Researches in Peking University on RDE

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Peking University
• Oscillations of Detonation Strength
• Effects of Equivalence Ratio
• Particle Path Method for Thermodynamic Cycle
• Effect of Injection on Front Number
• Array Hole Injection and Re-initiation
• Hollow Combustor
Experiment

Combustor

Over-view
Periodic Oscillations

Pressure (Bar)

Time (s)

Azimuthal distance (m)

Axial distance (m)

h=24.63mm

h=12.65mm

1290μs

1380μs
Mechanism of Oscillations

- Detonation wave gets stronger
- Pressure gets higher
- Gas feeding gets faster
- Non-feeding zone gets smaller

Small DISTURBANCE

Self-adjusting Mechanism

- Gas feeding gets slower
- Non-feeding zone gets larger
- Less fresh gas

- More fresh gas
- Gas feeding gets faster
- Non-feeding zone gets smaller
- Pressure gets lower
- Detonation wave gets weaker
2-D Euler equations in cylindrical coordinates
Chemical reaction model [1]

\[ \frac{d[H_2]}{dt} = -A(P)P^{-1.15}[H_2]^2[O_2]\exp\{-E_a(\varphi)/RT\} \]

Initial condition

Phenomenons with Equivalence Ratio $\phi$

- $\phi = 0.4, 0.6, 0.8$  No detonation
- $\phi = 1.0, 1.2, 1.4, 1.6$  Stable detonation
- $\phi = 1.8, 2.0$  No detonation
\( \varphi = 0.8 \)  No stable CRDWs
$\varphi = 0.8 \quad \text{No stable CRDWs}$
$\varphi = 1.4$  
Stable CRDWs
\( \varphi = 1.4 \)  Stable CRDWs

\[ T = 31.76 \, \mu s \]

detonation velocity by simulation 1962.1 m/s

(94.5% of theoretical)

velocity 2076.86 m/s
$\varphi = 1.8$  No stable CRDWs
$\phi = 1.8$  No stable CRDWs
\[ \varphi = 1.8 \quad \text{No stable CRDWs} \]
- Particle 1 is burned by detonation wave II
- Particle 2 is burned by the deflagration wave
- Particle 3 is burned by detonation wave I
Comparison with ZND model and 1D numerical simulation

P-V diagram and T-S diagram
Effects of injection pattern on number of detonation fronts

(a) Case 1  (b) Case 2  (c) Case 3  (d) Case 4

Strip  Spiral  Two-side slits  Central slit
More injection area > Sufficient fuel > Stronger detonation > Faster > Few fronts
Less injection area > Lacking fuel > Weaker detonation > Slower > More fronts
The **difference** of propulsive performance of the four new injection patterns is **small**. This is probably because the specific impulse is related to the characteristics of the propellant, which is hydrogen-air mixture in the present model.
Array Hole Injection

Pressure

Two-rows

Three-rows
Re-initiation in Experiments

Present

P. Wolanski’s experiment
Temperature
Cylindrical chamber is first proposed by Shao and Wang. (23rd ICDERS, 2009)

Cylindrical chamber is designed for dealing with the overheating problem.
Is it possible to use the whole head end for fuel injection?

- Annular cylindrical combustor
- Hollow combustor
Rotating Detonation in Hollow Chamber

无内柱，$P_{O_2} = 1.0$ MPa, $P_{H_2} = 0.6$ MPa

<table>
<thead>
<tr>
<th>$H_2/O_2$</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
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<tbody>
<tr>
<td>0.4</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>0.5</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>△</td>
<td>△</td>
</tr>
<tr>
<td>0.6</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>△</td>
<td>△</td>
<td>△</td>
</tr>
<tr>
<td>0.7</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>△</td>
<td>△</td>
<td>△</td>
<td>○</td>
</tr>
<tr>
<td>0.8</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>△</td>
<td>△</td>
<td>△</td>
<td>△</td>
</tr>
<tr>
<td>0.9</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>△</td>
<td>△</td>
<td>△</td>
<td>△</td>
</tr>
<tr>
<td>1.0</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>△</td>
<td>△</td>
<td>△</td>
<td>△</td>
</tr>
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</table>
Re-initiation phenomenon

Extinction and re-initiation

\[
\begin{align*}
t &= 1920 \, \mu s & t &= 1924 \, \mu s & t &= 1928 \, \mu s & t &= 1932 \, \mu s & t &= 1936 \, \mu s & t &= 1940 \, \mu s \\
t &= 1944 \, \mu s & t &= 1948 \, \mu s & t &= 1952 \, \mu s & t &= 1956 \, \mu s & t &= 1960 \, \mu s & t &= 1964 \, \mu s
\end{align*}
\]
Re-initiation phenomenon

Experiment by Y. Qi, Z. Wang
The re-initiation is caused by sharp and sudden increase of pressure.
Arrays of orifices Injection Patterns

Front View

\[ V = \frac{\pi d}{T} = 1850 \text{ m/s} \]

\[ V = 0.85V_{CJ} \]

Pressure history

Close-up of pressure history
Effects of mixing length on traveling frequency and corresponding amplitude

Fourier transforms of pressure transducer data
Domain of stable continuous detonations through a series of tests

Table 1 \( \text{H}_2\text{-O}_2 \) operating table of RDE with a 5 mm mixing distance

<table>
<thead>
<tr>
<th>( p_{\text{H}_2} )</th>
<th>0.6</th>
<th>0.8</th>
<th>1</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
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<tbody>
<tr>
<td>0.6</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>0.8</td>
<td>×</td>
<td>×</td>
<td>O</td>
<td>O</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>1</td>
<td>×</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Δ</td>
<td>Δ</td>
</tr>
<tr>
<td>1.2</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>1.4</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>1.6</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
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</table>

Table 5 \( \text{H}_2\text{-O}_2 \) operating table of RDE with a 10 mm mixing distance

<table>
<thead>
<tr>
<th>( p_{\text{H}_2} )</th>
<th>0.6</th>
<th>0.8</th>
<th>1</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>×</td>
<td>×</td>
<td>Δ</td>
<td>O</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>0.8</td>
<td>×</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Δ</td>
</tr>
<tr>
<td>1</td>
<td>×</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Δ</td>
</tr>
<tr>
<td>1.2</td>
<td>×</td>
<td>×</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>1.4</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>1.6</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>O</td>
</tr>
</tbody>
</table>

a, × donates failure to attain rotating detonation waves
b, Δ donates unstable or transient rotating detonation waves
c, O donates stable detonation waves
(a) $P_{O_2} = 0.5 \text{MPa}, \ P_{H_2} = 0.5 \text{MPa}, \ \text{background pressure} = 0.02 \text{MPa}$
(b) $P_{O_2} = 0.5 \text{MPa}, \ P_{H_2} = 0.5 \text{MPa}, \ \text{background pressure} = 0.03 \text{MPa}$
(c) $P_{O_2} = 0.5 \text{MPa}, \ P_{H_2} = 0.5 \text{MPa}, \ \text{background pressure} = 0.05 \text{MPa}$
(d) $P_{O_2} = 1.2 \text{MPa}, \ P_{H_2} = 0.8 \text{MPa}, \ \text{background pressure} = 0.1 \text{MPa}$
Conclusions

- Oscillation of detonation strength is due to the fresh gas injection.
- Disparate Equivalence Ratio leads to failure of detonation initiation.
- Less fuel leads to more detonation fronts.
- There is adjusting process between ignition and stable detonation.
- Re-initiation due to enhancement of pressure waves.
- Hollow combustor is successfully realized numerically and experimentally.
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Thank you for your attention!