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.
Introduction

• 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 \( (p_0 = 1 \text{ bar}; T_0 = 298 \text{ K}) \) and high-pressure conditions \( (p_0 = 10 \text{ bar}; T_0 = 550 \text{ K}) \).
  - Higher air temperature and pressure ➔ shorter ignition delay times
    - Change in combustion dynamics.
    - Increased operating frequency.
    - Necessitates fuel valving (to prevent pre-ignition).
    - Lower performance (pressure gain ~ 1.2%).
• 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.
Schematic of Pulse-Combustor

Pulse-combustor device used in experiments

Computational model

Fuel injector

Valve (fully closed position)

Inlet

Combustor

Valve (fully open position)

\begin{align*}
L_{pi} & = 19.3 \text{ in} \\
p_0 \quad T_0 & \text{ in}\end{align*}
Wave Diagram for a Pulse-Combustor

- compression wave
- expansion wave

Ideal wave diagram

- Combustion start
- Valve closes
- Mixing + chemical kinetics
- Valve opens
- Combustion start
- Valve closes

CFD simulation

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

Natural period of acoustic waves

\[ t \]

\[ \frac{p}{p_0} \]

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

\[ p_0 = 1 \text{ bar}, \; T_0 = 298 \text{ K} \]

\[ p_{\text{exp}} = 222 \text{ Hz}; \; f_{\text{cfd}} = 255 \text{ Hz} \]

\[ \frac{p_{\text{max}}}{p_0} = 1.87; \; \frac{p_{\text{avg}}}{p_0} = 1.16 \]
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).
**Jet-A Reaction Mechanism (K. Kundu, 2010)**

<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>C\textsubscript{12}H\textsubscript{21} + O\textsubscript{2} \rightarrow 11CH + 10H + O\textsubscript{2}</td>
<td>1.00 \times 10^{12}</td>
<td>0</td>
<td>3.75 \times 10^{4}</td>
</tr>
<tr>
<td></td>
<td>forward /C\textsubscript{12}H\textsubscript{21} 0.8/ ; forward /O\textsubscript{2} 0.8/</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>CH + O\textsubscript{2} \rightarrow CO + OH</td>
<td>2.00 \times 10^{15}</td>
<td>0.00</td>
<td>3.00 \times 10^{3}</td>
</tr>
<tr>
<td>3</td>
<td>CH + O \rightarrow CO + H</td>
<td>3.00 \times 10^{12}</td>
<td>1.00</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>H\textsubscript{2} + O\textsubscript{2} \rightleftharpoons H\textsubscript{2}O + O</td>
<td>3.98 \times 10^{11}</td>
<td>1.00</td>
<td>4.80 \times 10^{4}</td>
</tr>
<tr>
<td>5</td>
<td>H\textsubscript{2} + O \rightleftharpoons H + OH</td>
<td>3.00 \times 10^{14}</td>
<td>0.00</td>
<td>6.00 \times 10^{3}</td>
</tr>
<tr>
<td>6</td>
<td>H + O\textsubscript{2} \rightleftharpoons O + OH</td>
<td>4.00 \times 10^{14}</td>
<td>0.00</td>
<td>1.80 \times 10^{4}</td>
</tr>
<tr>
<td>7</td>
<td>H\textsubscript{2}O + O\textsubscript{2} \rightarrow H\textsubscript{2}O + 2O</td>
<td>3.17 \times 10^{12}</td>
<td>2.00</td>
<td>1.12 \times 10^{5}</td>
</tr>
<tr>
<td>8</td>
<td>CO + OH \rightleftharpoons CO\textsubscript{2} + H</td>
<td>5.51 \times 10^{7}</td>
<td>1.27</td>
<td>-7.58 \times 10^{2}</td>
</tr>
<tr>
<td>9</td>
<td>CO + H\textsubscript{2}O \rightleftharpoons CO\textsubscript{2} + H\textsubscript{2}</td>
<td>5.50 \times 10^{4}</td>
<td>1.28</td>
<td>-1.00 \times 10^{3}</td>
</tr>
<tr>
<td>10</td>
<td>CO + H\textsubscript{2} + O\textsubscript{2} \rightleftharpoons CO\textsubscript{2} + H\textsubscript{2}O</td>
<td>1.60 \times 10^{14}</td>
<td>1.60</td>
<td>1.80 \times 10^{4}</td>
</tr>
<tr>
<td>11</td>
<td>N + N +M \rightleftharpoons N\textsubscript{2} + M</td>
<td>2.80 \times 10^{17}</td>
<td>-0.75</td>
<td>0.0</td>
</tr>
<tr>
<td>12</td>
<td>N + O\textsubscript{2} \rightleftharpoons NO + O</td>
<td>6.40 \times 10^{9}</td>
<td>1.00</td>
<td>6.30 \times 10^{3}</td>
</tr>
<tr>
<td>13</td>
<td>N + NO \rightleftharpoons N\textsubscript{2} + O</td>
<td>1.60 \times 10^{13}</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>14</td>
<td>N + OH \rightleftharpoons NO + 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

$p_0$  $T_0$

$p_0$  $T_0$
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

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

- **Baseline**
  - \( f = 337 \text{ Hz} \)

- **10\% shorter combustor**
  - \( f = 342 \text{ Hz} \)

- **10\% larger combustor diameter**
  - \( f = 342 \text{ Hz} \)

- **“fat & short” (FASH)**
  - \( f = 344 \text{ Hz} \)
Pulse-Combustor Simulation at High-Pressure

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

\[
\begin{align*}
T/T_0 & \quad 4.8 \quad 0.5 \\
\text{fuel mass fraction} & \quad 0.1 \quad 0.0
\end{align*}
\]
Pulse-Combustor Simulations at High-Pressure

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

Baseline

\[ \bar{p} / p_0 = 1.11 \]

10% shorter combustor diameter

\[ \bar{p} / p_0 = 1.12 \]

10% larger combustor diameter

\[ \bar{p} / p_0 = 1.14 \]

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

10% larger combustor diameter

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

**Emission Index**

Dark: tailpipe entrance
Light: tailpipe exit

Emission Index for conventional gas turbine engines

$E_{NO_x}, \text{ g/kg}$

Compressor Pressure Ratio

Baseline, 10% shorter combustor, 10% larger combustor diameter, FASH
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

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

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

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

- \( D_{th} = 3.3 \text{ in} \), \( p_b / p_0 = 1.015 \)
- \( D_{th} = 2.7 \text{ in} \), \( p_b / p_0 = 1.019 \)
- \( D_{th} = 3.0 \text{ in} \), \( p_b / p_0 = 1.017 \)
- \( D_{th} = 2.4 \text{ in} \), \( p_b / p_0 = 1.022 \)
PES combustor based on the Baseline configuration

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

\[
\begin{align*}
D_{th} &= 3.3 \text{ in} & \bar{p} / p_0 &= 1.10 \\
D_{th} &= 2.7 \text{ in} & \bar{p} / p_0 &= 1.11 \\
D_{th} &= 3.0 \text{ in} & \bar{p} / p_0 &= 1.11 \\
D_{th} &= 2.4 \text{ in} & \bar{p} / p_0 &= 1.11
\end{align*}
\]
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

\[ p_0 = 10 \text{ bar}, \quad T_0 = 550 \text{ K} \]
PES combustor based on the Baseline configuration

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

- \( D_{th} = 3.3 \text{ in} \)
- \( D_{th} = 2.7 \text{ in} \)
- \( D_{th} = 3.0 \text{ in} \)
- \( D_{th} = 2.4 \text{ in} \)
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 to $A_{th}$.
  – 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.