Advancing Pressure Gain Combustion in Terrestrial Turbine Systems

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Purdue University
School of Aeronautics and Astronautics
Maurice J. Zucrow Laboratories
Introduction

PGC Technology for Terrestrial Turbine Systems

- Several Flavors of PGC
  - CV deflagrative devices
  - PDEs
  - RDEs

- Potential for large, single-technology gains in cycle efficiency
  - 4-7% for simple cycles
  - 1-3% in combined cycles

- Challenges to Overcome
  - Combustion ‘Instability’
  - Materials Considerations
  - Component Integration
  - Pollutant Emissions
  - Cost
Introduction

Rotating Detonation Engines

- ‘Continuous Spin’ Detonation
  - DDT occurs in the starting transient
  - Self-preserving

- Transverse, semi-bounded detonation wave propagation

- High specific power output

- Principal Challenges:
  - Unsteady mixing
  - Mixture stratification
  - Wave Stability/Propagation
  - Parasitic Deflagration
  - Shear Layer Instability
  - Shock Losses
Introduction

Current RDE Research Landscape in the USA

- Government
  - AFRL, Wright-Patterson AFB
  - DOE, NETL
  - NASA, Glenn Research Center

- Industry
  - Aerojet-Rocketdyne
  - General Electric
  - GHKN
  - United Technologies

- Academia
  - Naval Postgraduate School
  - Penn State University
  - Purdue University
  - University of Colorado, Boulder
  - University of Maryland
  - University of Michigan
  - University of Texas, Arlington

Fotia et al., SciTech, 2015

Background

Purdue High Pressure Rocket RDE Test Article
Background

Purdue High Pressure Rocket RDE Test Article
At Full Power:
P_c = 1200 psi
f = 8.1 KHz
F = 2300 lbf
mdot = 8.8 lbm/s
O/F = 2.7
Background

Purdue High Pressure Rocket RDE Testing

Purdue University
Maurice J. Zucrow
High Pressure Propulsion Laboratory

Rotating Detonation Engine
Hot-Fire 23
May 15, 2015
Background

Purdue High Pressure Rocket RDE Testing

Microphone Spectrogram

Load Cell Spectrogram

Tangential Acoustic Mode

Rotating Detonation Modes

Pre-burner Modes

Rotating Detonation Mode
Above data from test series 2, case 1 (0.89 lbm/sec at $\phi = 1.0$)

Chamber pressure increases during the burn due to increasing copper wall temperature and mild throat contraction
Background

Purdue High Pressure Rocket Rocket RDE Testing

- TCA Ignition
- Main Fuel Valve Close
- Thrust at 100% C*
- Pre-Burner Only Before 29 sec
- Main Fuel Valve Open
Purdue-UTSR Project Overview

Motivation

1) To develop scientific understanding of processes within an RDE, specifically those relating to application-related challenges.

2) To translate that understanding into the design RDE hardware for improved performance at representative cycle conditions

Objectives

1) Characterize the performance of injection/mixing systems in an RDE using an optically-accessible, linear platform with and advanced diagnostic methods

2) Establish an experimental methodology to assess pressure gain utilizing coupled global and local measurements performed at conditions relevant to terrestrial turbine systems (up to a P3 and T3 of 2.0 MPa and 800 K, respectively)

3) Evaluate the operation of an RDE combustion chamber over range of operating conditions

4) Quantify pollutant emission production over a wide range of operability
Purdue-UTSR Project Overview

Team

Steve Heister, Raisbeck Distinguished Professor (co-PI)

Carson Slabaugh, Assistant Professor (co-PI)

Swanand Sardeshmukh, Postdoctoral Researcher

Brandon Kan, Ph.D. student

Kyle Schwinn, Ph.D. student

Adam Holley and Chris Greene, UTRC advisors
Purdue-UTSR Project Overview

Experimental Infrastructure
Purdue-UTSR Project Overview

Experimental Infrastructure
Purdue-UTSR Project Overview

Experimental Infrastructure

Key Features:
- Five High Pressure Combustion Test Cells
- Clean, Well-Conditioned Laser Laboratory
- Three Remote Control Rooms
- Fabrication and Instrumentation Rooms
- Full Host of Zucrow Research Fluid Services
Measurement Capability

- Imaging (Path Averaged Signals)
  - Chemiluminescence
  - Schlieren (laser Schlieren)

- Planar Laser Induced Fluorescence
  - Hydroxyl (OH)

- Particle Image Velocimetry
  - Stereoscopic (Three Component, Planar Fields)
  - Ultra-High Bandwidth
Progress

Task Breakdown

1) Project Management and Planning
2) Baseline Canonical Experiments
3) Subscale Combustor Facility Development
4) Integral Measurement of Pressure Gain
5) Detailed Measurements of Exit Conditions
6) Emissions Measurements
7) Computational Model Development

‘Unwrapped’ RDE test article design is at CDR-level (left) with complementary simulation informing baseline injector design (above)
Task 2.0 Baseline Canonical Experiments

The Detonation Rig for Optical, Non-intrusive Experimental measurements (‘DRONE’)

- Rapid unsteady mixing
- Parasitic deflagration
- Semi-bounded detonation wave propagation

Computed structure of detonation wave propagation in RDE annulus. Adapted from Towery et al. (AIAA, 2014)
# Task 2.0 Baseline Canonical Experiments

## DRONE Development

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
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<tbody>
<tr>
<td>DRONE_0100</td>
<td>Test Stand and Facility Integration</td>
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<tr>
<td>DRONE_0200</td>
<td>Test Article Hardware</td>
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<td>Measurement/Ancillary Systems</td>
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Task 2.0 Baseline Canonical Experiments

DRONE Development
Task 2.0 Baseline Canonical Experiments

DRONE Development

Diagram showing a systems diagram with various components and connections labeled with pipes and valves. The diagram includes terms such as 6000 psi N2, MV-N2-100, and other labeled components.

Legend:
- ▲ VALVE (NORMALLY OPEN)
- ▼ VALVE (NORMALLY CLOSED)
- ☘ CHECK VALVE
- 🔥 RELIEF VALVE
- 🔧 MANUAL VALVE OPERATOR
- 🔧 SOLENOID VALVE OPERATOR
- 🔧 PNEUMATIC VALVE OPERATOR
- 🔴 CAVITATING VENTURI
- 🔴 FLOW MEASUREMENT DEVICE
- 🔴 PRESSURE REGULATOR
- 🔴 PRESSURE REGULATOR (HAND LOADED)
- 🔴 PRESSURE REGULATOR (COMPUTER LOADED)
- 🔴 FILTER
- 🔴 ORIFICE PLATE
- 🔴 THERMOCOUPLE
- 🔴 PRESSURE TRANSRECEIVER
- 🔴 HIGH FREQUENCY PRESSURE TRANSRECEIVER
- 🔴 PRESSURE GAUGE
- 🔴 ICON PROBE
- 1/2" Probe
- 1/4" Probe
- 1/2" Tube
- 1/4" Tube

Diagram includes components such as MV-N2-201, PV-N2-201, and other specified points.

11/03/2015
2015 University Turbine Systems Workshop
22
## Task 2.0 Baseline Canonical Experiments

### DRONE Development

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![Diagram of DRONE with labeled parts: Window Frame, End Plate, Walls, Front Plate, Detonation Injector, Pre-detonator, Window, Manifold, Instrumentation Ports]
Task 2.0 Baseline Canonical Experiments

Design Conditions

- Propellants
  - Fuel: gaseous methane
  - Oxidizer: gaseous methane (with potential diluent)

- Initial Conditions
  - $P = 1$ atm
  - $T = 298K$

- Detonation Properties (CH4-GOx)
  - (Cell Size) = 2.5 mm
  - $u_{CJ} = 2390$ m/s
Task 2.0 Baseline Canonical Experiments

Design Conditions

- Modularity optically-accessible test article hardware and ancillary components
- Starting conditions chosen for high confidence level
- Flow Rates
  - Fuel: 0.1288 lbm/s
  - Oxidizer: 0.5152 lbm/s
- Manifold Pressure Ratios
  - Fuel: 2.7
  - Oxidizer: 1.8
Branched Pre-Detonator

- H$_2$/O$_2$ Reactants
- Split Detonation is split through (multiple) legs with different path-lengths
  - ‘circumscription’ frequency is controlled by relative length of delay lines.
- Waves are recombined at detonation injector
- +/- 5 µs timing precision
Task 2.0 Baseline Canonical Experiments

Detonation Injector

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

$t = 80 \, \mu s$  $t = 100 \, \mu s$  $t = 120 \, \mu s$  $t = 140 \, \mu s$
Task 2.0 Baseline Canonical Experiments

Detonation Injector

20000 fps  1/184000 sec  +9.25 ms
Task 2.0 Baseline Canonical Experiments

Detonation Injector
Task 2.0 Baseline Canonical Experiments

Detonation Injector

150000 fps  1/150000 sec  +9.326667 ms
Task 7.0 Concurrent Modeling Effort

Informing Baseline Injector Designs

- Generalize Equation and Mesh Solver (GEMS) code
- Unsteady simulations beginning (very soon)
  - Boundary conditions informed by detonation injector tests

Computed density gradient field represented by shadowgraph

Static pressure map of the injector element with equivalence ratio contours and streamline coloring

Velocity and Mach number map of the injector element shows counter-rotating vortices mixing the reactants.
**Looking Forward**

**Fall 2015 – Spring 2016 Project Schedule**

<table>
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<tr>
<th>Task</th>
<th>Time Required</th>
<th>Estimated Completion</th>
</tr>
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<tbody>
<tr>
<td>Detailed Design of DRONE_0200 Test Article</td>
<td>12 weeks</td>
<td>11/20/2015</td>
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<tr>
<td>Demonstration of Branched Initiation</td>
<td>8 weeks</td>
<td>Complete</td>
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<tr>
<td>Test Article Fabrication</td>
<td>10 weeks</td>
<td>January</td>
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<tr>
<td>Detailed Design of DRONE_0300 Ancillary Systems</td>
<td>4 weeks</td>
<td>December</td>
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<tr>
<td>Ancillary System Fabrication</td>
<td>4 weeks</td>
<td>January</td>
</tr>
<tr>
<td>Facility Integration</td>
<td>4 weeks</td>
<td>03/01/2016</td>
</tr>
<tr>
<td>Validation of System Operations</td>
<td>2 weeks</td>
<td>03/15/2016</td>
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<tr>
<td>Pressure Checks, Leak Checks, etc.</td>
<td></td>
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<tr>
<td>Baseline Reacting Tests</td>
<td>2 weeks</td>
<td>04/01/2016</td>
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<tr>
<td>Verify Safe, Repeatable Operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Reduction Code Development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initiation of Advanced Optical Measurements</td>
<td>-</td>
<td>-</td>
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Looking Forward

Principal Measurements

- Conventional Instrumentation
  - Ion gauges
  - High-frequency pressure transducers

- Optical Measurements
  - High-speed Schlieren
  - Planar Laser-Induced Fluorescence (OH)

Simultaneous Schlieren and OH-PLIF
(Extracted from Pintgen et al, Combustion and Flame, 2012)
Looking Farther Forward

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Task 3.0

Subscale Combustor Development

- Representative cycle conditions easily attained
  - Targeting 2.0 MPa and 900 K
  - Continuous supply at up to 10 lbm/s
- Planned optical access to the region upstream of the chamber
Task 3.0

Scaling Concept

- Large engines require large facilities and lots of propellant to develop
- For RDE it is crucial to match detonation period, but do we need a complete annulus to do so?

Sector/Segment of Full-scale RDE

Low flow tube sized to pass detonation at correct frequency

\[
\frac{\text{Mdot}}{\text{mdot}} (\text{full scale})
\]

\[0 \leq \frac{x}{L} \leq 1\]
Task 4.0

Integral Measurements of Pressure Gain

- Integration of sub-scale combustor to Purdue’s 10K Stand
  - CTAP
  - Thrust

- Combined with standard rocket instrumentation suite
  - Ion gage in chamber
  - High frequency transducers in propellant manifolds and chamber
  - Microphone on combustor exit
  - High-speed camera on annulus
  - Several low-speed cameras and still photos of plume
Task 5.0

Detailed Exit Flow Measurements

- 10 KHz 3-component Stereoscopic PIV of exit velocity field
- PRANA/REAPER with FMC
  - Enhanced spatial resolution
  - Dynamic range
  - Reduced error
Emissions Characterization

- Water-cooled sampling probe
  - Hydraulic average with choked inlet holes
  - Quenched kinetics from sampling and probe cooling
- Sample gas drawn into purged vessel for analysis after completion of transient test operations
- Flame Ionization Detector (FID) measures unburned hydrocarbon concentration
- FTIR spectrometer measures NO, NO2, CO, CO2, H2O concentration
- Separate detector for O2 concentration
Summary

Progress and Current Outlook

● Progress is underway on DRONE development
  ○ Canonical platform to perform advanced measurements of key processes
  ○ Informing complementary numerical modeling effort

● Branched initiation device has been demonstrated
  ○ Tunable channel forcing with high precision
  ○ Pulses remain coupled into channel

● Concurrent efforts with high pressure rocket RDE are developing experience base for Tasks 3.0-6.0 in Years 2 and 3.