Outward propagation velocity and acceleration characteristics in hydrogen-air deflagration

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1-1 Combustion safety

Hydrogen

- Clean fuel
  - Zero carbon emission
  - Combustion product: $\text{H}_2\text{O}$
  - Generated by renewable energy source
  - Fuel of a fuel cell vehicle, e.g. TOYOTA MIRAI

- Dangerous gas
  - Wide flammable range
  - High burning velocity etc.

- Generation in a nuclear power plant
  - Radiation degradation of water
  - Reaction of Zr with water
1-2 Risk assessment

- Risk assessment
  i. Hazard Identification
  ii. Risk estimation
  iii. Risk evaluation
  iv. Risk reduction

Important!

Adequate estimation is necessary
- Flame propagation velocity
- Leakage and flow phenomena
  etc.

- Prediction of flame propagation velocity

Conventional method
(Propagation velocity of spherical flame)

\[ S_b = S_u \left( \frac{T_b}{T_u} \right) \]
1-3 Flame acceleration

- Intrinsic instability
  - Cellular flame front forms
    - Flame front area becomes larger
    - Flame propagation accelerates
  - In a huge space, cellular flame develops more

- For adequate estimation of flame propagation velocity, flame acceleration needs to be considered.

- Flame acceleration owing to intrinsic instability is influenced by initial conditions.
  - Initial temperature
  - Initial pressure
  - Gas composition (H₂, Air, CO₂, H₂O, etc.)
2. Objective

We aim to understand flame acceleration characteristics.

- Effect of equivalence ratio
- Effect of initial temperature

We will establish a brand-new model of flame propagation considering a flame acceleration.

Experiment

- Explosion test of Hydrogen-air mixture in a closed chamber at several equivalence ratios and initial temperatures
- Observation of flame propagation behavior using Schlieren photography
3-1 Experimental apparatus

Closed chamber
Volume: 73L  
Material: SUS304
Window
Diameter: 300mm  
Thickness: 140mm  
Material: Quartz  
Quantity: 4

Others
Ignition
Voltage: 7.5kV  
Energy: 110mJ
Data logger
Sampling rate: 10kHz
High speed video camera
Frame rate: 10kfps  
Resolution: 1024x1024pixels

Device list
Schlieren photography: Mizojiri SL-350  
High speed camera: Photron SA-X  
Pressure sensor: Kistler 6045A31  
Data logger: Keyence NR6000
3-2 Experimental procedure

① Heat up the chamber
② Vacuum the chamber
③ Fill the chamber with hydrogen and air
④ Ignite by spark at the center of the chamber after gas temperature reaches a target temperature
⑤ Ignition controller triggers data logger and high speed video camera at the same time as ignition

Device list
- Schlieren photography: Mizojiri SL-350
- High speed camera: Photron SA-X
- Pressure sensor: Kistler 6045A31
- Data logger: Keyence NR600
3-3 Experimental condition

- Initial condition
  Mixture: Hydrogen-air
  Pressure: 101.3kPa abs.

- Explosion test
  Explosion tests were performed 3 times in each case which is shown as blue in the table1.

Table 1 Test condition

<table>
<thead>
<tr>
<th>Initial temperature [deg C]</th>
<th>Equivalence ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0</td>
</tr>
<tr>
<td>50</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td></td>
</tr>
</tbody>
</table>
3-4 Experimental results

Equivalence ratio $\phi = 1.0$

Equivalence ratio $\phi = 0.5$
### 3-4 Experimental results

<table>
<thead>
<tr>
<th>Time</th>
<th>2.0 ms</th>
<th>4.0 ms</th>
<th>6.0 ms</th>
<th>8.0 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td></td>
</tr>
</tbody>
</table>

(a) \( \varphi = 1.0 \ (r_b = 2.0, 5.0, 10, 15 \ [\text{cm}]) \)

<table>
<thead>
<tr>
<th>Time</th>
<th>6.5 ms</th>
<th>13.0 ms</th>
<th>19.5 ms</th>
<th>26.0 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td></td>
</tr>
</tbody>
</table>

(b) \( \varphi = 0.5 \ (r_b = 2.0, 5.0, 10, 15 \ [\text{cm}]) \)
3-5 Flame propagation velocity -Effect of equivalence ratio-

- Flame propagation velocities increase with flame radius
- At small radius, influence of flame stretch appears

Initial temperature: 25 deg C
There is not noticeable difference in the dependencies of flame propagation velocity on flame radius at both temperatures.
4-1 Influence of flame stretch

- Flame propagation velocities of planar flames, $S_{b0}$, were obtained from the relation between flame propagation velocity, $S_b$, and flame stretch rate, $\kappa$.

- Flame radiuses, $r$, where flame propagation velocity separates from the regression line are defined as critical flame radius, $r_0$.

Relation between burning velocity and flame stretch rate

\[
S_s - S_{u0} = -L\kappa \\
S_b = -L\kappa \left(\frac{\rho_u}{\rho_b}\right) + S_{b0} = -L\frac{2S_b}{r} + S_{b0}
\]

- $S_s$: Burning velocity of stretched flame
- $S_{u0}$: Laminar burning velocity
- $L$: Markstein length
- $\kappa$: Flame stretch rate (= $2S_b/r$)
- $r$: Flame radius
- $r_0$: Critical radius
- $\rho_u$: Density of unburnt mixture
- $\rho_b$: Density of burnt gas
- $S_b$: Flame propagation velocity
- $S_{b0}$: Propagation velocity of planar flame

\[
S_b = 0.1267 \frac{2S_b}{r} + 441.8 \quad \therefore S_{b0} = 441.8
\]
4-2 Flame propagation velocity of planar flame

- Experimental data show good agreement with the data of other researchers
- Propagation velocity of planar flame becomes higher at higher initial temperature

Reference)
• At $\phi \geq 0.6$, critical radius becomes larger at higher initial temperature because formation of cellular flame is suppressed.
• At $\phi \leq 0.5$, critical radiuses at both temperature are nearly same because influence of flame stretch is stronger than influence of cellular flame.
5-1 Flame acceleration model

\[ S_b = \alpha \ln \left( \frac{r}{r_0} \right) + \beta \]

Influence of flame acceleration

\[ S_b = \frac{dr}{dt} \]

\[ \beta = S_{b0} \left( = S_{u0} \frac{\rho_u}{\rho_b} \right) \]

- \( r \): Flame radius
- \( r_0 \): Critical radius
- \( \rho_u \): Density of unburnt mixture
- \( \rho_b \): Density of burnt gas
- \( S_b \): Flame propagation velocity
- \( S_{b0} \): Propagation velocity of planar flame
- \( S_{u0} \): Burning velocity of flat flame
5-2 Influence of cellular flame

- Fitting flame propagation velocities by acceleration model, influence coefficients of flame radius, $\alpha$, were obtained.

\[ S_b = \alpha \ln \left( \frac{r}{r_0} \right) + \beta \]

\[ \beta_{\phi=0.6} = S_{b0,\phi=0.6} = 538.9 \]

\[ S_b = 182.7 \ln(r^*) + 538.9 \]

\[ \therefore \alpha = 182.7 \]
5-2 Influence of cellular flame

\[ S_b = \alpha \ln\left(\frac{r}{r_0}\right) + \beta \]

\[ \frac{S_b}{S_{b0}} = \frac{\alpha}{\beta} \ln\left(\frac{r}{r_0}\right) + 1 \]

\(\alpha/\beta\) is influence coefficient of flame radius on flame acceleration.

- Influence of flame radius becomes stronger at lower equivalence ratio
  \(\Rightarrow\) \(S_b/S_{b0}\) becomes larger owing to development of cellular flame.
- Influence of flame radius becomes weaker at higher initial temperature.
5. Summary

- As flame radius increased, cellular flame developed more and flame propagation velocity increased.

- Propagation velocity of planar flame obtained experimentally show good agreement with the data of other researchers.

- At lower equivalence ratio, cellular flame developed more and \( S_b/S_{b0} \) became larger.

- At higher initial temperature, flame propagation velocity of planar flame increased, and flame accelerations caused by cellular flame were suppressed.

- Based on these results, we proposed the flame acceleration model using logarithm of flame radius.
6. Future plan

- In order to understand more effects of initial temperature, explosion tests will be performed at higher initial temperature, 75 deg C.

- In order to see effects of composition of mixture gas, we will add CO$_2$ into mixture gas as first step.

- In order to see effects of initial pressure, we will conducted explosion tests at several pressures.
Thank you for your kind attention!!

Acknowledgment

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