Dual Mode Transition - Experiment

**PIs:** Chris Goyne, Jim McDaniel, Jack Edwards, Hassan Hassan, Ron Hanson and Andrew Cutler

**Research Staff:** Jay Jeffries, Bob Rockwell, Roger Reynolds and Roland Krauss

**Collaborators:** Paul Danehy, Glenn Diskin, Craig Johansen and Toshi Kouchi

**Graduate Students:** Brian Rice, Ben Tatman, Kristin Busa, Chad Smith, Elliott Bryner, Ian Schultz, Chris Goldenstein, Jesse Fulton, Gaetano Magnotti, Luca Cantu, Emanuela Gallo

AFSOR-NASA Hypersonics Fundamental Research Review

National Center for Hypersonic Combined Cycle Propulsion

June 16, 2011
Outline

• Goals and Objectives
• Collaboration and Customers
• Approach
• Research results
  – Hardware
  – Tunnel runs
  – Diagnostics
• Questions
Goals and Objectives
### Experiments and measurement techniques

<table>
<thead>
<tr>
<th>FOCUS AREA</th>
<th>DUAL INLET RIG</th>
<th>DUAL-MODE SCRAMJET (DMSJ)</th>
<th>SCRAMJET</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 - 4</td>
<td>4 - 6</td>
<td>5 - 10</td>
</tr>
<tr>
<td>NASA Glenn (conducted in collaboration with NASA)</td>
<td>University of Virginia Supersonic Combustion Facility</td>
<td>NASA HYPULSE at ATK GASL</td>
<td></td>
</tr>
<tr>
<td>High-speed inlet</td>
<td>Low-speed inlet</td>
<td>Isolator</td>
<td>Combustor</td>
</tr>
<tr>
<td>1) Turbulence-chemistry interaction and the advancement of fuel-air mixing, flame holding and diagnostics</td>
<td>-</td>
<td>-</td>
<td>CARS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PLIF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TDLAS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Tomographic and LOS)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PIV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Schlieren</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High freq. press.</td>
</tr>
<tr>
<td>2) Benchmark data sets for RANS, hybrid LES/RANS, and LES models</td>
<td>High freq. press.</td>
<td>High freq. press.</td>
<td>CARS and Rayleigh</td>
</tr>
<tr>
<td></td>
<td>Low freq. press.</td>
<td>Low freq. press.</td>
<td>PLIF</td>
</tr>
<tr>
<td></td>
<td>Schlieren</td>
<td>Schlieren</td>
<td>TDLAS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Tomographic and LOS)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PIV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Schlieren</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High freq. press. Low freq. press.</td>
</tr>
<tr>
<td></td>
<td>Low freq. press.</td>
<td>Low freq. press.</td>
<td></td>
</tr>
</tbody>
</table>

- PIV: Particle Image Velocimetry
- Schlieren: Shadowgraph
- CARS: Chemical Amplified Rayleigh Scattering
- TDLAS: Tunable Diode Laser Absorption Spectroscopy
- PLIF: Pressure-Locked Imaging Flowfield
- LOS: Line of Sight
Close-coupled collaboration

Experiment

FEA

CFD

National Center for Hypersonic Combined Cycle Propulsion
Collaboration and Customers
Dual-mode Collaboration

• Internal:
  – NCState
  – Stanford
  – GWU
  – UVa (Chelliah)

• External:
  – AFRL: DC DMSJ testing and inlet distortion, PIV
  – TRMC, T&E/S&T Program, APTT: SDPTE (Hy-V)
  – HiFIRE: Flowpath geometry
  – UTRC NASA NRA: H-C combustion
  – NASA Langley: Tomography, PLIF
  – NASA Glenn: CFD (Hy-V ground testing)
  – Embry-Riddle: CFD (Hy-V ground testing)
  – Tohoku University and JAXA, Japan
Model and Database Customers

• External:
  – NASA Hypersonics Project
  – HAPB NASA Langley
  – AFRL Propulsion Directorate
  – TRMC, T&E/S&T Program, APPT
  – NASA Glenn
  – Embry-Riddle
  – Industry partners
Approach
UVa Supersonic Combustion Facility

Capabilities:
- Electrically heated
- Continuous flow
- $T_0 = 1200$ K
- $H_2O$, $CO_2$ & $O_2$ addition
Dual-mode roadmap

Experiments
- 2009: Component data sets H₂, ramp
- 2010: DMSJ datasets w/ isolator H₂, ramp
- 2011: DMSJ datasets w/ isolator H₂, ramp
- 2012: Shock train control
- 2013: Fuel injection schemes

Diagnostics
- 2009: PIV, TDLAS (T, H₂O), TDLAT (T, H₂O)
- 2010: CARS (N₂, O₂, H₂) PIV, TDLAS (T, H₂O), TDLAT (T, H₂O)
- 2011: CARS (+ CO, CO₂, ethylene) PIV, TDLAS (+ CO₂), TDLAT (+ CO₂)
- 2012: CARS PIV, TDLAS (other species TBD), TDLAT

Numerical Modeling
- 2009: Generation 1 RANS
- 2010: Generation 2 LES/RANS and S-FMDF
- 2011: Generation 3 LES and EPV-FMDF

Focus Area 1: Reacting flow
Focus Area 2: Benchmark data
Focus Area 3: Perf. improvements

National Center for Hypersonic Combined Cycle Propulsion
Research Results - Hardware
Dual-Mode Flowpaths

Config. A
Combustor
Extender

Config. B
Combustor
TDLAT
Extender

Config. C
Isolator
Combustor
TDLAT
Extender

Config. D
Isolator
Combustor
Extender

National Center for Hypersonic Combined Cycle Propulsion
Modular DMSJ Flowpath

Mach 2 Nozzle
Isolator
Combustor
TDLAT Section
Extender

Exploded View
Research Results - Tunnel runs
Status

• Baseline design and fabrication completed for Configurations A-D
• Shakedown tests completed for Configurations A and B
• Optical access tested for Configurations A and B
• Thermal distortion and high temp. problems resolved for Configuration A (PIV windows yet to be tested)
• Thermal distortion solution established for Configuration B (tomography section solid walls)
• Pressure and heat flux data obtained for Configurations A and B
• Demonstration of CARS and PIV techniques on Configuration A underway
Thermal-Structural Finite Element Analysis

- Primary Purposes
  - Evaluate and improve hardware mechanical design
  - Validate thermal model by comparison to experiment
  - Provide detailed thermal boundary conditions for CFD

- Model details
  - Ethylene-glycol/water cooling throughout structure
  - Fuel injector side, TDLAT, and solid observation walls are coated with 0.015 in. zirconia TBC
  - Convection coefficients on internal flow path calculated from CFD results
Configuration A Results

Combustor
Extender

Normalized Wall Pressure (P/P_ref)

Pref = 37.0 kPa = Average Pressure at Nozzle Exit
H = 0.25 inches = Fuel Injector Ramp Height
Maximum 95% Confidence Interval = 0.59 kPa

Configuration A, Fuel Off
Configuration A, φ = 0.17

Fuel Injector Wall Temperature (K)

Configuration A, Fuel Off
Configuration A, φ = 0.17

Normalized Axial Distance from Fuel Injection (x/H)
Configuration B Results

Combustor TDLAT Extender

Normalized Wall Pressure (P/Pref)

Pref = 39.7 kPa = Average Pressure at Nozzle Exit
H = 0.25 inches = Fuel Injector Ramp Height
Maximum 95% Confidence Interval = 0.32 kPa

Fuel Injector Wall Temperature (K)

Configuration B, Fuel Off
Configuration B, $\phi = 0.17$

Normalized Axial Distance from Fuel Injection (x/H)
Comparison of Normalized Pressures
Configurations A and B

Normalized Wall Pressure (P/Pres)

H = 0.25 inches = Fuel Injector Ramp Height
Maximum 95% Confidence Interval = 0.59 kPa

Fuel Injector Wall Temperature (K)

Normalized Axial Distance from Fuel Injection (x/H)
H-C cavity and air throttle

- Design completed and fabrication in process
- Ethylene fuel as surrogate for cracked JP fuel
- Air throttle operation demonstrated

![Diagram of H-C cavity and air throttle]
Research Results
- Diagnostics
  - TDLAS
  - CARS and PLIF
  - TDLAT and PIV
Diagnostics for Configuration C

- **a**
  - SPIV, CARS, TDLAS

- **b**
  - SPIV, CARS, TDLAS, PLIF

- **c**
  - SPIV, CARS, TDLAS, PLIF, TDLAT, combustion efficiency

- **d**
  - CARS, TDLAS

- **e**
  - SPIV, CARS, TDLAS, PLIF, TDLAT, combustion efficiency

All dimensions in inches

* = Subject to change
Stanford TDLAS Measurements

- Non-intrusive, *in situ* diagnostics for facility characterization of temperature and combustion product species such as H$_2$O (and CO$_2$ w/HC fuel)
- Inlet plane and exit plane measurements completed
  - Translating measurements across four planes planned for fall 2011
CARS System at UVa

Installation of CARS system

Arrival of laser cart
Tunable Diode Laser Absorption Tomography (TDLAT)

Data analysis completed on initial data set from NRA

Temperature distribution from reconstruction of TDLAT measurements

Center line mole fraction profile from tomographic reconstruction of measurements made on the supersonic combustion tunnel

Mole fraction distribution from reconstruction of TDLAT measurements
TDLAT Upgrades

- Redesign of optics
  - More robust (vibration, shock loading)
  - Better signal quality
  - Improved alignment access

OLD DESIGN

NEW DESIGN

Right Angle Prism Mirror (replaces mirror with hole, preserves part of beam center)

Apertures (reduce interferences)

Retroreflector

National Center for Hypersonic Combined Cycle Propulsion
PIV Seeder Improvement

Design Improvements:

- Robust – fragile pickup-tube is now fully encased
- Easily disassembled for cleaning/maintenance
- Pickup-tube is now straight, shorter and interchangeable
Questions?
Backup
Design Requirements

• Isolator
  – Motivation: Shock-Train Characterization, Shock-b/l interaction
  – Measurement Techniques: PIV and Schlieren
  – Characteristics: Wall to wall optical access, Maximize window length, Minimize window frame obstruction, Modular wall design, re-use parts

• Combustor
  – Motivation: H₂ and H-C combustion
  – Measurement Techniques: CARS, Rayleigh, PLIF, TDLAS, TDLAT, PIV
  – Characteristics: Wall to wall optical access, Maximize window length, Minimize window frame obstruction, Modular wall design, optical access upstream of fuel injection, different types of fuel injection, capacity for high heat loads
Focus Area 1: Reacting flow turbulence statistics and the advancement of fuel-air mixing, flame holding and diagnostics

Progression of dual-mode transition experiments:

1. Component combustor tests
2. Transition induced via combustion of hydrogen
   - Complementary flight data from Hy-V (SDPTE) Program (TRMC)
3. Transition in presence of vitiation (existing data from NASA NRA)
4. Transition with hydrocarbon and hydrogen mixtures (ramp)
5. Transition with hydrocarbon fuel and cavity flame holder
   - Leverage HIFiRE F2 and AFRL configuration data
6. Fuel injection schemes to shorten isolator
Focus Area 2: Benchmark data sets for RANS, hybrid LES/RANS, and LES models

- Capture physics of turbulent reacting flows and transient nature of dual-mode transition
- Spatially and temporally resolved (turbulent flow statistics)
- Measurement of combustion species
- CARS, PLIF, PIV, TDLAS (LOS and tomography)
- Static temp, N\(_2\), O\(_2\), H\(_2\), CO, CO\(_2\), H\(_2\)O, H-C, OH (qualitative), three-component velocity
- Long test time (2 hrs) → point wise statistics converged
Focus Area 3: Performance improvements and control of mode-transition

- Experimental and numerical study of the dual-mode precombustion shock train
- Investigate means of detecting and controlling shock train
- Build comprehensive database (time resolved pressure, three-component velocity field, Schlieren) for isolator
- Use second-generation LES/RANS models to develop real-time shock train control strategies
- Aim at preventing inlet unstart via isolator pressure monitoring, shock train detection and combustor fuel modulation
**TDLAT Spectroscopy**

NTT Electronics fiber coupled PM distributed feedback lasers temporally multiplexed:

| Transition* | Line center Frequency $v_0$ (cm$^{-1}$) | Transition Reference Line strength $S_{ref}$ (cm/molecule) | Lower State Energy Level $E''$ (cm$^{-1}$) | $|E_1''-E_2''|$ (cm$^{-1}$) |
|-------------|----------------------------------------|----------------------------------------------------------|----------------------------------------|--------------------------------------|
| KB1         | 7185.60                                | 7.73E-22                                                | 1045.10                                | 744.9                                |
| KB2         | 7444.36                                | 4.44E-23                                                | 1790                                   |                                      |

Simulated absorption spectra from HITRAN 2006 for:
- $T = 850$ K
- $P = 1$ atm
- $X_{H2O} = .12$

Higher $E''$ to minimize ambient water absorption

$\geq 700$ cm$^{-1}$ for good temperature sensitivity

*Designations of transitions are used only for convenience in referencing transitions.*
Tunable Diode Laser Absorption Tomography (TDLAT)

Planned work and Schedule

- **UVa**
  - Improve fundamental spectroscopy
    - Design ✔️, fabricate ✔️, test (in progress) new optical system
    - Optimize data acquisition and motion control system (~11 min per run) ✔️
    - Reconfigure analysis code for more accurate reconstructions (in progress)
    - Develop numerical simulation tool to examine reconstruction artifacts (July)
    - Benchtop test on flat flame burner (August)
    - Design new mounting hardware for the new MSCT (November)
    - Measurement at exit of new MSCT (January 2012)

- **NASA Langley**
  - Utilize TDLAT system for measurements on NASA Langley direct-connect facility (August, October)
    - Optimize data acquisition and motion control system for shorter facility run times (~40 sec per run) ✔️
    - Expand data acquisition and motion control system to accommodate 5 simultaneous measurement points (in progress)
    - Design and fabricate additional mounting hardware (in progress)
PIV Seeders

Freestream seeder

Fuel seeder

![Freestream seeder](image1)

![Fuel seeder](image2)

![Graph 1](image3)

![Graph 2](image4)