An experimental study has been conducted at the Air Force Research Laboratory (AFRL) at Edwards Air Force Base to explore the coupling between a coaxial jet flame and transverse acoustic perturbations. A new experimental facility at AFRL was used to expose a single H2/O2 shear coaxial diffusion flame to controlled acoustic resonances. A variety of chamber conditions including acoustic resonance properties were considered. The acoustic frequency and amplitude were selected relative to the characteristic frequency and dynamic pressure of the reacting injector flow. Placing the flame within the pressure node and antinode was also considered. Diagnostics employed high-speed imaging including backlight visualization and OH* chemiluminescence. The images were analyzed using proper orthogonal decomposition to identify the natural frequencies and organized structure of the unforced jet flame. These techniques were used to elucidate the effects of forcing, including the structure and relative importance of forced modes relative to the natural flame behavior.
The Response of Cryogenic H2/O2 Coaxial Jet Flames to Acoustic Disturbances

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Outline

• Background and objectives
• Experimental facility
  • Overview of features
  • Current operating conditions
• Unforced characteristics
  • With and without flame
  • Spectral features
• Forced flame results
  • With and without flame
  • Pressure node and antinode
  • Dynamic mode decomposition analysis
• Conclusions and future work
Background

- Combustion systems can no longer be designed to meet modern requirements without considering system dynamics.

- Combustion dynamics always includes acoustic waves, and in enclosed systems, acoustic waves can often reach detrimental amplitudes—e.g., combustion instabilities.

- Achieving modern thermodynamic efficiencies requires achieving increasingly higher chamber pressures, sometimes exceeding the critical pressure of the reactants—e.g., liquid rockets, future gas turbines.

- When the combustion systems are for propulsion, limited tankage dictates that on-board propellants be stored in condensed form—e.g., kerosene, liquid oxygen in rockets.
Objectives

• Accordingly, we consider here the dynamics of a high pressure, chemically reacting, multiphase, acoustically driven shear flow in the form of a coaxial jet flame
  – Canonical flow
  – Geometry is applicable to liquid rockets
  – Subcritical and supercritical pressures
  – With and without acoustic waves at various amplitudes
  – Traceable to past research on non-chemically reacting coaxial jets
  – Liquid oxygen and gaseous hydrogen, also applicable to liquid rockets
    • Future: kerosene

• Objectives
  – Effect of variations in the above quantities; regime maps
  – Effect of the presence of chemical reactions; comparison between cold and hot
  – Effect of the presence of neighboring coaxial jet flames
**Coaxial Jets/Flames**

**Geometry parameters**

- **Area ratio**
  \[ AR = \frac{D_3^2 - D_2^2}{D_1^2} \]
- **Dimensionless post thickness**
  \[ t \frac{D_1}{D_1} \]

**Flow parameters**

- **Reynolds number**
  \[ \text{Re}_i = \frac{\rho_i U_i D_1}{\mu_1} \]
  \[ \text{Re}_o = \frac{\rho_2 U_2 (D_3 - D_2)}{\mu_2} \]
- **Jet mass ratio**
  \[ J = \frac{\dot{m}_i}{\rho_i U_i^2} \]
  \[ r = \frac{U_2}{U_1} \]
- **Mixing ratio**
  \[ MR = \frac{\dot{m}_i}{\dot{m}_o} \]
  \[ s_1 = \frac{\rho_2}{\rho_i} \]
  \[ s_2 = \frac{\rho_3}{\rho_2} \]

**Inflow boundary conditions**

- Mean velocity profiles
- RMS fluctuation profiles
- Spectral content

**Acoustic frequencies**

1. **Transverse Acoustic mode from chamber/siren**
   - \( f = f(c, \text{geometry}) \)

2. **Acoustic modes propellant lines**
   - \( f \sim c/2L \)

**Hydrodynamic frequencies**

1. **Post wake**
   - \( St = ft/U_{ch} \)

2. **Shear layer instabilities**
   - \( St_q = f\theta/U_{ch} \)

3. **Jet preferred modes**
   - \( St = fD_{ij}/U_{ij} \)
Feedback loop

Control volume

Acoustic waves

Fluid dynamic instability

Unsteady Heat release

Break this link

Frequency and amplitude controlled independently

New Experimental Facility

Features

– Frequency and amplitude independent of combustion – accurate control of frequency and amp.
– Pressurization independent of combustion – accurate control of pressure.
  • Subcritical and supercritical pressures
– Precise cryocooler – accurate control of temperature to within ±1 K.
– Chamber-within-a-chamber
  • Outer chamber contains pressure – pressure containing elements remain cool
  • Inner chamber contains acoustics and combustion only – allows finer adjustment of inner elements
– High amplitude piezosirens specially designed for high pressure
– On-axis windows for shadowgraph, Schlieren, chemiluminescence, OH* emission
– Off-axis windows for PIV/PLIF
– Fully developed turbulent injector flows – well known boundary conditions
Receptivity

- Shift pressure normalization from chamber pressure to injector dynamic pressure
- Normalize the frequency by the preferred mode of the coaxial jet
- Identify receptivity inception point—threshold for coupling between acoustics and flame

\[ \frac{P'}{\bar{P}} \rightarrow \frac{P'}{\rho U^2 / 2} \]

\[ F = \frac{f_{\text{forcing}}}{f_{\text{jet}}} \]

Curves depend on frequency ratio

Inception point

Local slope: sensitivity

Inception point

Local slope: sensitivity

Heat release fluctuation amplitude q'/Q

Dimensionless acoustic amplitude \[ \frac{p'}{1/2 \rho U^2} \]

Dimensionless acoustic amplitude \[ \frac{p'}{1/2 \rho U^2} \]
Receptivity Study

Just completed a detailed receptivity study on nonreacting coaxial jets (Wegener Ph.D.)

- Scaling law for preferred mode frequency for coaxial jet
- Verified characteristic velocity for frequency scaling law
- Receptivity characteristics for pressure node and anti node conditions for two momentum flux ratios
Receptivity

\[ u'(m/s) \]

**J = 2**

- **Pressure node**
  - Forced
  - Natural

- **Pressure antinode**
  - \( \frac{p'}{1/2 \rho U^2} \)
  - Forced
  - Natural

**J = 6**

- **Pressure node**
  - Forced
  - Natural

- **Pressure antinode**
  - \( \frac{p'}{1/2 \rho U^2} \)
  - Forced
  - Natural

Approved for public release; distribution unlimited
Experimental Conditions

- New injector
  - \( D_1 = 1.4 \text{ mm} \)
  - \( \text{AR} = 1.68 \)
  - \( t/D_1 = 0.27 \)
- \( \text{MR} = 6 \)
- \( J = 2.7 \)
- Liquid O\(_2\) inner jet @ 130 K
- Gaseous H\(_2\) @ 250 K
- \( \text{O}_2 \) velocity: 3 m/s
- \( \text{H}_2 \) velocity: 83 m/s
- \( \text{O}_2 \) Re \( \approx 4.7 \times 10^4 \)
- \( \text{H}_2 \) Re \( \approx 2.2 \times 10^4 \)
- Fully-developed turbulent flow conditions
- Chamber pressure 3.4 MPa (500 psi) \( \rightarrow \) subcritical
Results

• Unforced cases
  – With and without the flame
  – Qualitative features
  – Spectral characteristics

• Forced cases
  – With and without the flame
  – Dynamic mode decomposition (DMD) isolation of the forced mode characteristics
  – Pressure node and antinode cases
  – Different frequencies
Unforced Jet/Flame Behavior

Unfiltered backlit/chemiluminescence

H₂/O₂ no flame

H₂/O₂ with flame

Water condensation on the window
Spectral Features of Unforced Cases

Shear layer?  
$x/D_1 = 4$

Coaxial jet preferred mode  
$x/D_1 = 7$

$x/D_1 = 8$
Spectral Features of Unforced Cases

x/D₁ = 4

x/D₁ = 7

x/D₁ = 8
Spectral Features of Unforced Cases
Forced Jets/Flames

Pressure node forcing
1950 Hz, 1.5 V input

H₂/O₂ no flame

H₂/O₂ with flame

Flame dramatically attenuates the flapping of the jet column, and the LOX core is apparently much longer.
Forced Flames

Pressure node forcing

Voltage input to amplitude

0 V  0.5 V  1.0 V  1.5 V  2.0 V

Increasing forcing strength
DMD Reconstructions

Decomposition/reconstruction Form:

\[ I(x, y, t) = \bar{I}(x, y) + \text{Re} \left( \sum_{i=1}^{n} \tilde{A}_i \exp(\tilde{\lambda}_i t) \tilde{D}_i(x, y) \right) \]

- Mean image
- Real part only
- Complex constant
- Complex spatial DMD modes
- Complex time dependence

Reconstructions with:

- 2 modes
- 10 modes
- 100 modes
- 248 (all) modes

0 < x/D_1 < 10
Original data
Dynamic Mode Decomposition

Dynamic mode decomposition (DMD) applied to first 10 inner jet diameters

Pressure node, max forcing, 1950 Hz

Forced mode

Convective flame structures

Amplitude

real

imaginary

f (Hz)
Dynamic Mode Decomposition

Dynamic mode decomposition (DMD) applied to first 10 inner jet diameters

Pressure node, max forcing, \textbf{3090 Hz}

Forced mode

Reduced relative amplitude, degraded receptivity?

Convective flame structures

Higher wavenumbers
Forced Flames

Pressure antinode forcing

Voltage input to amplitude

0 V  0.5 V  1.0 V  1.5 V  2.0 V

Increasing forcing strength
Dynamic Mode Decomposition

Dynamic mode decomposition (DMD) applied to first 10 inner jet diameters

Pressure antinode, max forcing, 1900 Hz

real
imaginary

Amplitude

f (Hz)
Dynamic Mode Decomposition

Dynamic mode decomposition (DMD) applied to first 10 inner jet diameters

Pressure antinode, max forcing, **2950 Hz**
DMD Reconstructions

Pressure antinode, max forcing, **2950 Hz**

- 2 modes
- 4 modes
- 6 modes
- 10 modes
- 100 modes
- 548 modes
Convection Velocities

\[ U_c = f \lambda \]

Burning structures travel slower than the estimated convection velocity based on the Dimotakis (1986) expression of 7.5 m/s.

\[ U_c = \frac{\rho_1^{1/2} U_1 + \rho_2^{1/2} U_2}{\rho_1^{1/2} + \rho_2^{1/2}} \]
Conclusions

• **Unforced reacting and nonreacting** \( \text{H}_2/\text{O}_2 \) **flows**
  • Flame appears to delay mixing and lengthen the liquid core length
  • Slight changes in spectral content

• **Forced flames**
  • Qualitatively similar to nonreacting forced coaxial flows
  • Pressure node forcing
    • Flame response is antisymmetric
    • Potentially degraded response at higher frequency
  • Pressure antinode forcing
    • No obvious changes in the raw images
    • DMD extracts the spatial mode responding to the forcing
  • Response seems to be tilted axisymmetric mode or possibly a combination of axisymmetric and helical modes
What’s Next?

• More detailed quantification of the spectral content in unforced coaxial jet flames
  • Effects of flame sheet on frequency content
  • Isolation and scaling of dominant “preferred modes”
  • Search for injector conditions with strong inner-post wake instabilities

• Forced flames
  • Detailed exploration of relative frequency and amplitude
  • OH* chemiluminescence
  • Different injector flow conditions
  • Quantitative optical diagnostics (OH PLIF)
Dynamic mode decomposition (DMD) applied to first 10 inner jet diameters

Pressure antinode, max forcing, **2950 Hz**

Convective flame structures

**real**

**imaginary**
New Experimental Facility

Capabilities

- Cryogenic propellant temperature control with high accuracy (±1 K)
- Sub- and super-critical chamber pressure ($p_c$ up to 10.4 MPa)
- High amplitude acoustic forcing ($p'/p_c$ ~ 0.02)
- Coaxial injector with extended length for fully developed turbulent flow ($l_e/D > 110$)
- High-speed diagnostic tools
  - Pressure transducer(s) natural frequency > 100 kHz
  - Time-series backlit imaging ($f > 25$ kHz)
  - Off-axis windows for future PIV/PLIF measurements