Purdue PGC Research Team

Postdoctoral Researchers:
Dr. Rohan Gejji,
Dr. Swanand Sardeshmukh

Ph.D. student:
Brandon Kan

M.S. Students:
Kyle Schwinn,
Ian Walters

Steve Heister,
Professor (co-PI)

AFOSR Team

UTSR Team

Carson Slabaugh,
Assistant Professor (co-PI)

David Stechmann,
Ph.D. student

Kota Mikoshiba,
Ph.D. student

Wes Anderson,
Ph.D. student

Dasheng Lim,
Ph.D. student

Jenna Humble
M.S. student

School of Mechanical Engineering
School of Aeronautics and Astronautics
Project Objectives

We seek to understand the nature of injection, mixing, and ignition in rotating detonation combustion processes through the application of advanced measurement techniques. This information will enable the development of predictive models describing these dynamics, which will be verified with experiments at representative cycle conditions.

- Task 1.0: Program Management
- Task 2.0: Injection Dynamics Characterization
- Task 3.0: Subscale Combustor Development
- Task 4.0: Evaluation of Pressure Gain
- Task 5.0: Detailed Inlet/Exhaust Measurements
- Task 6.0: Emissions Measurements
- Task 7.0: Model Development
Progress After Year 1

- **Task 2.0: Injection Dynamics Characterization**
  - Overview of the DRONE experiment
  - Results from early testing
- **Task 3.0: Subscale Combustor Development**
  - APEX test stand design status
  - Test article configuration discussion
- **Task 4.0: Evaluation of Pressure Gain**
- **Task 5.0: Detailed Inlet/Exhaust Measurements**
- **Task 6.0: Emissions Measurements**
- **Task 7.0: Model Development**
  - Injection Dynamics Models
  - 2-D Combustion Model
  - Comprehensive 3-D Model

Iso-surfaces of $M = 1.35$ shaded by equivalence ratio from 3D LES of single fuel-injector hole-pair.

School of Mechanical Engineering
School of Aeronautics and Astronautics
DRONE System Overview

Detonation Initiator System

Semi-Bounded Detonation Channel

Multi-Pulse Detonation Injector

Instrumented Window Blank

Optical Window

Open End-wall

Reactant Manifolds

School of Mechanical Engineering
School of Aeronautics and Astronautics
DRONE System Overview

- Designed to enable high-fidelity imaging measurements in the reaction zone
  - Planar Laser-Induced Fluorescence
  - Focused Schlieren
- Methane – Oxygen (GOx)
- Ambient Initial Conditions
- Nominal Cell Size
  - $\lambda = 2.5\ mm$
- Nominal (Ideal) Wave Speed
  - $u_{CJ} = 2390\ m/s$
Staggered Fuel Injection Holes with Central Oxidizer Slot

Injection Pressure Drops Tuned Between Fuel and Oxidizer for Staged Dynamic Response

Single Plate Injector Sandwiched Between Walls and Manifolds
Channel Forcing with Detonator

- Controlling Multi-Pulse Flashback by Staggering Tube Exit into the Detonation Channel
- Modulating Pulse-Separation Delay Lines of Branched Detonation
- Exploiting Dynamic Response of Injector to Refill Channel for Successive Pulses.
Channel Forcing with Detonator

$t = 0 \mu s$  $t = 20 \mu s$  $t = 40 \mu s$  $t = 60 \mu s$

$t = 80 \mu s$  $t = 100 \mu s$  $t = 120 \mu s$  $t = 140 \mu s$
System Integration

Complete DRONE Assembly
School of Mechanical Engineering
School of Aeronautics and Astronautics

DRONE with Optomechanical Structure
School of Mechanical Engineering
School of Aeronautics and Astronautics
First Hot-Fire

- Transient system response was acceptable:
  - $\phi = 0.92$
  - $\frac{\dot{m}}{A_{chamber}} = 75 \frac{kg}{s m^2}$

- A periodic oscillation developed after $\approx 50 ms$
  - Remained throughout the entire test

- Fluctuation amplitudes $\approx 10 - 30 \ psi$
  - Measured with flush-mounted PCB transducers installed into the combustion chamber wall.

School of Mechanical Engineering
School of Aeronautics and Astronautics
### Flow Conditions:

<table>
<thead>
<tr>
<th>$\dot{m}_o$</th>
<th>$\dot{m}_f$</th>
<th>$\phi$</th>
<th>$\dot{m}/A_c$</th>
<th>$u_{CJ}$</th>
<th>$u_i$</th>
<th>$u_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.39 \frac{kg}{s}$</td>
<td>$0.054 \frac{kg}{s}$</td>
<td>0.58</td>
<td>$101 \frac{kg}{s} \frac{1}{m^2}$</td>
<td>$2080 \frac{m}{s}$</td>
<td>$(1948) \frac{m}{s}$</td>
<td>$(1573) \frac{m}{s}$</td>
</tr>
</tbody>
</table>
Dynamic Mode Decomposition of the images reveals strong coherence in spatio-temporal dynamics.

- Fundamental mode at 6740 Hz
- Strong periodic content at the harmonics.

Transverse motion of the combustion wave is well-resolved

- Injection, ignition, ... and transition
Observing DDT
- Acceleration along the injector face
- Steepening and coalescence

Product mixing causes contact ‘pocket’ deflagration

Instantaneous flow-field visualization
Exploring Parameter Space

**23 Conditions Tested**
- Parametric variation of mass-flux ($\sim M_c$) and equivalence ratio
- Heavily-instrumented with transducers and ion probes in the chamber as well as the propellant manifolds.
- Focused Schlieren in the (upstream) window location

**Unanimously consistent, self-excited, high-frequency instabilities**

<table>
<thead>
<tr>
<th>Case</th>
<th>$\dot{m}/A_C$</th>
<th>$\phi$</th>
<th>$u_{CJ}$</th>
<th>$u_i$</th>
<th>$u_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$77.5 \frac{kg}{s} \frac{1}{m^2}$</td>
<td>0.95</td>
<td>$2360 \frac{m}{s}$</td>
<td>$2300 \frac{m}{s}$</td>
<td>$1500 \frac{m}{s}$</td>
</tr>
<tr>
<td>$B$</td>
<td>$108 \frac{kg}{s} \frac{1}{m^2}$</td>
<td>0.58</td>
<td>$2080 \frac{m}{s}$</td>
<td>$1950 \frac{m}{s}$</td>
<td>$1570 \frac{m}{s}$</td>
</tr>
<tr>
<td>$C$</td>
<td>$105 \frac{kg}{s} \frac{1}{m^2}$</td>
<td>1.24</td>
<td>$2500 \frac{m}{s}$</td>
<td>$2400 \frac{m}{s}$</td>
<td>$1250 \frac{m}{s}$</td>
</tr>
</tbody>
</table>
Typical test sequence

- 500 – 900 ms of combustion
- Nitrogen purge pre- and post-
- Oxygen-lead with timed fuel injection relative to ignition
- Some transience in both reactant supplies from regulator response

Good agreement in measured absolute pressures within manifold

- GE UNIK-5000s sampled at 500 Hz
- Kulite WCT-312Ms sampled at 500 kHz
School of Mechanical Engineering
School of Aeronautics and Astronautics

Wave-Form Comparison

<table>
<thead>
<tr>
<th>Condition</th>
<th>$\dot{m}/A_c$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$77.5 \frac{kg \ 1}{s \ m^2}$</td>
<td>0.95</td>
</tr>
<tr>
<td>$B$</td>
<td>$108 \frac{kg \ 1}{s \ m^2}$</td>
<td>0.58</td>
</tr>
<tr>
<td>$C$</td>
<td>$105 \frac{kg \ 1}{s \ m^2}$</td>
<td>1.24</td>
</tr>
</tbody>
</table>
Weak Chamber Dynamics

- **Condition A**
  - Near Stoichiometric
  - Lowest Mass flux
  - Very little distinction in spectral content measured at different locations.
  - Effects of amplitude modulation evident.
Narrowband Amplification

**Condition B**
- Fuel Lean ($\phi = 0.58$)
- Increased Mass Flux
- Strong periodic content, even at the closed end.
- Steepening and amplification of the wave across the injector face
- Fundamental frequency = 6760 Hz

**HF-CC-01**

**HF-CC-02**

School of Mechanical Engineering
School of Aeronautics and Astronautics
(More) Narrowband Amplification

HF-CC-01

- Condition C
  - Fuel Rich ($\phi = 1.24$)
  - Increased Mass Flux
  - Strong periodic content, even at the closed end with increase strength of harmonic content across the injector face
- Increased fundamental frequency
  - 10050 Hz

HF-CC-02

School of Mechanical Engineering
School of Aeronautics and Astronautics
Oxidizer Manifold Coupling (?)

- Oxidizer manifold shows no clear presence of these frequencies
  - At condition C, there exists a very weak peak at 10050 Hz, only during the hot-fire.
  - In general, there is no shared frequency with the chamber PSD

\[ \bar{p}_{ox} \approx 50 \text{ psi}_a \]
\[ p'_c \approx 50 \text{ psi} \]
Fuel Manifold Dynamics

- The fuel manifold couples very strongly with the chamber dynamics.
  - No significant coherence in the pre-combustion spectral content
  - Exact correspondence to the chamber measurements once combustion is initiated

- This is despite the fact that the mean fuel manifold pressure is significantly greater than the oxidizer manifold pressure.
Imminent Measurements in DRONE

Planar laser-induced fluorescence
- OH (10 kHz, with DPSS)
- CH2O (10-100 kHz, with MOPA-PBL)
- Simultaneous Schlieren
- Resolving flame structure

MOPA-PBL System online
- $O(10^2)$ Increase in Pulse Energy at 10 kHz Repetition Rate

Tradeoff with DPSS
- Complexity
- Signal Strength
- Resolution (in time and space)
Further exploration of multi-kHz excitation mechanisms:
- Injection, mixing, ignition, and DDT
- Manifold-chamber coupling

Translation of this understanding into a reduced-order, system model:
- Working towards a design tool for an unsteady combustor

Concept for a longer, (more) modular DRONE
Scaling to Cycle Conditions

- Leveraging of that model into the second phase of this experimental work, at high pressure.
  - Subscale Combustor Development
  - Evaluation of Pressure Gain
  - Detailed Inlet/Exhaust Measurement
  - Emissions Measurements

Rendering from high-pressure build-up
To bring RDE to production, we desperately need system model.

- How does performance (# of waves) change with throttle setting?
- How does injector response influence performance?
- How does manifold response influence performance?
- How does chamber length/width influence performance?
- How does engine start?

System response is primarily due to:

- Injection system dynamic response
- Transient mixing characteristics
- Propellant combination, operating conditions, etc...
Injector Response Crucial Element of Operability Model

Fuel Injector Response

Air Injection Response

Pressure waves propagating upstream into manifold

School of Mechanical Engineering
School of Aeronautics and Astronautics
Mixing Profile Affects Wavespeed

- CEA calculation at $\phi=1$ with portion of propellants inerted for C-J calculation
- Measured wavespeeds agree with trend – larger number of waves has smaller amount of time to mix

$$V_{CJ} = \sqrt{2(\gamma^2 - 1)Q}$$

School of Mechanical Engineering
School of Aeronautics and Astronautics
School of Mechanical Engineering
School of Aeronautics and Astronautics

Quasi-Steady Operability Model

\[ \eta = \eta(h) \quad q = q(\eta) \]

\[ \gamma_1 p_1 M_1 / \sqrt{T_1} = \gamma_2 p_2 M_2 / \sqrt{T_2} \]

\[ p_1 (1 + \gamma_1 M_1^2) = p_2 (1 + \gamma_2 M_2^2) \]

\[ T_1 (1 + \gamma_1 - \frac{1}{2} M_1^2 + \frac{q}{C_{p1} T_1}) = T_2 (1 + \gamma_2 - \frac{1}{2} M_2^2) \]

Input mixing effcy
Heat release from CEA calculation

Jump conditions \((p_2, T_2, M_2)\) from conservation laws

Fill height from injection dynamics

Wave impulse from jump condition and fill height

Coding of model nearly complete - fully 1-D unsteady model also in work

As community we need to think more about mixing efficiency profiles
Summary

- DRONE platform exhibits self-excited, detonative behavior
  - Strong dependence on equivalence ratio and mass flux observed
  - Continued exploration underway
  - Future work in characterization of manifold dynamics, injector geometry, ...

- Multi-dimensional combustion modeling of DRONE unsteady injection, mixing, and ignition.

- System modeling in work to assess operability and aid in combustor design

- Large-scale test stand development underway
  - Supporting both UTSR and Aerojet Rocketdyne efforts

- Initial test article design to begin in the coming months, informed by the most recent understanding from DRONE and modeling efforts.