**4. TITLE AND SUBTITLE**
Large Eddy Simulations of Transverse Combustion Instability in a Multi-Element Injector

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**14. ABSTRACT**
Viewgraph/Briefing Charts

**15. SUBJECT TERMS**
N/A
Large Eddy Simulations of Transverse Combustion Instability in a Multi-Element Injector

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² HyPerComp, Inc.
Combustion instability is an organized, oscillatory motion in a combustion chamber sustained by combustion.

CI caused a four year delay in the development of the F-1 engine used in the Apollo program
- > 2000 full scale tests
- > $400 million for propellants alone (2010 prices)

Irreparable damage can occur in less than 1 second.

"Combustion instabilities have been observed in almost every engine development effort, including even the most recent development programs"

Single Element Studies

Short Post  
Marginally Stable

Intermediate Post  
Unstable

Long Post  
Stable

Long Post  
Unstable

CVRC Experiment  
Purdue University
Transverse Instability Combustor

- Transverse Instability Combustor – TIC
- Experimental rig developed at Purdue University
- Four major iterations to date
- Rectangular chamber with 7 elements
- Linear array of 7 elements
- Injectors are similar to the single element work
- Instability is self-excited
<table>
<thead>
<tr>
<th>Single Element</th>
<th>Multi-element</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Less expensive</td>
<td>• More expensive</td>
</tr>
<tr>
<td>• Smaller domains</td>
<td>• Larger domains</td>
</tr>
<tr>
<td>• Substantial work published</td>
<td>• Complex geometries</td>
</tr>
<tr>
<td>• Wall effect is exaggerated</td>
<td>• Less literature, limited work</td>
</tr>
<tr>
<td></td>
<td>• Captures inter-element interactions</td>
</tr>
</tbody>
</table>
**TIC Configuration**

**Dual Purpose Experiment:**
1. Self-excited transverse instability
2. Observe combustion response of the study element to high amplitude transverse instabilities

Injector elements are similar to the longitudinal experiment

½ Wave resonator, Couples with 1T

Driving Elements

OX Manifold

Choked Inlets

Study Element

High Freq Pressure Transducers

Optical Access

Tapered Nozzle
## TIC Experiments

<table>
<thead>
<tr>
<th></th>
<th>TIC 1a</th>
<th>TIC 1b</th>
<th>TIC 1c</th>
<th>TIC 1d</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oxidizer</strong></td>
<td>H$_2$O$_2$</td>
<td>H$_2$O$_2$</td>
<td>H$_2$O$_2$</td>
<td>H$_2$O$_2$</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Driving</strong></td>
<td>JP-8</td>
<td>RP-1</td>
<td>CH$_4$</td>
<td>CH$_4$</td>
</tr>
<tr>
<td><strong>Study</strong></td>
<td>C$<em>{12}$H$</em>{26}$</td>
<td>C$_2$H$_6$</td>
<td>CH$_4$</td>
<td>CH$_4$</td>
</tr>
<tr>
<td><strong>Oxidizer Inlet</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Driving</strong></td>
<td>Perforated Plate</td>
<td>Perforated Plate</td>
<td>Perforated Plate</td>
<td>Choked Venturi</td>
</tr>
<tr>
<td><strong>Study</strong></td>
<td>Perforated Plate</td>
<td>Choked Slots</td>
<td>Choked Slots</td>
<td>Choked Venturi</td>
</tr>
<tr>
<td><strong>Notes</strong></td>
<td>Two-phase flow</td>
<td></td>
<td>Multiple study ox-post lengths considered</td>
<td>Multiple ox-post lengths considered</td>
</tr>
<tr>
<td><strong>Companion Simulations</strong></td>
<td></td>
<td>3-element</td>
<td></td>
<td>3 &amp; 7-element</td>
</tr>
</tbody>
</table>

This Study
Amplitude Control – TIC 1a&b

- Fuel & Oxidizer
- Oxidizer Only

Increasing Amplitude
Two Distinct Modeling Approaches

**Full Simulation**
- Captures self-excited instability
- Captures inter-element interactions
- Amplitude is difficult to control
- Expensive

**Reduced Model**
- Does not capture driving
- Limited inter-element interactions
- Amplitude is prescribed
- Low cost
## Test Configurations

<table>
<thead>
<tr>
<th></th>
<th>Configuration 1</th>
<th>Configuration 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unstable</td>
<td>Stable</td>
</tr>
<tr>
<td>Injector Setup</td>
<td>⚫⚫⚫⚫⚫⚫⚫⚫⚫</td>
<td>⬜⚫⚫⚫⚫⚫⚫⚫</td>
</tr>
<tr>
<td>p′ (%p_c)</td>
<td>65</td>
<td>8</td>
</tr>
<tr>
<td>p′, kPa</td>
<td>620</td>
<td>70</td>
</tr>
<tr>
<td>1W Frequency, Hz</td>
<td>2032</td>
<td>1855</td>
</tr>
</tbody>
</table>

### Explanation:

- Outer driving injectors flow RP1, center study element flows C2H6.
- Oxidizer is decomposed hydrogen peroxide, 58% H2O, 42% O2.

### Additional Data:

<table>
<thead>
<tr>
<th></th>
<th>Temp., K</th>
<th>Mass Flow, kg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidizer</td>
<td>1029</td>
<td>0.196</td>
</tr>
<tr>
<td>RP1</td>
<td>298</td>
<td>0.033</td>
</tr>
<tr>
<td>C2H6</td>
<td>319</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Distribution Statement A: Approved for Public Release; Distribution Unlimited. PA Clearance #16346
Simulation Details

- Multi-block structured mesh, 15.63 M
- LESLIE – reacting flow LES code
- RP1 is modeled as C_{10}H_{22}
- Specified mass flow inlets (reflecting)
- Finite rate kinetics

\[
\begin{align*}
C_2H_6 + \frac{5}{2}O_2 & \rightarrow 2CO + 3H_2O \\
C_{10}H_{22} + \frac{21}{2}O_2 & \rightarrow 10CO + 11H_2O \\
CO + \frac{1}{2}O_2 & \rightarrow CO_2 \\
CO_2 & \rightarrow CO + \frac{1}{2}O_2
\end{align*}
\]
The KE spectrum is used to help assess the grid resolution.

Good Agreement with the -5/3 slope for both cases.
Side Wall, Pressure

Similar amplitudes
Side Wall, PSD

Bifurcated second harmonic, the frequency is less than the twice the first mode frequency

Well defined second harmonic at twice the first mode frequency
Chamber Center, Pressure

Lower amplitudes compared with the side wall, consistent with a pressure node of the 1W mode.
Chamber Center, PSD

Excited 1W and 2W, not consistent with a transverse mode

Excited 2W, consistent with a transverse mode
### PSD Summary

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Experiment</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W Frequency, Hz</td>
<td>2032</td>
<td>2440</td>
</tr>
<tr>
<td>$p'$, kPa</td>
<td>620</td>
<td>259</td>
</tr>
<tr>
<td>$p_c$, kPa</td>
<td>965</td>
<td>1148</td>
</tr>
<tr>
<td>$p'/p_c$</td>
<td>65%</td>
<td>23%</td>
</tr>
</tbody>
</table>

**Configuration 1**

**Configuration 4**

- Predicted amplitude for the unstable case is too low, PSD analysis indicates that it may not be a transverse instability.
- Amplitude prediction for the stable case is of the same order of magnitude.

In both cases the chamber pressure and frequency are too high.

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Stable Configuration

Point of analysis for a single representative cycle
Unsteady Pressure

Transverse mode in the chamber

Longitudinal modes are setup in the injectors

Center element (located at 1W node) shows excitation
Center Element PSD

The center element is responding to the 2W frequency.

The amplitude of the response is larger than the 2W response in the chamber.
Driving Elements

Time 5 – low pressure on the right side of the chamber

Fuel consumption close to the injector plate
Small amounts of fuel consumption in the cup
Pockets of fuel rich fluid away from the injector plate
Driving Elements

Time 8 – high pressure on the right side of the chamber

Fuel consumption has moved downstream
No fuel consumption in the cup
Fuel rich fluid is contained to the shear layer
Study Element

Time 5 – low pressure in the center element

Detached flame

No burning in the cup region

Pockets of fuel rich fluid away from the injector plate
Study Element

Time 7 – high pressure in the center element

Flame remains detached

No burning in the cup region (unlike single element studies)

Pockets of fuel rich fluid away from the injector plate remain
Unstable Configuration

Point of analysis for a single representative cycle
Unsteady Pressure

Week transverse mode in the chamber (near the injector plate only)

All injector elements are excited
The center element is responding to the 1W and 2W frequencies.

The amplitude of the response is larger than the 1W and 2W responses in the chamber.
Driving Elements

Time 5 – low pressure on the right side of the chamber

Consumption rates of the two driving injectors is different

Larger quantities of fuel are present in the outside injector
Driving Elements

Time 9 – high pressure on the right side of the chamber

Fuel consumption amplified at high pressure
Small consumption of fuel in the cup region
Significant unburned fuel present
Time 6 – low pressure in the center element

Burning inside the cup region
Very little fuel present the combustor

Study Element
Time 4 – high pressure in the center element

Majority of burning is inside the cup

Very little fuel present the combustor

Very different from case 4 which showed a detached flame
Summary

• Reasonable agreement between the experiment and simulation for the stable case
  — Different injector response mechanism than was observed in single element studies

• Unstable configuration did not have a good agreement
  — Lack of a transverse wave

• Very different behavior of the center element for the two cases
  — Case 1 – burning in the cup, responding to 1W and 2W mode
  — Case 4 – detached flame, responding to the 2W mode
Summary

• Instability mechanism present in the single element longitudinal studies were not present in either case.

• Future Work, Look at:
  — Ideal gas assumption for RP1
  — Grid resolution, flame was further downstream from the injector than single element studies, the grid may have been too coarse in that region