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 ($p_0 = 1$ 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)

Valve (fully open position)

Fuel injector

Inlet

Combustor

Schematic of Pulse-Combustor

$\text{Fuel mixer}$

$\text{Inlet}$

$\text{Combustor}$

$\text{Exhaust (tailpiece)}$

$\text{Valve}$

$p_0$

$T_0$

$2.5 \text{ in}$

$1.25 \text{ in}$

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

Ideal wave diagram

- compression wave
- expansion wave

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

Natural period of acoustic waves

CFD simulation

Valve fully closed
Valve closing start
Valve fully open
Valve opening start
Fuel used in experiments: liquid gasoline
Fuel used in CFD: gaseous jet-A

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

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

\[ p_{\text{max}} / p_0 = 1.87; \quad p_{\text{avg}} / p_0 = 1.16 \]
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_{11}H_{21} + O_2 ⇌ 11CH + 10H + O_2</td>
<td>1.00 × 10^{12}</td>
<td>0.0</td>
<td>3.75 × 10^4</td>
</tr>
<tr>
<td></td>
<td>forward /C_{11}H_{21} 0.8/ ; forward /O_2 0.8/</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>CH + O_2 ⇌ CO + OH</td>
<td>2.00 × 10^{15}</td>
<td>0.0</td>
<td>3.00 × 10^3</td>
</tr>
<tr>
<td>3</td>
<td>CH + O ⇌ CO + H</td>
<td>3.00 × 10^{12}</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>H_2 + O_2 ⇌ H_2O + O</td>
<td>3.98 × 10^{11}</td>
<td>1.0</td>
<td>4.80 × 10^4</td>
</tr>
<tr>
<td>5</td>
<td>H_2 + O ⇌ H + OH</td>
<td>3.00 × 10^{14}</td>
<td>0.0</td>
<td>6.00 × 10^3</td>
</tr>
<tr>
<td>6</td>
<td>H + O_2 ⇌ O + OH</td>
<td>4.00 × 10^{14}</td>
<td>0.0</td>
<td>1.80 × 10^4</td>
</tr>
<tr>
<td>7</td>
<td>H_2O + O_2 ⇌ H_2O + 2O</td>
<td>3.17 × 10^{12}</td>
<td>2.0</td>
<td>1.12 × 10^5</td>
</tr>
<tr>
<td>8</td>
<td>CO + OH ⇌ CO_2 + H</td>
<td>5.51 × 10^{7}</td>
<td>1.27</td>
<td>-7.58 × 10^2</td>
</tr>
<tr>
<td>9</td>
<td>CO + H_2O ⇌ CO_2 + H_2</td>
<td>5.50 × 10^{4}</td>
<td>1.28</td>
<td>-1.00 × 10^3</td>
</tr>
<tr>
<td>10</td>
<td>CO + H_2 + O_2 ⇌ CO_2 + H_2O</td>
<td>1.60 × 10^{14}</td>
<td>1.60</td>
<td>1.80 × 10^4</td>
</tr>
<tr>
<td>11</td>
<td>N + N + M ⇌ N_2 + M</td>
<td>2.80 × 10^{17}</td>
<td>-0.75</td>
<td>0.0</td>
</tr>
<tr>
<td>12</td>
<td>N + O_2 ⇌ NO + O</td>
<td>6.40 × 10^{9}</td>
<td>1.00</td>
<td>6.30 × 10^3</td>
</tr>
<tr>
<td>13</td>
<td>N + NO ⇌ N_2 + O</td>
<td>1.60 × 10^{13}</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>14</td>
<td>N + OH ⇌ NO + H</td>
<td>6.30 × 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

\[ p_0 = 10 \text{ bar}, \quad T_0 = 550 \text{ K}, \quad \Phi = 0.66 \]

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

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

- **Baseline**
  - $f = 337 \text{ Hz}$
  - $T/T_0$
    - 4.8
    - 0.5
  - fuel mass fraction
    - 0.1
    - 0.0

- **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

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

Baseline combustor

FASH combustor

primary vortex          secondary vortex

(a) \( t = 0.00 \) ms

(b) \( t = 0.50 \)

(c) \( t = 1.00 \)

(d) \( t = 1.50 \)

(e) \( t = 2.00 \)

(f) \( t = 2.50 \)

(g) \( t = 3.05 \)

\( T/T_0 \)

4.8  0.5

fuel mass fraction

0.1  0.0

(a) \( t = 0.00 \) ms

(b) \( t = 0.50 \)

(c) \( t = 1.00 \)

(d) \( t = 1.50 \)

(e) \( t = 2.00 \)

(f) \( t = 2.50 \)

(g) \( t = 2.90 \)
Pulse-Combustor Simulations at High-Pressure

\( p_0 = 10 \) bar, \( T_0 = 550 \) 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

\[ \bar{p} / p_0 = 1.14 \]
Pulse-Combustor Simulations at High-Pressure

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

Baseline

10% larger 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

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

- Mass averaged temperature (K) vs. Cycle #
- Mass averaged total pressure ratio vs. Cycle number
- \( \bar{p} / p_0 = 1.12 \) vs. Time (ms)
PES combustor based on the Baseline configuration

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

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

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

- \( D_{th} = 3.3 \text{ in} \), \( \bar{p} / p_0 = 1.10 \)
- \( D_{th} = 2.7 \text{ in} \), \( \bar{p} / p_0 = 1.11 \)
- \( D_{th} = 3.0 \text{ in} \), \( \bar{p} / p_0 = 1.11 \)
- \( D_{th} = 2.4 \text{ in} \), \( \bar{p} / p_0 = 1.11 \)
PES combustor based on the Baseline configuration

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

\( D_{th} = 2.4 \text{ in} \)

\( \frac{p_b}{p_0} = 1.022 \)
PES combustor based on the Baseline configuration

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

- \( D_{th} = 3.3 \text{ in} \)
- \( D_{th} = 3.0 \text{ in} \)
- \( D_{th} = 2.7 \text{ in} \)
- \( D_{th} = 2.4 \text{ in} \)
PES combustor based on the Baseline configuration

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

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

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

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

\[ D_{th} = 2.4 \text{ in} \]
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 $A_{th}$.
  – 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.