Development of Criteria for Flameholding Tendencies within Premixer Passages for High Hydrogen Content Fuels

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UTSR Workshop
Oct 4, 2012
Contract DE-FE0007045; Joe Stoffa, Contract Monitor

Outline

• Motivation
• Background
• Research Questions and Project Goal
• Approach and Schedule
• Test Rig Development
• Current Status
Motivation

- Trends in Advanced Lean Burning Gas Turbines*
  - Higher Combustor Inlet Temperatures
  - Improved Fuel/Air Mixing
  - Risk of Auto-Ignition/Flashback
  - Role of Fuel Type/Composition

Major Question

If a Reaction is Initiated in the Premixer, Will the Reaction be “Held” on a Wall Recess?

* Stationary Gas Turbine Engines
Motivation

High Hydrogen Content Fuels On N.G. injectors

Desired: Tools to guide premixer design for robustness relative to flame attachment and disgorgement

Background

- Large Body of Literature on Blowoff / Flameholding
- Findings
  - Only ~25% Focus on Natural Gas, <10% Hydrogen
  - Most Focus on Centerbody Stabilization vs. Wall Effects
  - Most Seek How to Stabilize, Not How to Avoid
- Studies of Particular Relevance
  - Cambel, et al. (1957, 1962)
  - Wall Perturbations
  - Limited Conditions
  - Propane
  - No Variation in Temperature
  - No Variation in Pressure
  - No Geometry Effect Noted
  - No Fuel Effects
  - No Vitiation Effects
Background

Large Body of Literature on Blowoff/Flameholding

- Findings
  - Only ~25% Focus on Natural Gas, <10% Hydrogen
  - Most Focus on Centerbody Stabilization vs. Wall Effects
  - Most Seek How to Stabilize, Not How to Avoid

- Studies of Particular Relevance
  - Cambel, et al. (1957, 1962)
    - Wall Perturbations
    - Limited Conditions
  - Cambel suggested mechanism “similar to centerbody stabilized”
  - If true....correlation work for CB Stabilized
    - Damköhler scaling seems to capture behavior
    - e.g., work of Lefebvre, others
    - e.g., Shanbhogue, Husain, and Lieuwen

\[
\phi_{LBO} = \left\{ \frac{2.25 \left[ 1 + 0.4U \left( 1+u' \right) \right]}{P^{0.25} T_o e^{-r/150} D_x \left( 1-B_r \right)} \right\}^{0.16}
\]

Ballal and Lefebvre, 1979
Research Questions

Major Question
If a Reaction is Initiated in the Premixer,
Will the Reaction be “Held” on a Wall Recess?

Related Question #1
To What Extent do “Damköhler Type” expressions (based mainly on bluff body stabilized flames) apply to “small” wall recesses and/or perturbations?
(Wall quenching/heat transfer mechanism should influence situation more so than bluff body situation)

Research Questions

Major Question
If a Reaction is Initiated in the Premixer,
Will the Reaction be “Held” on a Wall Recess?

Related Question #2
If the reaction holds on a wall feature, what is required to dislodge it (experience suggests strong hysteresis)
Research Questions

Major Question

If a Reaction is Initiated in the Premixer,
Will the Reaction be “Held” on a Wall Recess?

Related Question #3

What is role of T, P, fuel composition, and level of vitiation?

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Research Questions

Major Question

If a Reaction is Initiated in the Premixer,
Will the Reaction be “Held” on a Wall Recess?

Related Question #4

How does the geometry of the wall feature affect the flameholding tendency?
Project Goal

- Develop design guides to predict flameholding tendencies within premixer passages as a function of:
  - Pressure
  - Temperature
  - Fuel Type/Composition
  - %O₂ in the air (vitiation levels)
  - Geometry Features

Approach and Schedule
Approach

- Preparation
  - Fuel/Module Selection*
  - Fabrication
  - Diagnostics / Rig Setup
  - Commissioning

- Experimental Studies

- Analyze and Correlate Results

*Input from OEMs in early stages of project

Preparation

- The test rig will leverage existing high pressure testing capability developed through support of NASA, DOE, and industry
UCICL HIGH PRESSURE FACILITY 1/08
AIR & NATURAL GAS SYSTEMS

4 lb/s air; 1000 deg F preheat; diluents (stored tanks)
Pressures to 18 atm

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UCICL HIGH PRESSURE FACILITY 1/08
WATER QUENCH & DI WATER SYSTEMS

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Test Rig Development

- Initial test plan envisioned using an existing “go/no go” test section

Current Project:
High Speed OH* Imaging will be used as well
Phantom 7.2 CMOS w/ external intensifier
Test Conditions

Test Conditions

- Pressure: Up to 7 atm (*more if possible*)
- Velocity: Up to 70 m/s (*higher if possible*)
- Preheat: 500°F-1000°F (may be limited by autoignition)
- Fuel: $\Phi=0.6-1.0$
  - Hydrogen Containing Fuels (expected to be limiting case)
  - Natural Gas Fuels

*Input from OEMs in early stages of project

Test Rig Development

- Initial test plan envisioned using an existing “go/no go” test section

- Discussions with OEMs indicated a mismatch with desired test conditions
  - Limited to 6 atm, 60 m/s
Updated Test Section

• While available test section seemed attractive…..
  – Too large to hit the desired velocities and pressures

Velocity/Turbulence Mapping
Velocity/Turbulence Mapping

- Mean Velocity

2 atm, 100 ft/s

2 atm, 200 ft/s

7 atm, 165 ft/s

Velocity/Turbulence Mapping

- $u'/U$

2 atm, 100 ft/s

2 atm, 200 ft/s

7 atm, 165 ft/s

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**Fuel Distribution**

- [HC], ppm

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**Updated Test Section**

- While available test section seemed attractive.....
  - Too large to hit the desired velocities and pressures
  - Insufficient flow conditioning/fuel distribution
    - Need to revise injection strategy

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2" x 2"
Facility Air Flow = f(Vel, T, P)

Facility Preheating T = f(Vel, P)

OEM Input: higher velocity → mass flow → iterate on cross section

OEM Input: 1000 F acceptable → velocity → iterate on cross section
Facility Heat Rejection = f(\phi, Vel, T, P)

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Managing required heat rejection:
Actual run times not expected to be long enough to require full heat rejection

Updated Test Section

- While available test section seemed attractive.....
  - Too large to hit the desired velocities and pressures

Updated Test Section
1.76” x 0.76”
Hits velocities at temperatures of interest while allowing sufficient heat rejection

2” x 2”
Test Section Sizing

Is 1.76" x 0.76" cross section representative of engine premixing sections?

GE DLN
Test Section Sizing

Is 1.76” x 0.76” cross section representative of engine premixing sections?

Siemens Gas Injector/Premixer

Updated Test Section

• While available test section seemed attractive.....
  – Too large to hit the desired velocities and pressures
  – Insufficient flow conditioning/fuel distribution
    • Need to revise injection strategy
Flow Development

- Previous test section had poor velocity and fuel distributions. Attributed to short entrance length.
- The proper entrance length is calculated as:

Entrance Length Calculation:

For rectangular pipes use hydraulic diameter:

\[ L_e = 4.4DRe^{\frac{1}{2}} = \frac{\rho \nu D}{\mu} \]

Where P is the perimeter: \(2(L+W)\). Reynolds number is then:

\[ Re = \frac{4\nu}{\mu} \]

Entrance length is:

\[ L_e = 4.4 \cdot \frac{4\nu}{\mu} \left( \frac{4\nu}{\mu} \right)^{\frac{1}{2}} = 4.4 \left( \frac{4\nu}{\mu} \right)^{\frac{1}{2}} \left( \frac{4\nu}{\mu} \right)^{\frac{1}{2}} = 8.8 \left( \frac{L+W}{\mu(L+W)} \right) \]

Substituting in dimensions:

\( L = 1.76'' = 0.0447m \)
\( W = 0.76'' = 0.0193m \)
\( \nu = 1.3 \text{ lb/s} = 0.59 \text{ kg/s} \)
\( \mu (500\text{F}) = 2.8 \times 10^{-5} \text{ Ns/m}^2 \)

\[ L_e = 8.8 \left( \frac{0.0447(0.0193)}{2(0.59)} \right)^{1/2} = 8.8 \left( \frac{0.0447(0.0193)}{2(0.59)(2.8 \times 10^{-5})} \right)^{1/2} = (0.1118)(0.658 \times 10^{-5})^{1/2} \]

\[ L_e = 1.11m = 44'' \]
Updated Test Section

While available test section seemed attractive.....

- Too large to hit the desired velocities and pressures
- Insufficient flow conditioning/fuel distribution
  - Need to revise injection strategy
- Limited Optical Access??

Optical windows and test feature have same base so that the test feature can be moved upstream or downstream of ignition source

Round base of test feature insert allows test feature to be rotated
Updated Test Section

Flow

Pilot Fuel Port
Igniter Port
Tube-Insert Windows
Pressure/Temperature Ports

Flow

Insert for turbulence generating panel

Round windows can either be used for optical access or test feature inserts

Test Rig Assembly

Fuel

Test Section with three optical access points on two plains

Pilot Fuel

Air
Initial Test Features*

Reverse Step

Rivet/bolt-exposed length can be varied by loosening swage fitting on underside

Vane/Strut- Feature can be rotated

* Based on OEM Input

Status

Test Section Development: 80% Complete
Test Facility Interfacing: 60% Complete
Ready For Commissioning: end of 2012

Flameholder Test Section

Flameholder Flow Developer
## Status

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<th>Year 2</th>
<th>Year 3</th>
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