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Outward propagation velocity and acceleration characteristics in hydrogen-air deflagration

Nagaoka University of Technology

Toshiyuki KATSUMI
Hiroyuki KOBAYASHI
Takuro AIDA
Hiroki AIBA
Satoshi KADOWAKI

1-1 Combustion safety

- ■ Hydrogen
  - ✓ Clean fuel
    - Zero carbon emission
    - Combustion product: H_2O
    - 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

Explosion!

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)
=(Burning velocity)×(Thermal expansion)

Not enough!

$$S_b = S_u\left(\frac{T_b}{T_u}\right)$$

1-3 Flame acceleration

- Intrinsic instability
  - ✓ Cellular flame front forms
    - ⇨ Flame front area becomes larger
    - ⇨ Flame propagation accelerates

Cellular flame

Flame acceleration

  - ✓ 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 (H_2, Air, CO_2, H_2O, 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

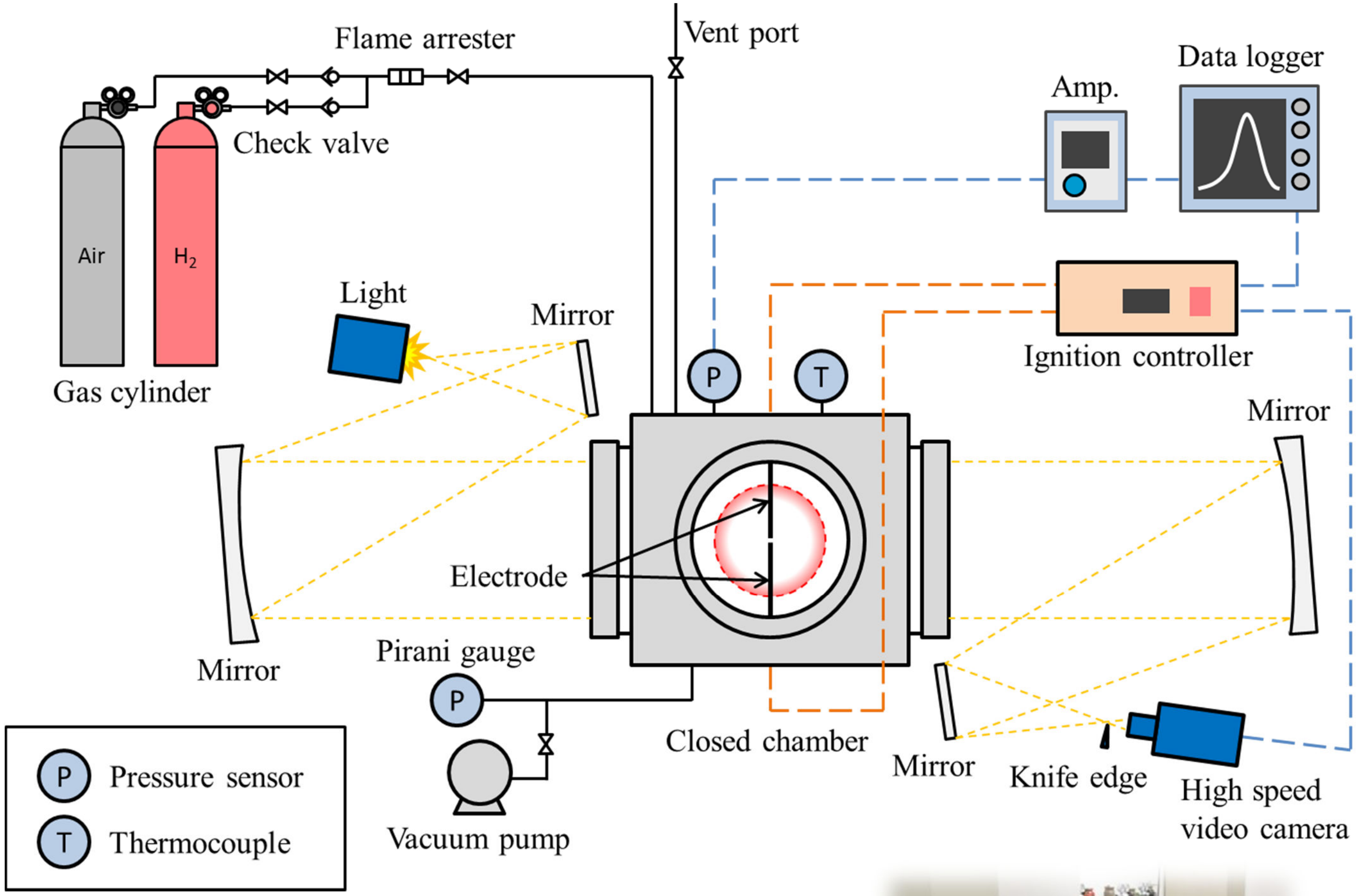
Volume: 73L
Material: SUS304
Window
- Diameter: 300mm
- Thickness: 140mm
- Material: Quartz
- Quantity: 4

Others

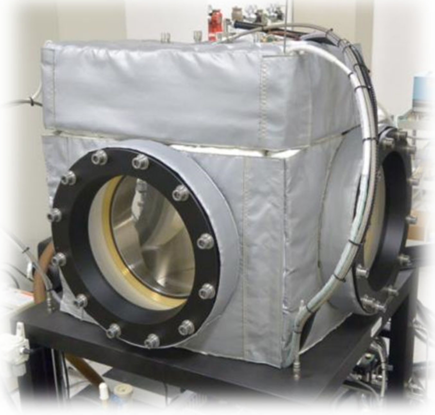
Ignition
- Voltage: 7.5kV
- Energy: 110mJ

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 NR600



3-2 Experimental procedure

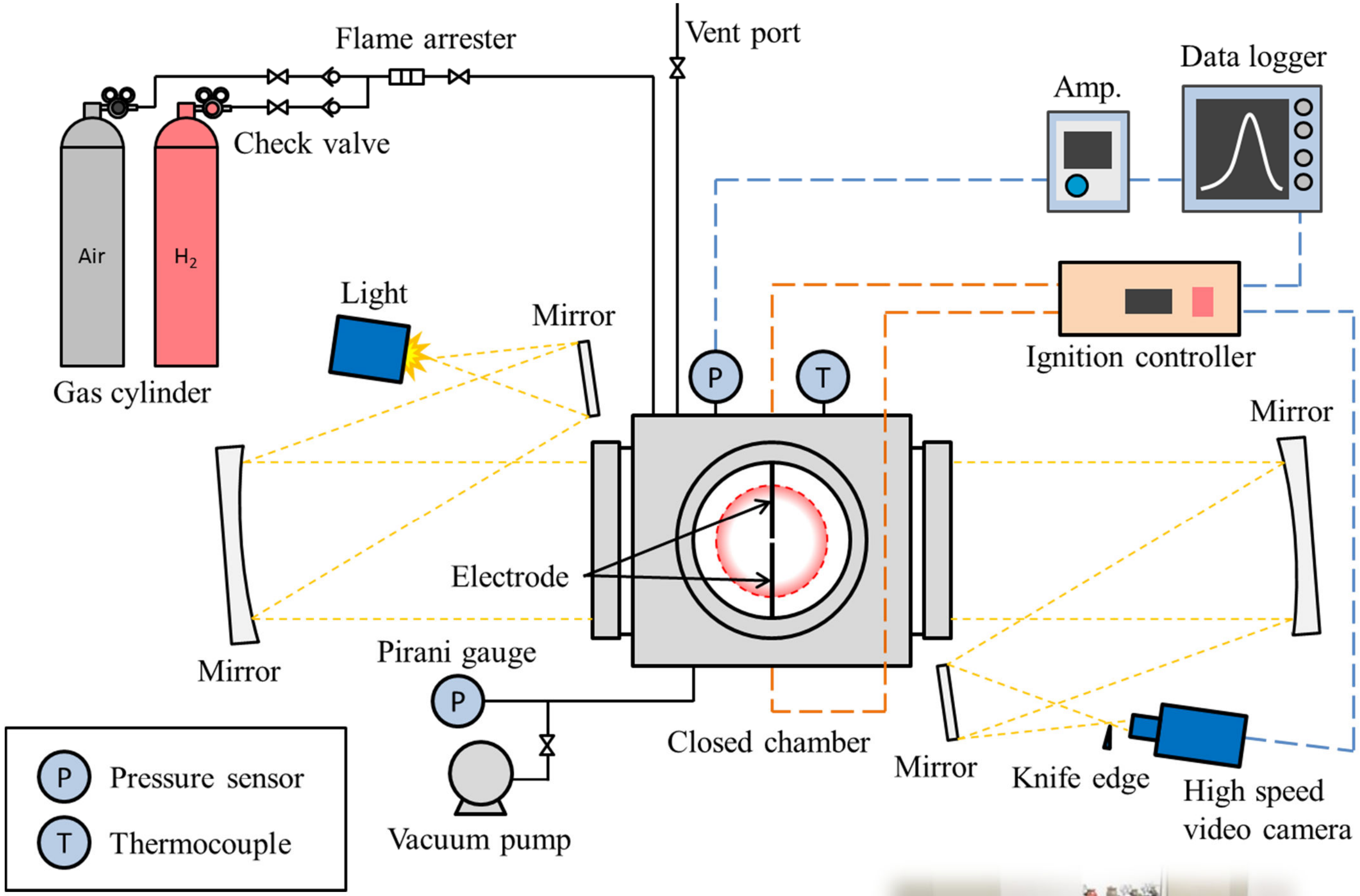
① Heat up the chamber

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



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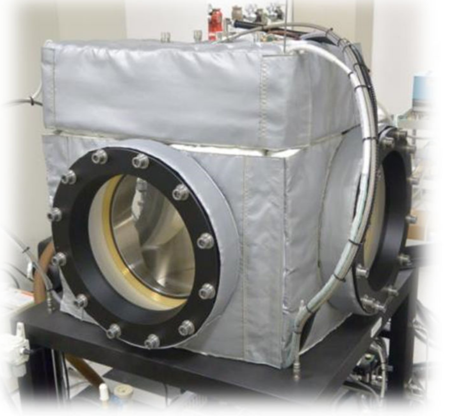


3-3 Experimental condition

- Initial condition

  Mixture: Hydrogen-air

  Pressure: 101.3kPa abs.

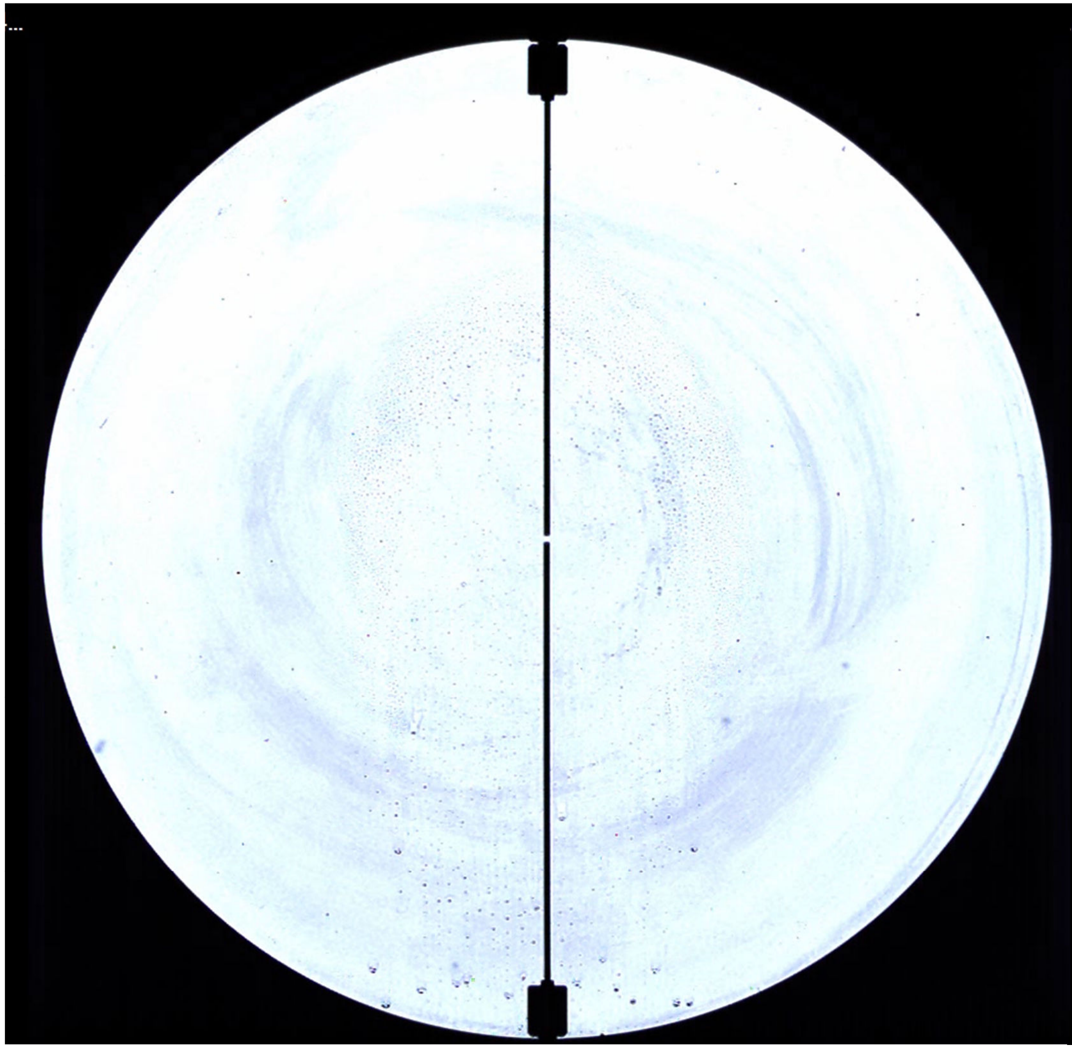
- Explosion test

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

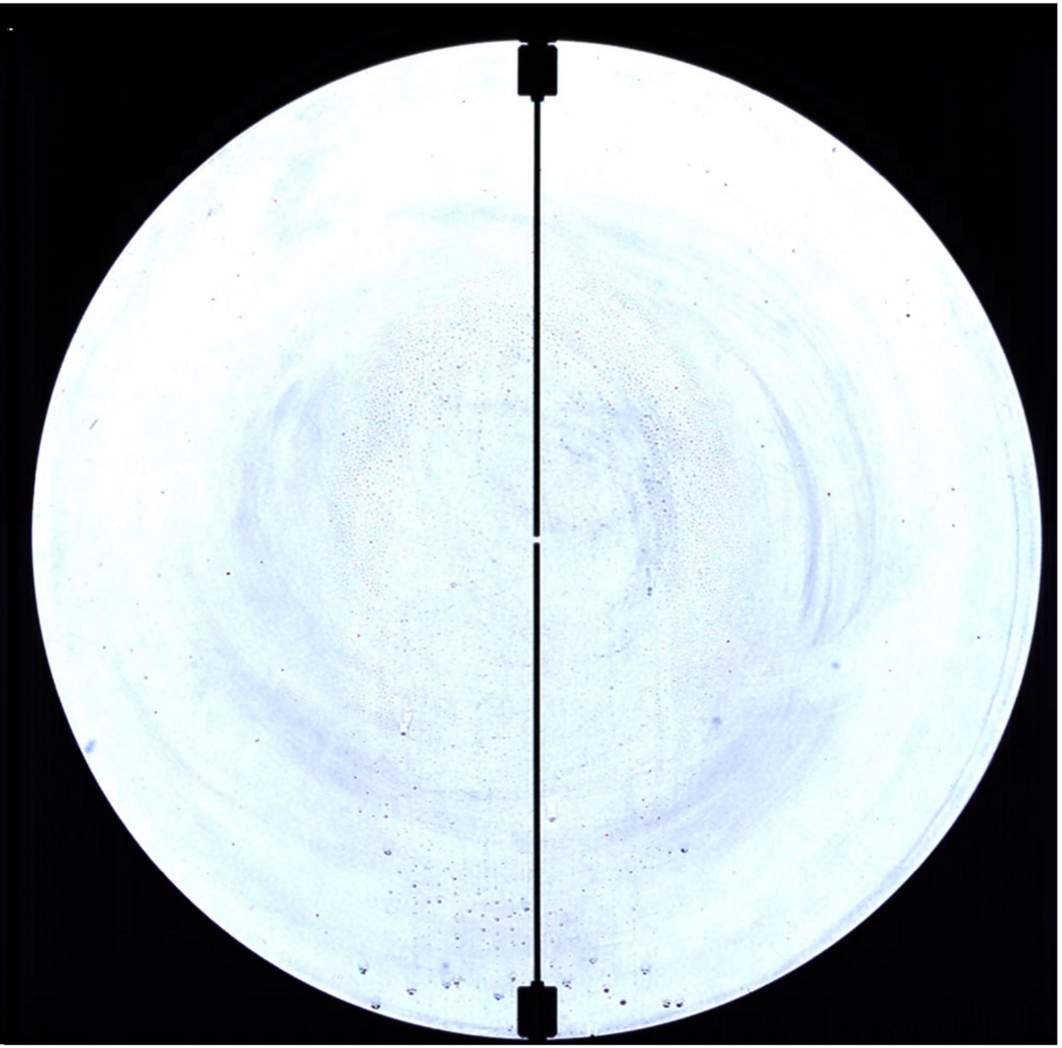
Table1 Test condition

Initial temperature [deg C]	Equivalence ratio									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
25	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
50	⬜	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
75	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜

3-4 Experimental results

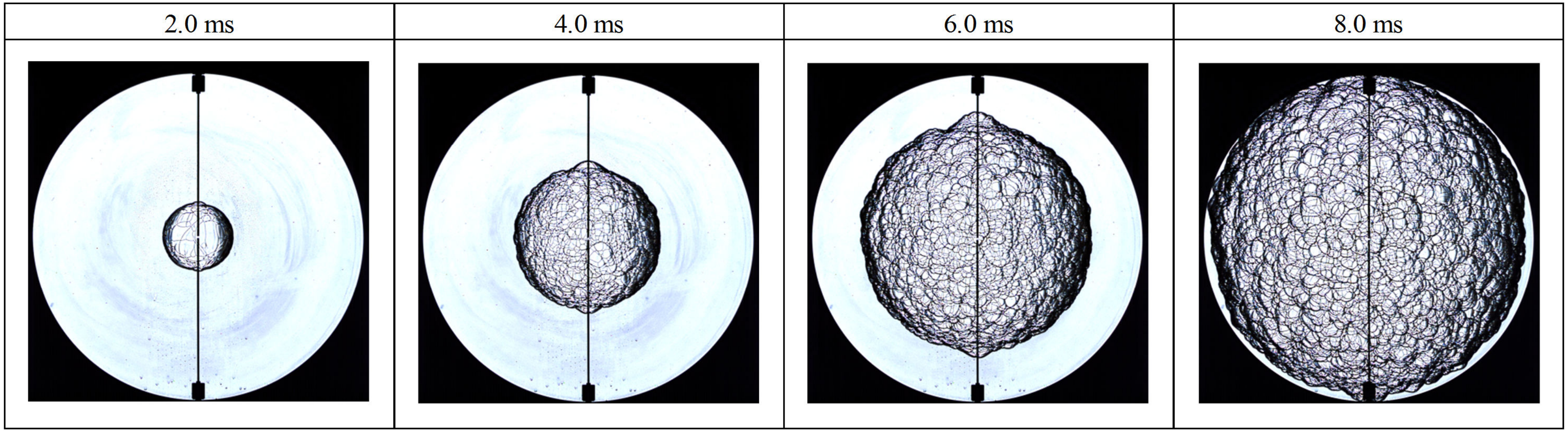


Equivalence ratio $\varphi = 1.0$

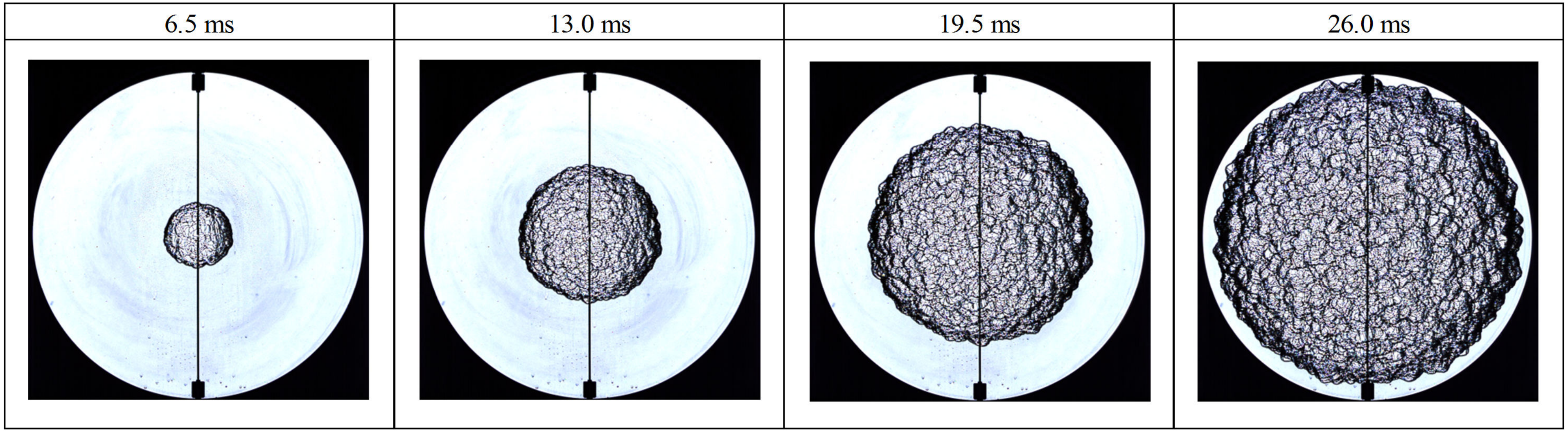


Equivalence ratio $\varphi = 0.5$

3-4 Experimental results

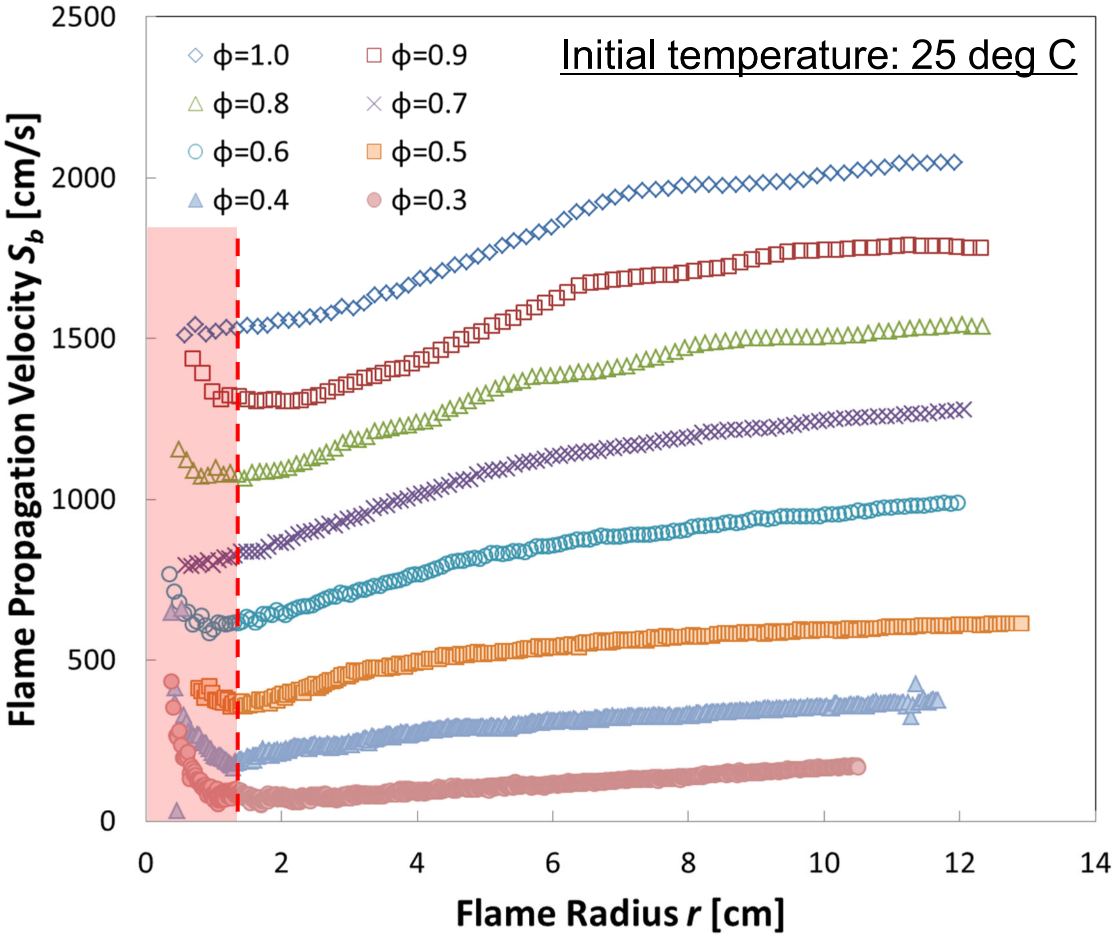


(a) $\varphi = 1.0$ ($r_b = 2.0$, 5.0 , 10 , 15 [cm])



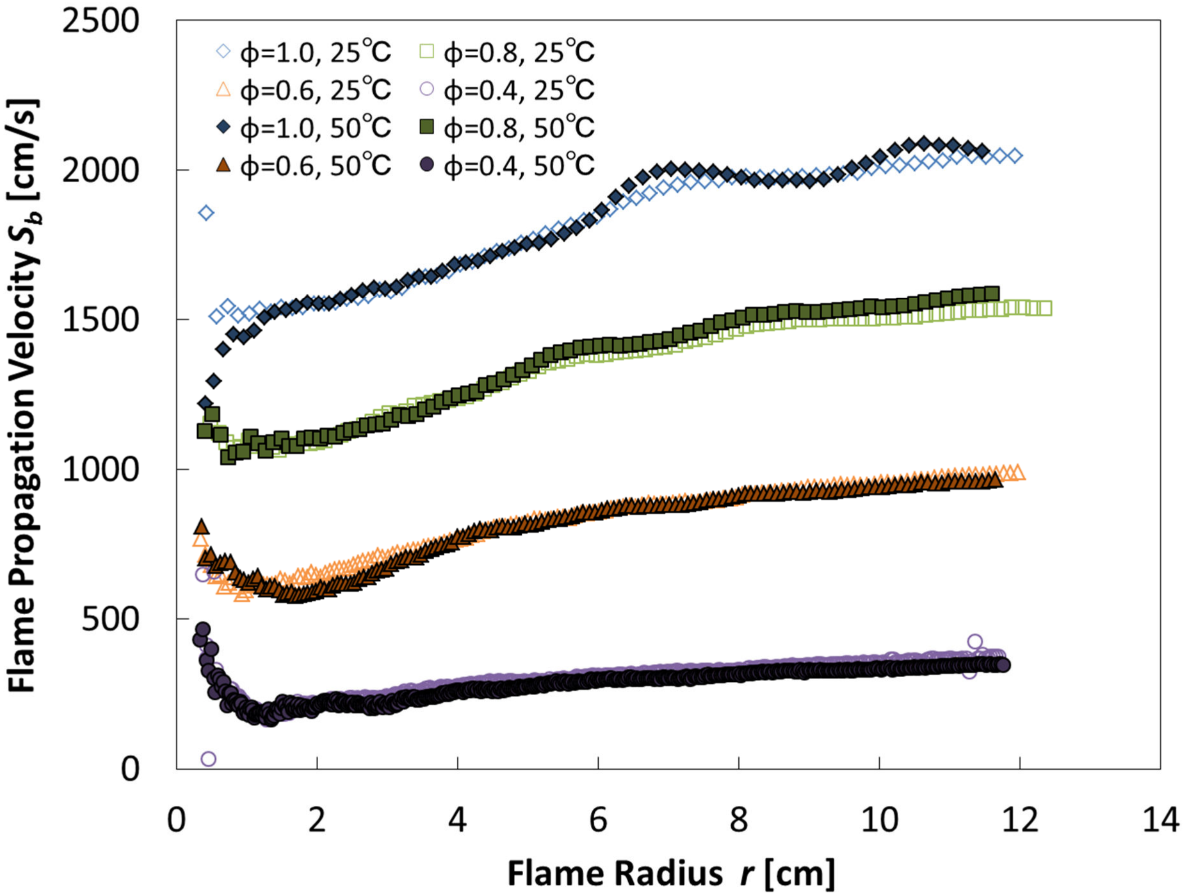
(b) $\varphi = 0.5$ ($r_b = 2.0$, 5.0 , 10 , 15 [cm])

3-5 Flame propagation velocity -Effect of equivalence ratio-



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

3-6 Flame propagation velocity -Effect of initial temperature-



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

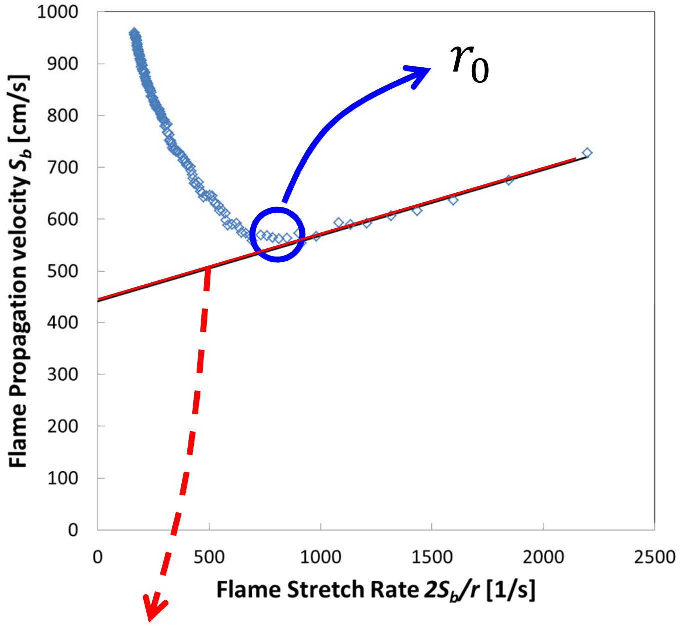
Relation between burning velocity and flame stretch rate

$$S_s - S_{u0} = -L\kappa$$

$$\Rightarrow S_b = -L\kappa\left(\frac{\rho_u}{\rho_b}\right) + S_{b0} = \boxed{-L\frac{2S_b}{r} + S_{b0}}$$

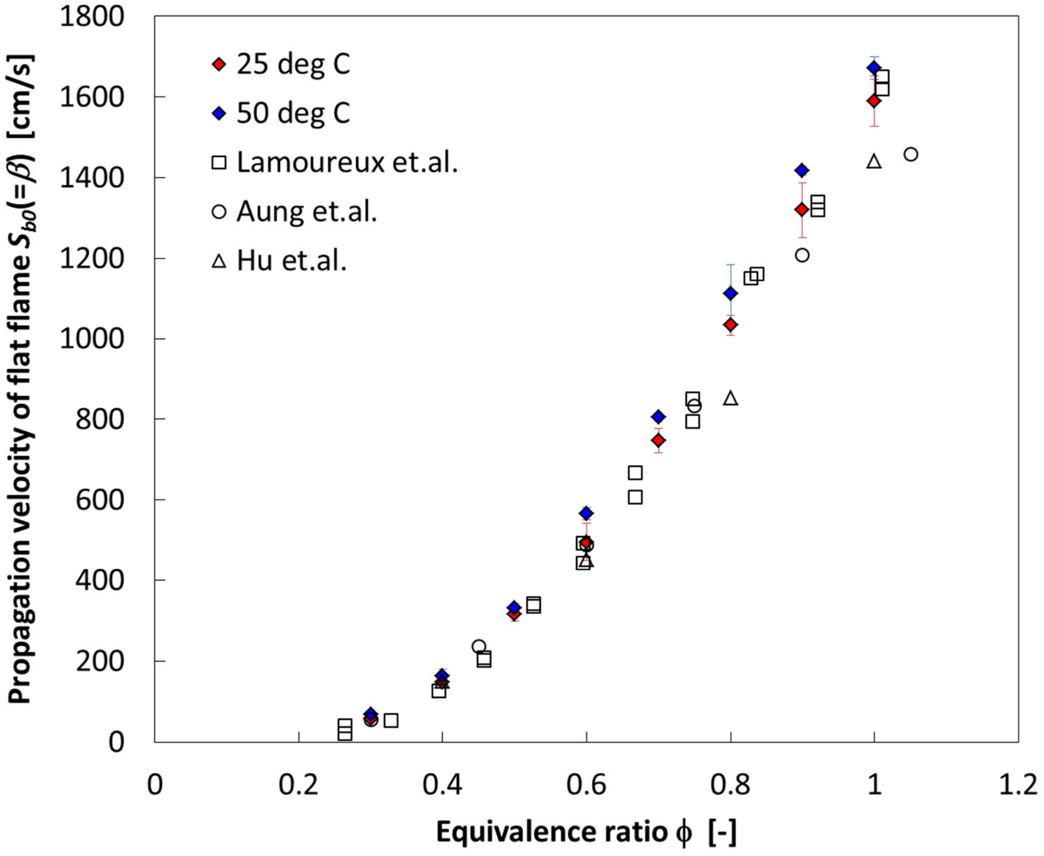
S_s; Burning velocity of stretched flame
S_{u0}; Laminar burning velocity
L; Markstein length
κ; Flame stretch rate $(= 2\,S_b/r)$
r; Flame radius
r_0; Critical radius
ρ_u; Density of unburnt mixture
ρ_b; Density of burnt gas
S_b; Flame propagation velocity
S_{b0}; Propagation velocity of planar flame

e.g.) Case of φ=0.6



$$S_b = 0.1267\frac{2S_b}{r} + 441.8 \qquad \therefore S_{b0} = 441.8$$

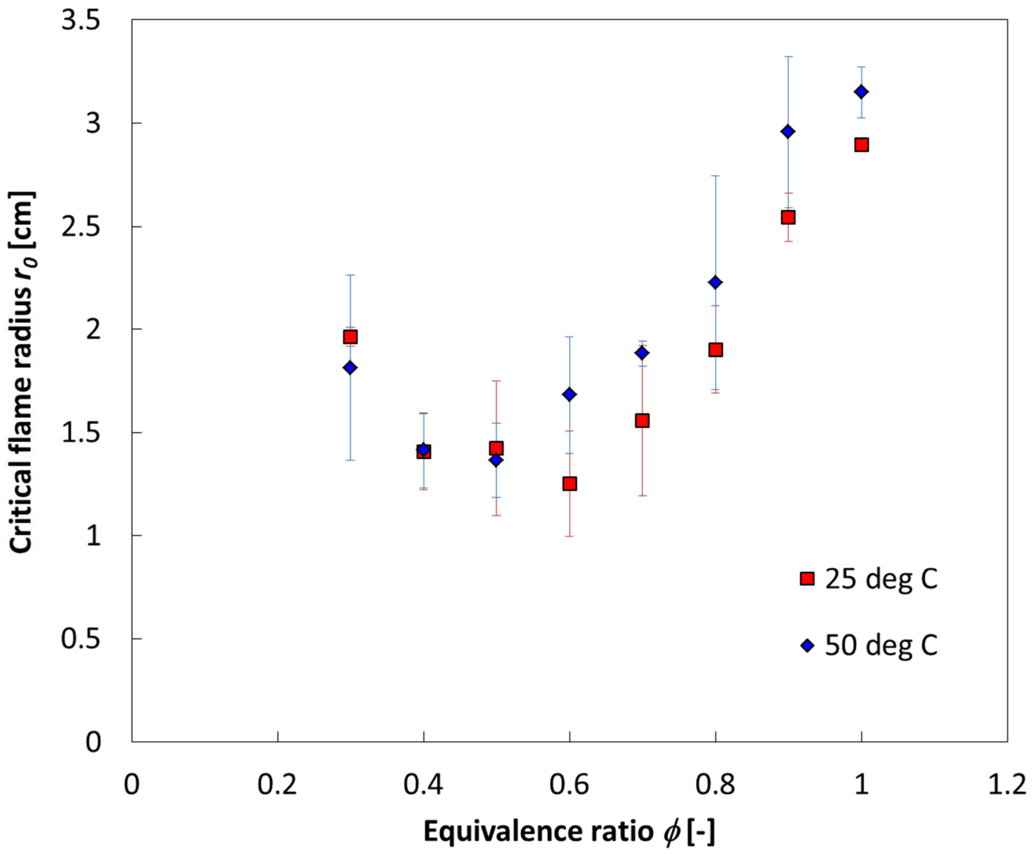
4-2 Flame propagation velocity of planar flame



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

Reference) Lamoureux, N., Chaumeix, N.D., Paillard, C.E., *Experimental Thermal and Fluid Science* 27: 385–393 (2003)
Aung, K.T., Hassan, M. I., and Faeth, G.M., *Combust. Flame* 109:1-24(1997)
Hu, E., Huang, Z., He, J. and Miao, H., *Int J. Hydrogen Eng.* 34:8741-8755(2009)

4-3 Critical flame radius



- At $\phi \geqq 0.6$, critical radius becomes larger at higher initial temperature because formation of cellular flame is suppressed.
- At $\phi \leqq 0.5$, critical radiuses at both temperature are nearly same because influence of flame stretch is stronger than influence of cellular flame.

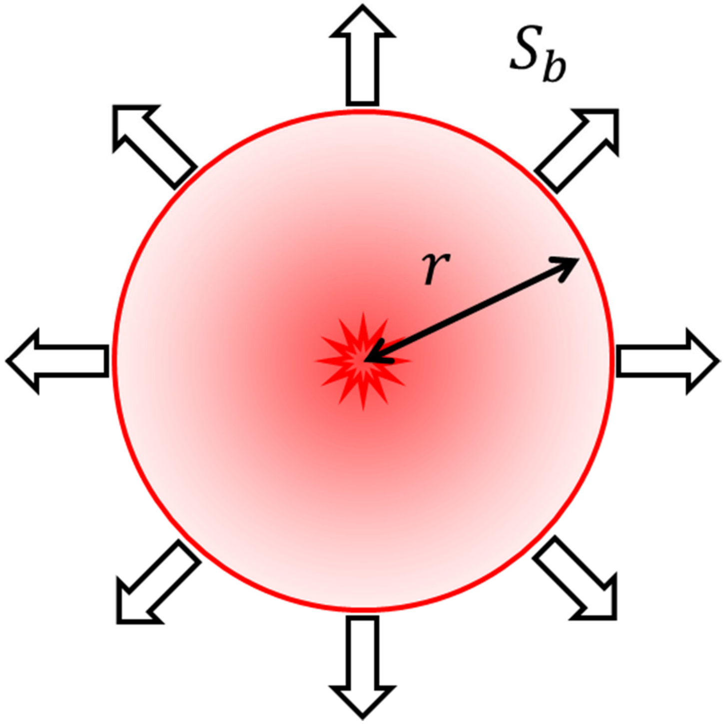
5-1 Flame acceleration model

$$\boxed{S_b = \underbrace{\alpha \ln\left(\frac{r}{r_0}\right)} + \beta}$$

Influence of flame acceleration

$$S_b = \frac{dr}{dt}$$

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

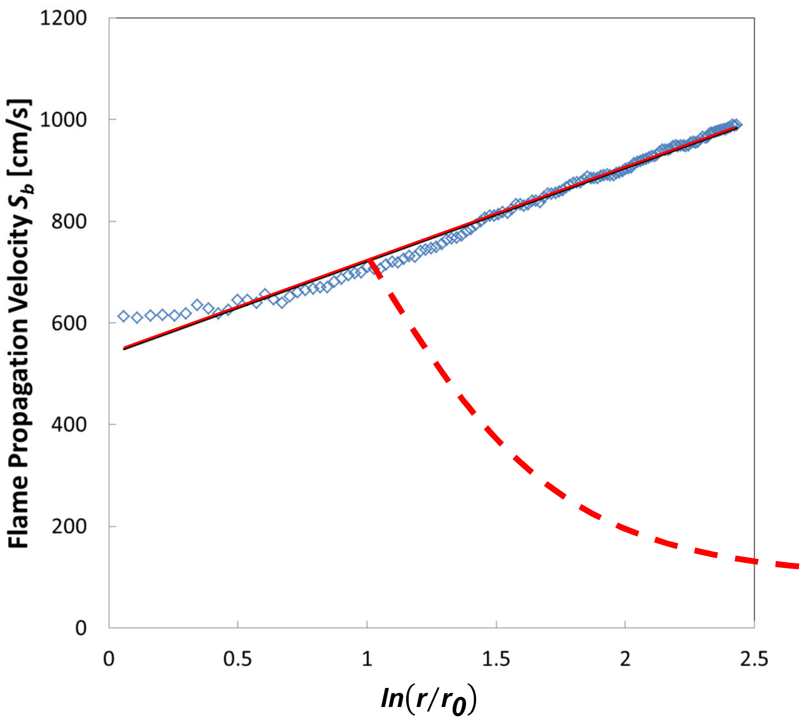


r; Flame radius
r_0; Critical radius
ρ_u; Density of unburnt mixture
ρ_b; Density of burnt gas
S_b; Flame propagation velocity
S_{b0}; Propagation velocity of planar flame
S_{u0}; Burning velocity of flat flame

5-2 Influence of cellular flame

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

<u>e.g. Case of *φ*=0.6</u>



Curve fitting $(r \geqq r_0)$

Acceleration model

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

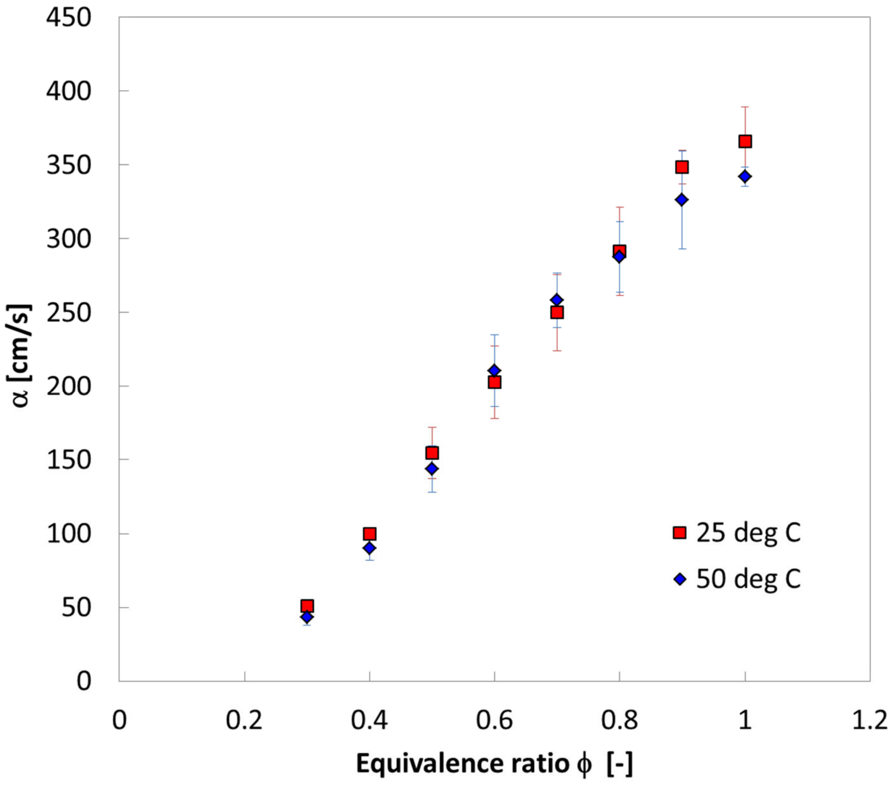
$$\beta_{\phi=0.6} = S_{b0,\phi=0.6} = 538.9$$

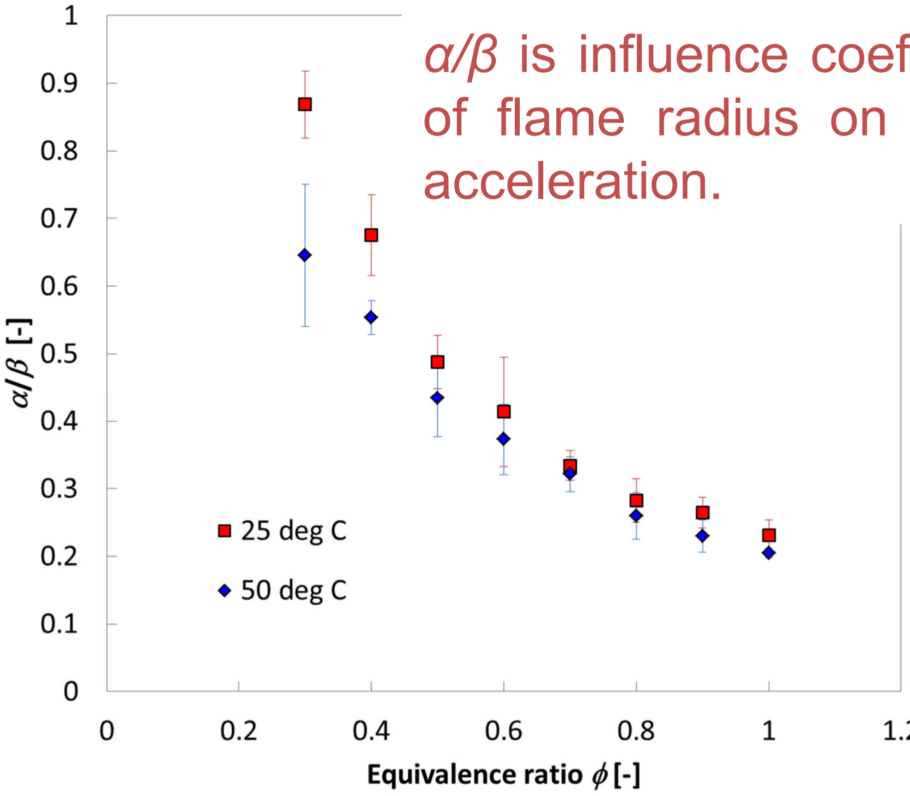
$$S_b = 182.7\ln(r^*) + 538.9$$

$$\therefore \alpha = 182.7$$

5-2 Influence of cellular flame

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





α/β is influence coefficient of flame radius on flame acceleration.

- Influence of flame radius becomes stronger at lower equivalence ratio

⇒ 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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