Parametric Study of Pulse-Combustor-Driven Ejectors at High-Pressure

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Overview

- **Objectives**
  - Investigate the performance characteristics of shrouded pulse-combustor configurations at high pressure conditions.
  - The goal is to design configurations that maximize pressure gain while achieving a thermal environment acceptable to a turbine, and maintain acceptable levels of NOx emissions and flow non-uniformities

- **Approach**
  - Utilize new computational platform, developed in previous studies, for studying pulse-combustors.
• Conventional gas turbine engine combustors based on steady, constant pressure combustion incur total pressure losses that can range from 4% to 8%.

• Pressure-gain concepts:
  – Pulse Detonation-Based devices
  – Wave Rotors
  – Pulse-combustors

• Pulse-combustors are unsteady, resonant thermo-acoustic devices in which heat released by combustion is coupled with the acoustic field.
  – Experiments at atmospheric conditions demonstrated pressure gain of $\sim 3.5\%$ (Paxson and Dougherty 2005).
  – Preliminary CFD calculations at high-pressure conditions demonstrated pressure gain of $\sim 1.2\%$ (Yungster et al. 2013).
  – Maximum theoretical pressure-gains estimated at $\sim 7\%$ (Kentfield 1993).
Introduction

• Advantages of Pulse-combustors over alternative pressure gain concepts:
  – Avoids the mechanical complexities of higher pressure gain concepts.
  – Pulse combustors are known to produce low NOx.
  – Flow non-uniformities at exit of pulse-combustor are substantially reduced.

• Disadvantages of Pulse-combustors:
  – Pressure-gains attainable are typically lower than those for wave rotors or detonation based devices (which can reach up ~ 35%).
Introduction

- Most previous studies of pulse-combustors have been carried out at atmospheric conditions.
- Practical aerospace applications of pressure-gain combustion systems necessitates operation at high-pressure conditions.
- Previous study (Yungster, Paxson and Perkins, 2013) analyzed differences in the operation of pulse-combustors at atmospheric ($p_0 = 1$ bar; $T_0 = 298$ K) and high-pressure conditions ($p_0 = 10$ bar; $T_0 = 550$ K).
  - Higher air temperature and pressure $\Rightarrow$ shorter ignition delay times
    - Change in combustion dynamics.
    - Increased operating frequency.
    - Necessitates fuel valving (to prevent pre-ignition).
    - Lower performance (pressure gain $\sim 1.2\%$).
Introduction

• A recent study (Yungster, Paxson and Perkins, 2014) identified the factors limiting the pressure-gain at high-pressure conditions.
  – New pulse-combustor configurations were developed which were able to achieve performance levels at high-pressure conditions comparable to those observed at atmospheric conditions.
• However, suboptimal fuel distribution within the pulse-combustor was still limiting performance.
• The pulse-combustor by itself is not suitable to replace a conventional combustor in a gas turbine engine, and must be shrouded and combined with an ejector.
Pulse-combustor device used in experiments

Computational model

Valve (fully closed position)

Fuel injector

Valve (fully open position)

Inlet

Combustor

\[ p_0 \quad T_0 \]

2.5 in

1.25 in

\[ L_{pi} = 19.3 \text{ in} \]
Wave Diagram for a Pulse-Combustor

Ideal wave diagram

- Compression wave
- Expansion wave

Combustion start
Valve closes
Valve opens
Mixing + chemical kinetics

Natural period of acoustic waves

CFD simulation

Valve fully closed
Valve closing start
Valve fully open
Valve opening start

\( t \)
\( x \)

\( p/p_0 \)

1.7
0.7
Fuel used in experiments: liquid gasoline
Fuel used in CFD: gaseous jet-A

\( p_0 = 1 \text{ bar}, T_0 = 298 \text{ K} \)

\( f_{\text{exp}} = 222 \text{ Hz}; \quad f_{\text{cfd}} = 255 \text{ Hz} \)

\( \frac{p_{\text{max}}}{p_0} = 1.87; \quad \frac{p_{\text{avg}}}{p_0} = 1.16 \)

\( p_0 = 10 \text{ bar}, T_0 = 550 \text{ K} \)

\( \frac{p_{\text{max}}}{p_0} = 1.45; \quad \frac{p_{\text{avg}}}{p_0} = 1.06 \)

\( \frac{p_{\text{max}}}{p_0} = 2.01; \quad \frac{p_{\text{avg}}}{p_0} = 1.11 \)
Numerical Model

- In-house developed CFD code.
- Axisymmetric Navier-Stokes Equations for multi-species, thermally perfect, chemically reacting gas.
- Detailed chemistry capability
  - Kundu’s jet-A/air reaction mechanism (14-steps, 13-species).
    (has been successfully used in detonation and LDI combustor studies).
- Second-order TVD differencing scheme.
- Fully implicit BDF time marching algorithm.
- Spallart-Allmaras one-equation turbulence model.

**Approach**

- Conduct numerical simulations of the pulsejet-based devices for multiple cycles until limit-cycle operation is reached (8-25 cycles).
<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>A</th>
<th>n</th>
<th>E††</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \text{C}<em>{11}\text{H}</em>{21} + \text{O}_2 \leftrightarrow 11\text{CH} + 10\text{H} + \text{O}_2 )</td>
<td>(1.00 \times 10^{12})</td>
<td>0</td>
<td>(3.75 \times 10^4)</td>
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<tr>
<td></td>
<td>forward /\text{C}<em>{11}\text{H}</em>{21} 0.8/ ; forward /\text{O}_2 0.8/</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td>( \text{CH} + \text{O}_2 \leftrightarrow \text{CO} + \text{OH} )</td>
<td>(2.00 \times 10^{13})</td>
<td>0.00</td>
<td>(3.00 \times 10^3)</td>
</tr>
<tr>
<td>3</td>
<td>( \text{CH} + \text{O} \leftrightarrow \text{CO} + \text{H} )</td>
<td>(3.00 \times 10^{12})</td>
<td>1.00</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>( \text{H}_2 + \text{O}_2 \leftrightarrow \text{H}_2\text{O} + \text{O} )</td>
<td>(3.98 \times 10^{11})</td>
<td>1.00</td>
<td>(4.80 \times 10^4)</td>
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<tr>
<td>5</td>
<td>( \text{H}_2 + \text{O} \leftrightarrow \text{H} + \text{OH} )</td>
<td>(3.00 \times 10^{14})</td>
<td>0.00</td>
<td>(6.00 \times 10^3)</td>
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<tr>
<td>6</td>
<td>( \text{H} + \text{O}_2 \leftrightarrow \text{O} + \text{OH} )</td>
<td>(4.00 \times 10^{14})</td>
<td>0.00</td>
<td>(1.80 \times 10^4)</td>
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<tr>
<td>7</td>
<td>( \text{H}_2\text{O} + \text{O}_2 \leftrightarrow \text{H}_2\text{O} + 2\text{O} )</td>
<td>(3.17 \times 10^{12})</td>
<td>2.00</td>
<td>(1.12 \times 10^5)</td>
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<tr>
<td>8</td>
<td>( \text{CO} + \text{OH} \leftrightarrow \text{CO}_2 + \text{H} )</td>
<td>(5.51 \times 10^7)</td>
<td>1.27</td>
<td>(-7.58 \times 10^2)</td>
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<tr>
<td>9</td>
<td>( \text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2 )</td>
<td>(5.50 \times 10^4)</td>
<td>1.28</td>
<td>(-1.00 \times 10^3)</td>
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<tr>
<td>10</td>
<td>( \text{CO} + \text{H}_2 + \text{O}_2 \leftrightarrow \text{CO}_2 + \text{H}_2\text{O} )</td>
<td>(1.60 \times 10^{14})</td>
<td>1.60</td>
<td>(1.80 \times 10^4)</td>
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<tr>
<td>11</td>
<td>( \text{N} + \text{N} + \text{M} \leftrightarrow \text{N}_2 + \text{M} )</td>
<td>(2.80 \times 10^{17})</td>
<td>-0.75</td>
<td>0.0</td>
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<tr>
<td>12</td>
<td>( \text{N} + \text{O}_2 \leftrightarrow \text{NO} + \text{O} )</td>
<td>(6.40 \times 10^9)</td>
<td>1.00</td>
<td>(6.30 \times 10^3)</td>
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<tr>
<td>13</td>
<td>( \text{N} + \text{NO} \leftrightarrow \text{N}_2 + \text{O} )</td>
<td>(1.60 \times 10^{13})</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>14</td>
<td>( \text{N} + \text{OH} \leftrightarrow \text{NO} + \text{H} )</td>
<td>(6.30 \times 10^{11})</td>
<td>0.50</td>
<td>0.0</td>
</tr>
</tbody>
</table>

†Forward rate coefficient; units are moles, seconds, centimeters, calories and Kelvins.
Modified Pulse-Combustor and Axisymmetric Computational Domain.

original combustor

modified combustor
Baseline configuration
\( p_0 = 10 \text{ bar}, \ T_0 = 550 \text{ K}, \ \Phi = 0.66 \)

\[ f = 325 \text{ Hz} \]
Pulse-Combustor Simulations at High-Pressure

$p_0 = 10$ bar, $T_0 = 550$ K, $\Phi = 0.72$

- Baseline
  - $f = 337$ Hz

- 10% shorter combustor
  - $f = 342$ Hz

- 10% larger combustor diameter
  - $f = 342$ Hz

- “fat & short” (FASH)
  - $f = 344$ Hz
Pulse-Combustor Simulation at High-Pressure

\[ p_0 = 10 \text{ bar}, \ T_0 = 550 \text{ K}, \ \Phi = 0.72 \]

Baseline combustor

FASH combustor
Pulse-Combustor Simulations at High-Pressure

\( p_0 = 10 \text{ bar}, \quad T_0 = 550 \text{ K}, \quad \Phi = 0.72 \)

**Baseline**

- \( \bar{p} / p_0 = 1.11 \)
- \( \bar{p} / p_0 = 1.14 \)

**10% larger combustor diameter**

- \( \bar{p} / p_0 = 1.12 \)
- \( \bar{p} / p_0 = 1.14 \)

**10% shorter combustor**

**FASH combustor**
Pulse-Combustor Simulations at High-Pressure

\( p_0 = 10 \text{ bar}, \ T_0 = 550 \text{ K}, \ \Phi = 0.72 \)

Baseline

10\% shorter combustor diameter

10\% shorter combustor

FASH combustor
Emission Index

$p_0 = 10\text{ bar, } T_0 = 550\text{ K, } \Phi = 0.72$

Dark: tailpipe entrance
Light: tailpipe exit

Emission Index for conventional gas turbine engines
PES combustor based on the FASH configuration

\[ p_0 = 10 \text{ bar}, \; T_0 = 550 \text{ K}, \; \Phi = 0.67 \]

\[ f = 353 \text{ Hz} \]
PES combustor based on the FASH configuration

\[ p_0 = 10 \text{ bar}, \ T_0 = 550 \text{ K}, \ \Phi = 0.67 \]

\[ \bar{p} / p_0 = 1.12 \]
PES combustor based on the Baseline configuration

\( p_0 = 10 \text{ bar}, \ T_0 = 550 \ K \)

\( D_{th} = 3.3 \text{ in} \quad p_b / p_0 = 1.015 \)

\( D_{th} = 2.7 \text{ in} \quad p_b / p_0 = 1.019 \)

\( D_{th} = 3.0 \text{ in} \quad p_b / p_0 = 1.017 \)

\( D_{th} = 2.4 \text{ in} \quad p_b / p_0 = 1.022 \)
PES combustor based on the Baseline configuration

\[ p_0 = 10 \text{ bar}, \ T_0 = 550 \text{ K} \]

\[ D_{th} = 3.3 \text{ in} \quad \bar{p} / p_0 = 1.10 \]

\[ D_{th} = 2.7 \text{ in} \quad \bar{p} / p_0 = 1.11 \]

\[ D_{th} = 3.0 \text{ in} \quad \bar{p} / p_0 = 1.11 \]

\[ D_{th} = 2.4 \text{ in} \quad \bar{p} / p_0 = 1.11 \]
PES combustor based on the Baseline configuration

\[ p_0 = 10 \text{ bar}, \ T_0 = 550 \text{ K} \]

\[ D_{th} = 2.4 \text{ in} \]

\[ p_b / p_0 = 1.022 \]
PES combustor based on the Baseline configuration

\[ p_0 = 10 \text{ bar}, \quad T_0 = 550 \text{ K} \]

\[ D_{th} = 3.3 \text{ in} \]

\[ D_{th} = 2.7 \text{ in} \]

\[ D_{th} = 3.0 \text{ in} \]

\[ D_{th} = 2.4 \text{ in} \]
PES combustor based on the Baseline configuration

\( p_0 = 10 \text{ bar} \), \( T_0 = 550 \text{ K} \)

- \( D_{th} = 3.3 \text{ in} \)
- \( D_{th} = 3.0 \text{ in} \)
- \( D_{th} = 2.7 \text{ in} \)
- \( D_{th} = 2.4 \text{ in} \)
Summary

• The first part of this study analyzed new pulse-combustor configurations that were aimed at improving the fuel distribution in the pulse-combustor.
  – The new configurations produced higher average combustor pressures.
  – The higher pressures, however, were achieved at the cost of higher NO production.
  – The emission index levels were comparable to those achieved in conventional gas turbine engines.

• The performance of various pulse-combustor driven ejector configurations were investigated computationally, focusing on the effects of ejector throat area.
  – The pressure gain of the PES combustor configuration increased inversely proportional $A_{th}$.
  – The highest pressure gain achieved was 2.8%, while maintaining the NOx EI < 10.

Future Work

• Based on the results presented, higher pressure gains are likely achievable by combining the FASH-based PES combustor with the 2.4 in throat diameter ejector.
• The optimal ejector throat area and its location relative to the pulse-combustor has not yet been determined.
• Further performance improvements can potentially be achieved by improving the valve and inlet configurations to minimize pressure losses.
• New configurations currently being tested completely decouple the valve dynamics from the fuel injection process, allowing for further optimization of the fuel injection timing.