FULL-SCALE</td>
</tr>
<tr>
<td>Total flowrate per Element (lbm/s)</td>
<td>1.178</td>
<td>0.295</td>
</tr>
<tr>
<td>Ox. Preburner O/F</td>
<td>165</td>
<td>GO₂/GH₂ and H₂O**</td>
</tr>
<tr>
<td>Ox. Preburner Temperature (°F)</td>
<td>~700</td>
<td>~700</td>
</tr>
<tr>
<td>Fuel Preburner O/F</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Fuel Preburner Temperature (°F)</td>
<td>~900</td>
<td>~900</td>
</tr>
<tr>
<td>Injection Velocity</td>
<td>SAME</td>
<td>SAME</td>
</tr>
<tr>
<td>Ox. Preburner/Fuel Preburner Flowrate Ratio</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Total O₂/Total H₂</td>
<td>6.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

* ¼ Pressure Condition  
** Propellants Yield Correct Temperature and Species as Full-scale
RAMAN SPECTROSCOPY

- Used to Determine Major Species Concentrations Downstream of the Rocket Injector
- Modular Rocket Design Allows Optical Access to Be Moved to Various Locations
- ICCD Camera With Bandpass Filters Allows $O_2$, $H_2$, and $H_2O$ Measurements With One Species Per Rocket Firing
RAMAN SPECTROSCOPY

- Raman Signal Specific to Each Species
- Linearly Proportional to Species Number Density
RAMAN SPECTROSCOPY SETUP
(FILTER APPROACH)

Test Cell

1.5 m focusing lens

Instrument Cell

532 nm Nd:YAG Laser

Joule meter

Pulse Generator

Camera Controller

ICCD Camera

Polarizer

Filters

Beam Stop

Rocket Test Section

Image Storage & Processing Computer

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RAMAN FILTERS

- O₂ Filter:  
  Center Wavelength: 581 nm  
  Bandwidth: 10 nm

- H₂O Filter:  
  Center Wavelength: 662 nm  
  Bandwidth: 10 nm

- H₂ Filter:  
  Center Wavelength: 682 nm  
  Bandwidth: 10 nm
SPECIES MEASUREMENTS

(ROCKETDYNE INJECTOR; 0.5 in. AXIAL DISTANCE)
TEMPERATURE PROFILE

(ROCKETDYNE INJECTOR; 0.5 in. AXIAL DISTANCE)
SUMMARY OF INITIAL EXPERIMENTS

• Raman Spectroscopy With Filter Approach Prevented Discrimination of H₂ Rotational Line From O₂ Vibrational Line

• Significant Heat Loss in Preburners Resulted in Lower Temperature Gases Exiting From Both Preburners

• Decision to Run Fuel Preburner at Higher O/F to Obtain Correct Gas Temperature

• Decision to Run Oxidizer Preburner at O/F=165 (GO₂/GH₂) To Hopefully Yield Correct Gas Temperature
PREBURNER TEMPERATURE EXPERIMENTS

• Operated Each Preburner Individually To Assess Hot Gas Temperature
• Thermocouples Mounted at Various Locations Within Preburner Provided Hot Gas Temperatures
• For Fuel Preburner, O/F Was Progressively Increased to Yield Correct Exit Gas Temperature (~ 900 F)
• For Oxidizer Preburner, Only GO₂/GH₂ Propellants Were Used at O/F=165 Since GO₂/GH₂ Runs Hotter Than LOX/GH₂
FUEL PREBURNER ONLY
(TEMPERATURE MEASUREMENTS AT O/F=0.45)

Gas Temperature At Main Injector ~ 350 F
FUEL PREBURNER ONLY

(TEMPERATURE MEASUREMENTS AT O/F=1.12)

Rocket Injector Face
Fuel Preburner
Main Chamber
Rocket Injector
Fuel Preburner (Right Side, Rocket End)
Fuel Preburner (Left Side, Rocket End)

Gas Temperature At Main Injector ~ 900F

Temperature (Deg. F)

0 200 400 600 800 1000 1200 1400 1600 1800 2000

Time (sec)

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OXIDIZER PREBURNER ONLY
(TEMPERATURE MEASUREMENTS AT O/F=165)

Gas Temperature At Main Injector ~ 700 F
# REVISED FLOW CONDITIONS

<table>
<thead>
<tr>
<th></th>
<th>Initial Flow Conditions</th>
<th>Revised Flow Conditions</th>
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</thead>
<tbody>
<tr>
<td>Preburner Propellants</td>
<td>GO_2/GH_2</td>
<td>GO_2/GH_2</td>
</tr>
<tr>
<td>Main Chamber Pressure (psia)</td>
<td>750</td>
<td>750</td>
</tr>
<tr>
<td># of Injection Elements</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Injector Element Geometry</td>
<td>FULL-SCALE</td>
<td>FULL-SCALE</td>
</tr>
<tr>
<td>Total flowrate per Element (lbm/s)</td>
<td>0.295</td>
<td>0.322</td>
</tr>
<tr>
<td>Ox. Preburner O/F</td>
<td>GO_2/GH_2 and H_2O**</td>
<td>GO_2/GH_2 at O/F=165</td>
</tr>
<tr>
<td>Ox. Preburner Temperature (°F)</td>
<td>~400 (measured)</td>
<td>~700 (measured)</td>
</tr>
<tr>
<td>Fuel Preburner O/F</td>
<td>0.45</td>
<td>1.12</td>
</tr>
<tr>
<td>Fuel Preburner Temperature (°F)</td>
<td>~350 (measured)</td>
<td>~900 (measured)</td>
</tr>
<tr>
<td>Injection Velocity</td>
<td>SAME</td>
<td>SAME</td>
</tr>
<tr>
<td>Ox. Preburner/Fuel Preburner Flowrate Ratio</td>
<td>4.0</td>
<td>2.733</td>
</tr>
<tr>
<td>Total O_2/Total H_2</td>
<td>6.0</td>
<td>6.65</td>
</tr>
</tbody>
</table>
RAMAN SPECTROSCOPY SETUP  
(SPECTROMETER APPROACH)

- Allows Single Shot Collection of All Major Species
- Allows Shot-to-shot Comparison of Species Concentrations
- Reduces Ambiguity Regarding Hydrogen Rotational Interference With Oxygen Signal
PRESSURE PROFILE FOR FULL FIRING
(SHEAR COAXIAL INJECTOR, F.P. O/F=1.12, O.P. O/F=1.65)

- Main Chamber (MC) P1
- FP Chamber P1
- OP Chamber P1

Pressure (psia) vs Time (sec)

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RAMAN MEASUREMENTS
(SHEAR COAXIAL INJECTOR; 0.5 in. AXIAL DISTANCE)

RADIAL LOCATION

O₂, H₂O, H₂

WAVELENGTH

+ r

- r

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SPECIES MEASUREMENTS
(SHEAR COAXIAL INJECTOR; 0.5 in. AXIAL DISTANCE)
TEMPERATURE MEASUREMENTS
(SHEAR COAXIAL INJECTOR; 0.5 in. AXIAL DISTANCE)
SUMMARY

• Experimental Testbed For Uni-element Gas/Gas Injector Studies At Realistic Conditions Has Been Fabricated and Verified

• Experiments for Characterizing Mixing/Combustion of Gas/Gas Injectors With Raman Spectroscopy Has Been Initiated
ACKNOWLEDGEMENTS

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