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Enhancement of Reaction and Stability of Ammonia Flames using Hydrogen Addition and Swirling Flows

***Akihiro Hayakawa**, Akinori Ichikawa, Yoshiyuki Arakawa, Taku Kudo and Hideaki Kobayashi*

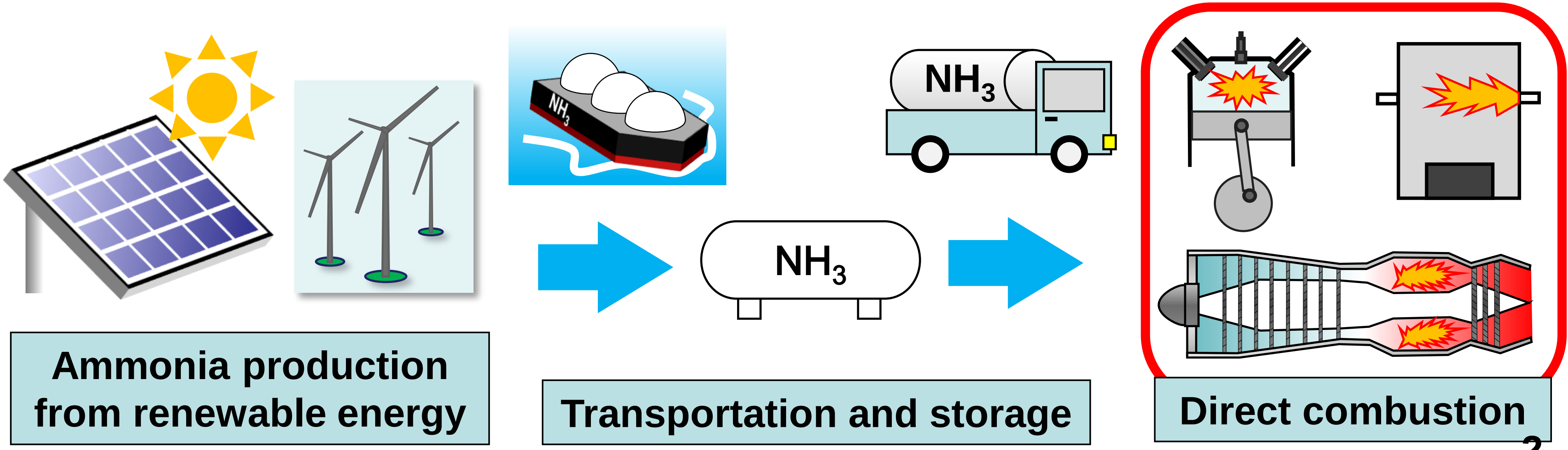
Institute of Fluid Science, Tohoku University, Japan

Outline

1. Background and objectives
2. Reaction enhancement by the hydrogen addition
   - Experimental evaluation of laminar burning velocity of ammonia/hydrogen/air flames at the high pressures
3. Stabilization enhancement by a swirling flow
   - Stabilization limit of ammonia/air premixed flame on a gas turbine-like combustor
4. Conclusions

Background

- Ammonia(NH_3) as a hydrogen-energy carrier
  - New manufacturing process using alternative fuels and high efficiency conversion to hydrogen
- Features of ammonia
  - High hydrogen capability (hydrogen mass density: approx. 18 wt%)
  - Storage and transportation are easy because ammonia liquidizes approx. at 8.5 atm in the room temperature.
  - Infrastructures for ammonia manufacturing and distribution have already been established.



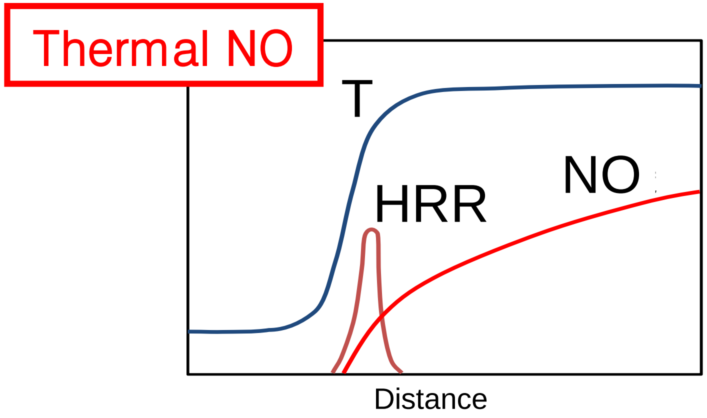
Application of NH_3 as a fuel

✓ Ammonia combustion = **Carbon-free combustion**

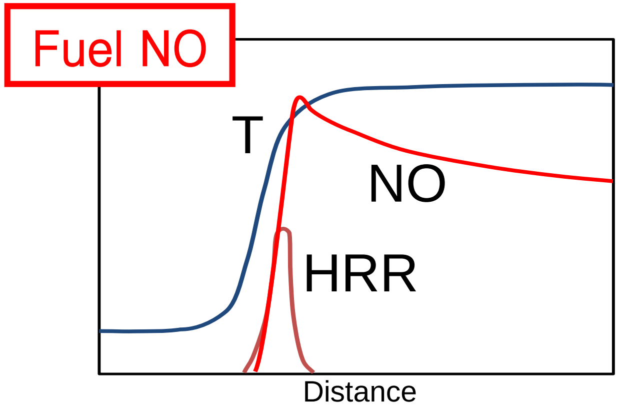
$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$$

Issues of the ammonia combustion

- Improvement of lower combustion intensity (Lower burning velocity, narrower flammable range etc.).
- Large amount of NO_x should be formed because NH_3 includes N atom.



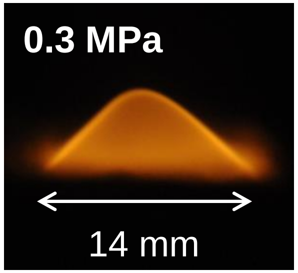
Structure of HC flame



Structure of NH_3 flame

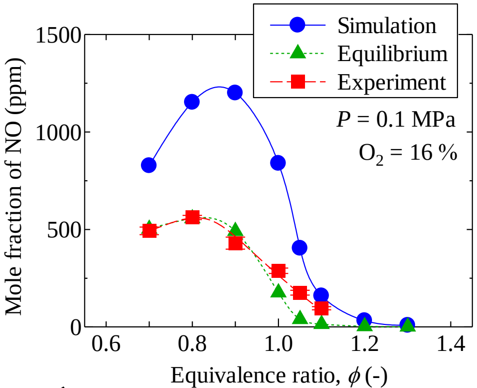
Fundamental characteristics of ammonia flames should be clarified.

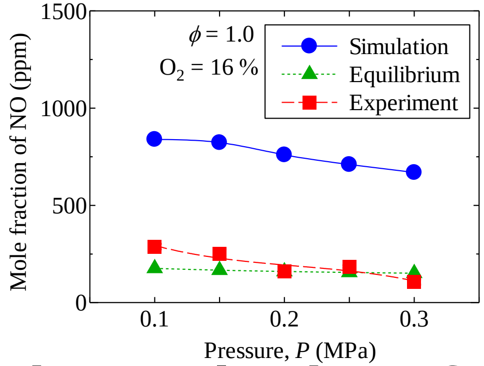
Recent studies



Burner stabilized ammonia/air flame

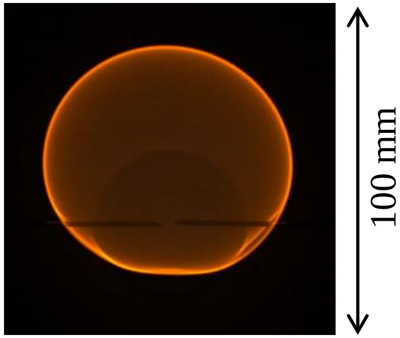
✓ NO formation/reduction mechanism [1]



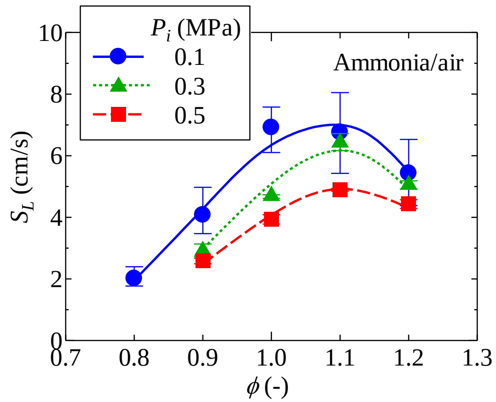


✓ NO **decreases** with the increase in equivalence ratio and mixture pressure.

✓ Laminar burning velocity of ammonia/air flames [2]



Spherically propagating ammonia/air flame

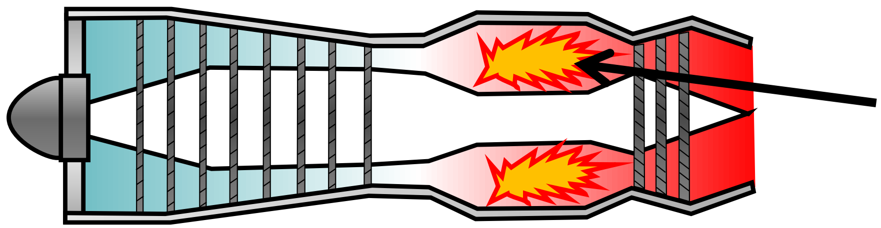


✓ Maximum value of laminar burning velocity of ammonia/air flame is about **7 cm/s**, and is about **1/5** of methane/air flame.

Fundamental flame characteristics is being studied.

[1] A. Hayakawa et al., Mechanical Engineering Journal, Vol. 2, No. 14-00402. 2015.
[2] A. Hayakawa et al., Fuel, Vol. 159, pp. 98-106, 2015.

Flame enhancement



Actual combustor:
{High speed combustion
High pressure combustion
for a high combustion load

Enhancement of the ammonia flame:

- **Reaction enhancement by the hydrogen addition**

  Higher combustion intensity, production from ammonia and carbon free

  ✓ Frigo and Gentili[3]: Hydrogen added ammonia is adopted to SI engine.

  ✓ Laminar burning velocities of ammonia/hydrogen/air flame were clarified by Lee et al.[4], Kumar et al.[5] and Li et al.[6].

    - All experiments were performed at the atmospheric pressure.

- **Stabilization enhancement by a swirling flow**

  Swirling flow is adopted in an actual gas turbine combustor to increase the flame stability. There is no study of ammonia flame on a swirl combustor.

[3]S. Frigo and Gentili, Int. J. of Hydrogen Energy 38 2013: 1607-1615, [4] Lee et al. Int. J. Hydrogen energy 35 2010; 11332-11341, [5] Kumar and Meyer. Fuel 108 2013;166-176, [6] Li et al. Int. J. Energy Research 38 2014; 214-1223.

Objective of this study

Objective

To achieve flame enhancement of ammonia flame:

- Reaction enhancement of ammonia by the hydrogen addition
- Stability enhancement by a swirling flow.

- Experimental investigation of laminar burning velocity of ammonia/hydrogen/air premixed flames using a constant volume combustion chamber up to 0.5 MPa.
- Flame stabilization limit of ammonia/air premixed flame on a gas turbine like swirl combustor.

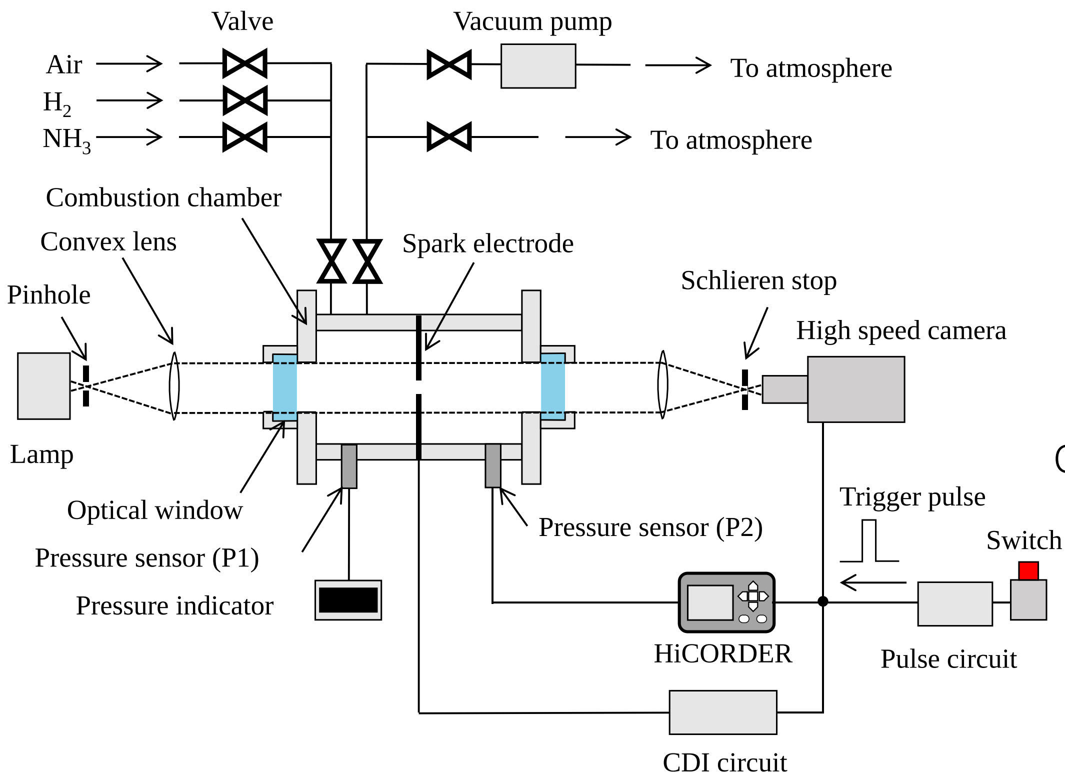
Topic 1

Reaction enhancement by hydrogen addition

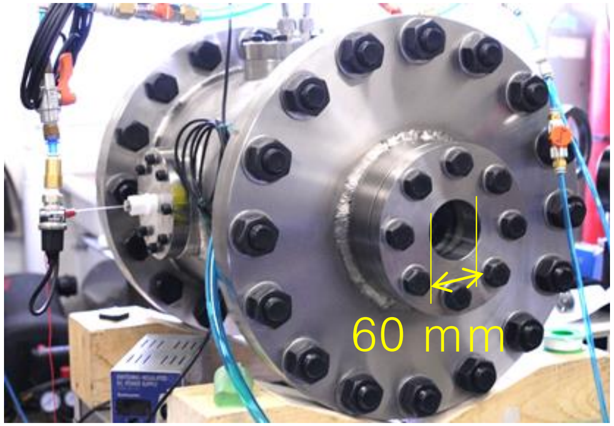
- Experimental evaluation of laminar burning velocity and Markstein length
- Comparison between experimental and numerical results

Detail:
A. Ichikawa, A. Hayakawa, Y. Kitagawa, K.D.K.A. Somarathne, T. Kudo and H. Kobayashi, Laminar burning velocity and Markstein length of ammonia/hydrogen/air premixed flames at elevated pressures, *International Journal of Hydrogen Energy*, Vol. 40, pp. 9570-9578, 2015

Experimental setup



Experimental setup



Constant volume combustion chamber

Hydrogen ratio in fuel

$$x_{H2} = \frac{[H_2]}{[H_2] + [NH_3]}$$

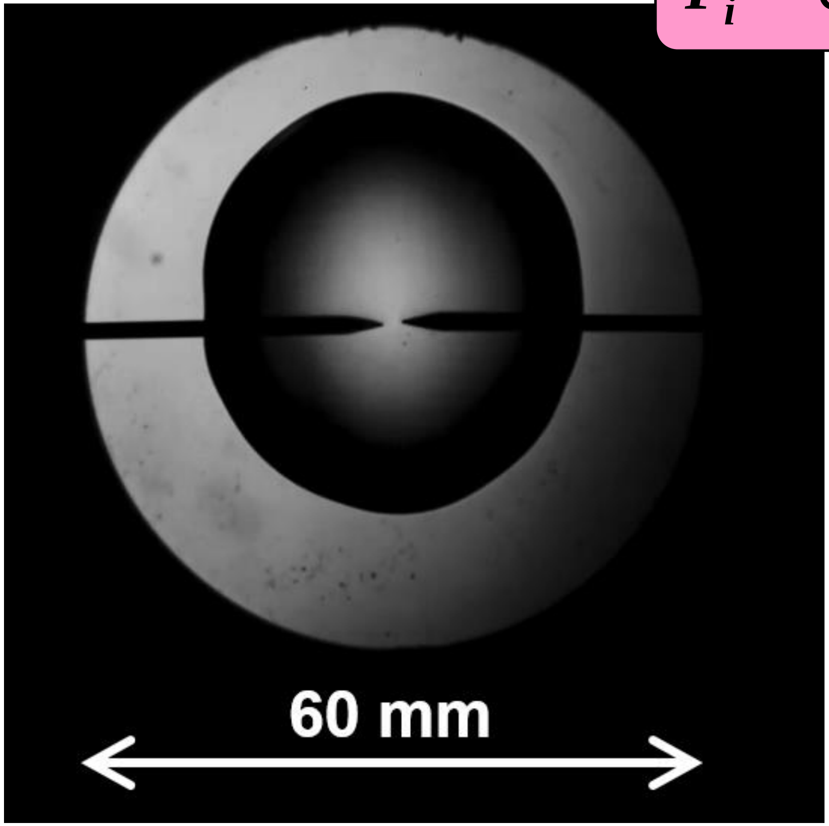
[X]：Mole fraction of X

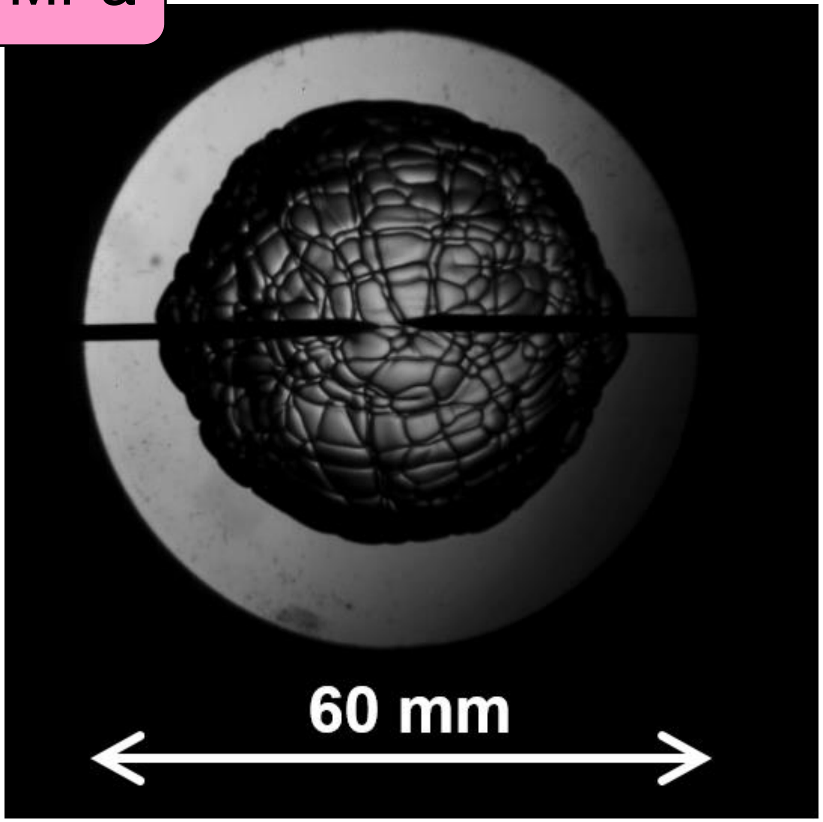
- Volume： approx. 23 L
- Observation windows： ϕ 60 mm
- Diameter of the electrodes： 1.5 mm
- Distance of the electrodes： 2 mm
- Electrostatic energy： 0.28 – 2.8 J

- Mixture：NH_3/H_2/air
- Initial temperature： 298 K
- Initial mixture pressure, P_i： 0.1, 0.3, 0.5 MPa
- Equivalence ratio, ϕ： 1.0 (stoichiometry)
- x_{H2}：0 – 1.0

High-speed schlieren images

P_i = 0.5 MPa





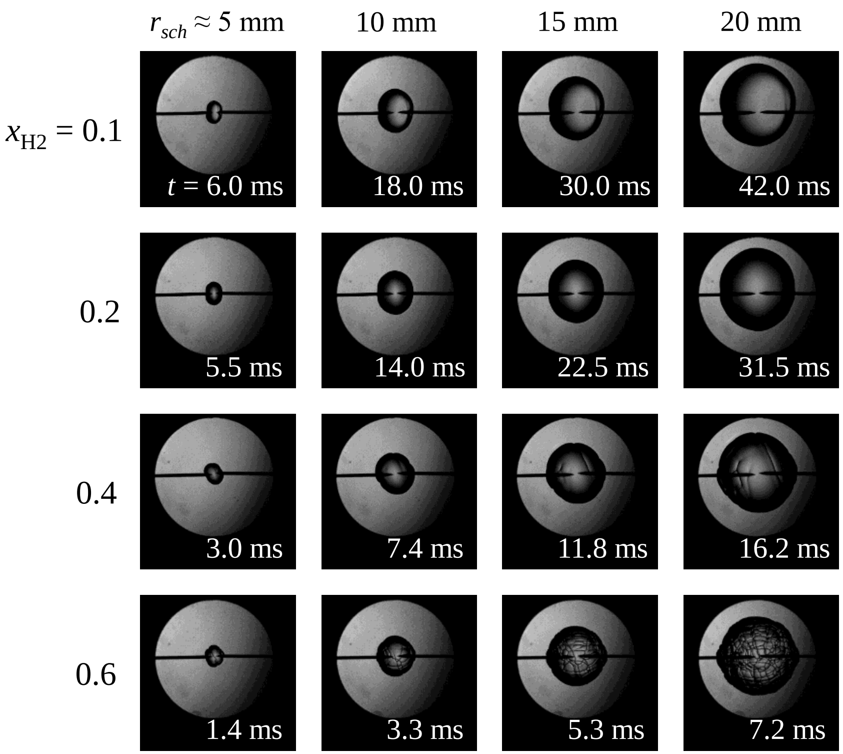
x_{H2} = 0.2
5000 fps

x_{H2} = 0.6
10000 fps

Observation of flames

Effects of hydrogen addition

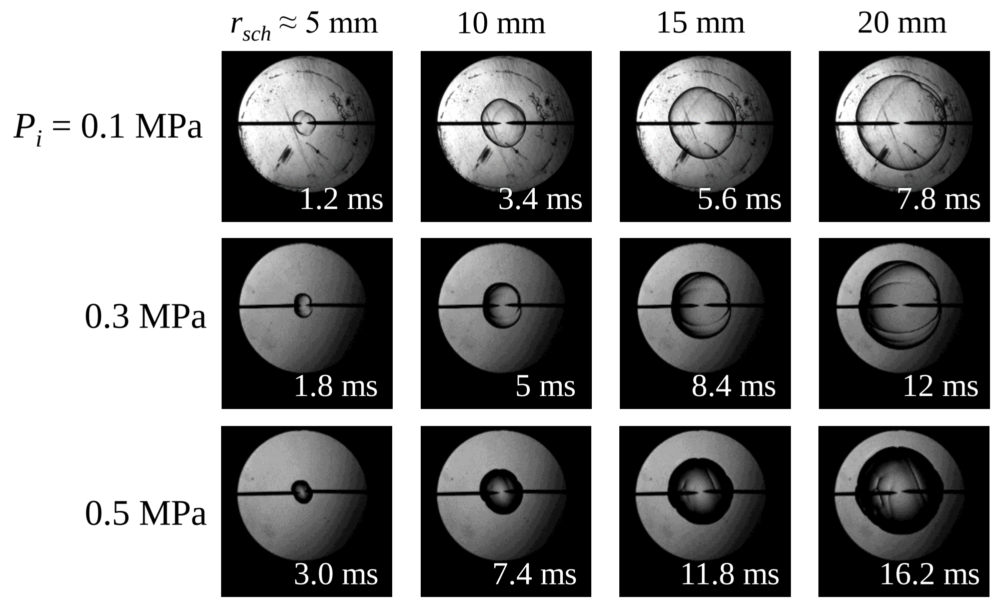
P_i = 0.5 MPa



- ✓ Flame propagation speed increases with x_{H2}.
- ✓ Flame front wrinkling can be observed at high x_{H2}.

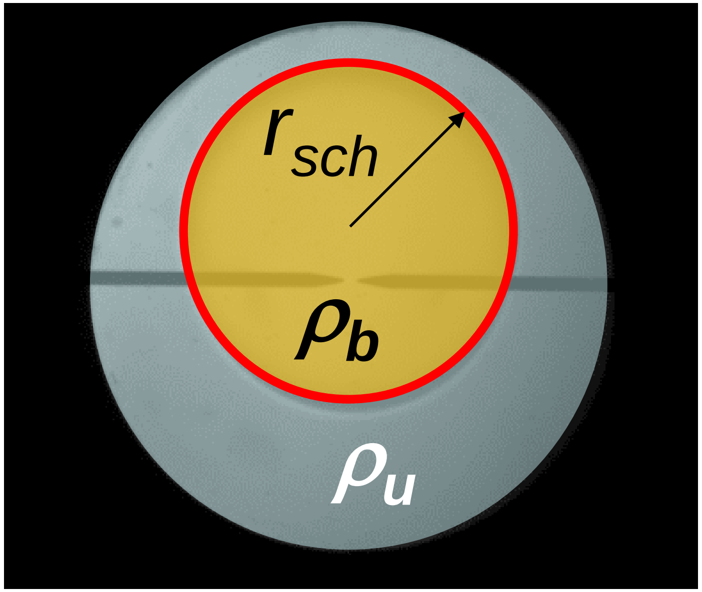
Effects of pressure

x_{H2} = 0.4



- ✓ Flame propagation speed decreases with P_i.

Analysis of spherical flames

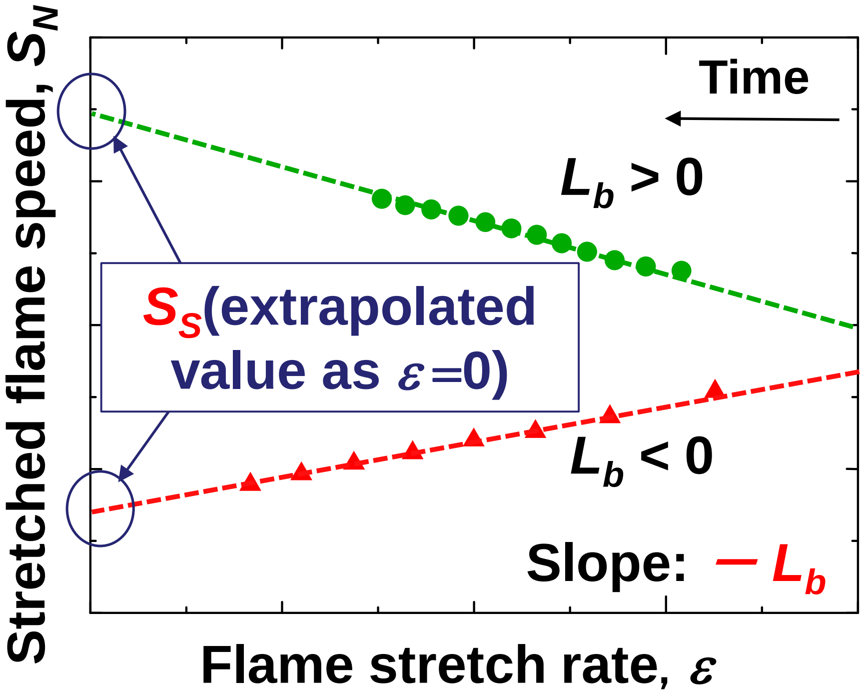


$$S_N = \frac{dr_{sch}}{dt} \ldots\ldots(1)$$

$$\varepsilon = \frac{1}{A}\cdot\frac{dA}{dt} = \frac{2}{r_{sch}}\cdot\frac{dr_{sch}}{dt} \ldots\ldots(2)$$

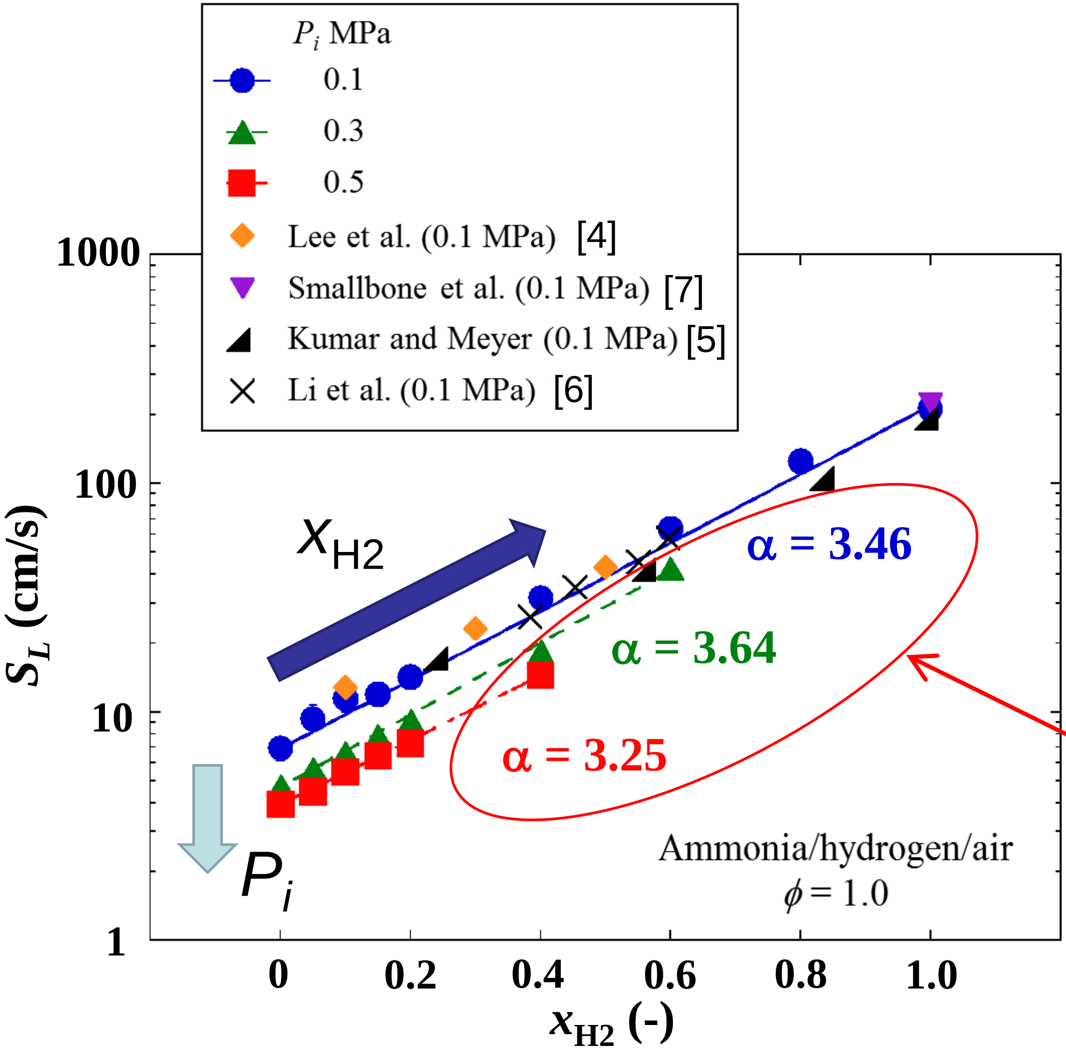
$$S_S - S_N = L_b \cdot \varepsilon \ldots\ldots(3)$$

$$S_L = \frac{\rho_b}{\rho_u}\cdot S_S \ldots\ldots(4)$$



S_N : Stretched flame speed
ρ_u: Unburned mixture density
ρ_b: Burned gas density
r_{sch}: Flame radius, t: time, ε: Flame stretch rate
A: Flame front area ($= 4\pi r_{sch}^2$)
S_S: Unstretched flame peed
S_L: Unstretched laminar burning velocity
L_b: Burned gas Markstein length

Unstretched laminar burning velocity, S_L



As hydrogen ratio increases, S_L increases linearly on semilog graph. (The vertical axis is shown as log scale.)

$$\frac{S_L(x_{H2})}{S_L(x_{H2}=0)} = \exp(\alpha \cdot x_{H2}) \quad (5)$$

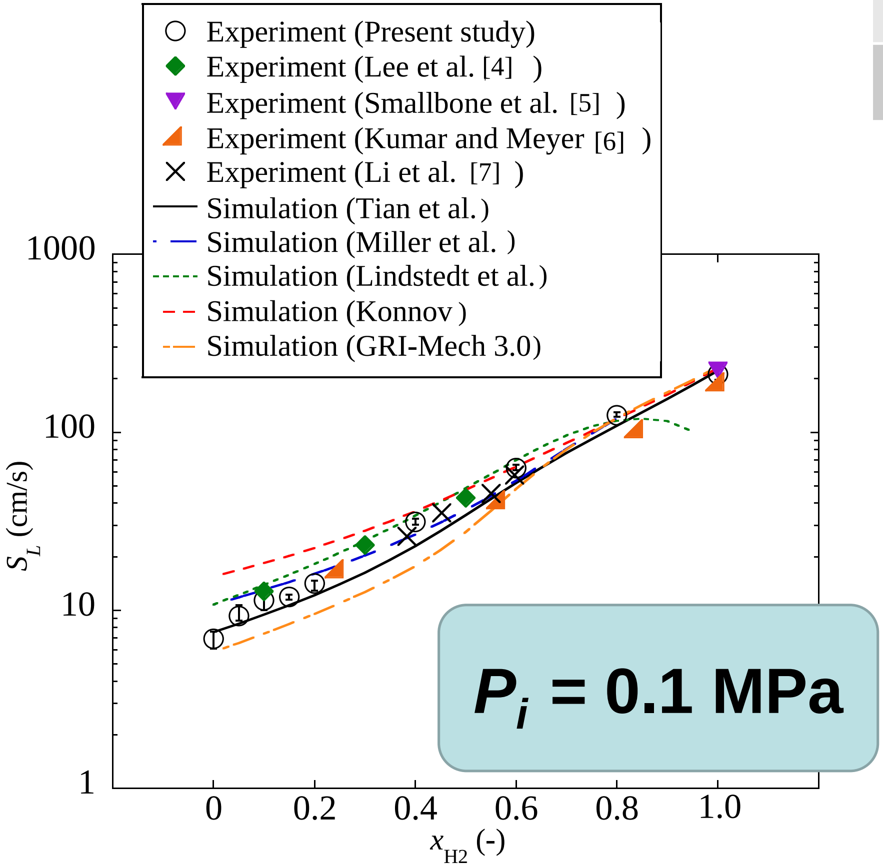
α : constant

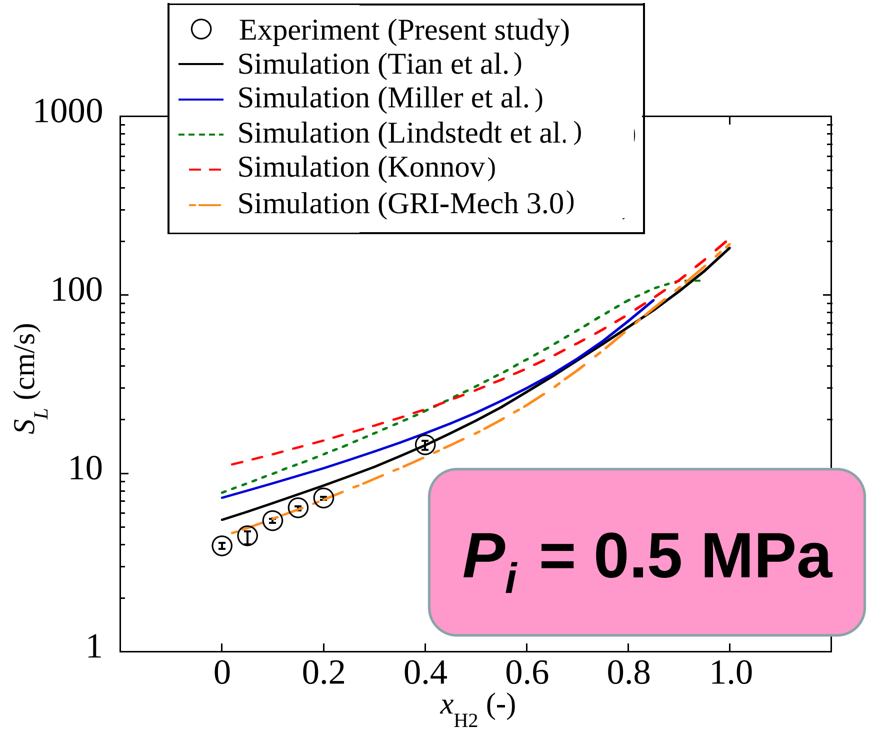
- The values of α are about 3.5 at all initial mixture pressures.
- It can be presumed that the effects of pressure on hydrogen addition is small.

[4] Lee et al. Int. J. Hydrogen energy 35 2010;11332-11341 , [5] Kumar and Meyer. Fuel 108 2013;166-176, [6] Li et al. Int. J. Energy Research 38 2014;1214-1223, [7] Smallbone et al. J. Thermal. Sci. Technol 1 2006;31-41

Comparison of S_L with numerical values

Mechanism	Year	Species	Reactions
Tian et al.	2009	84	703
Miller et al.	1983	23	98
Konnov	2009	129	1231
GRI-Mech 3.0	2000	53	325
Lindstedt et al.	1994	21	95



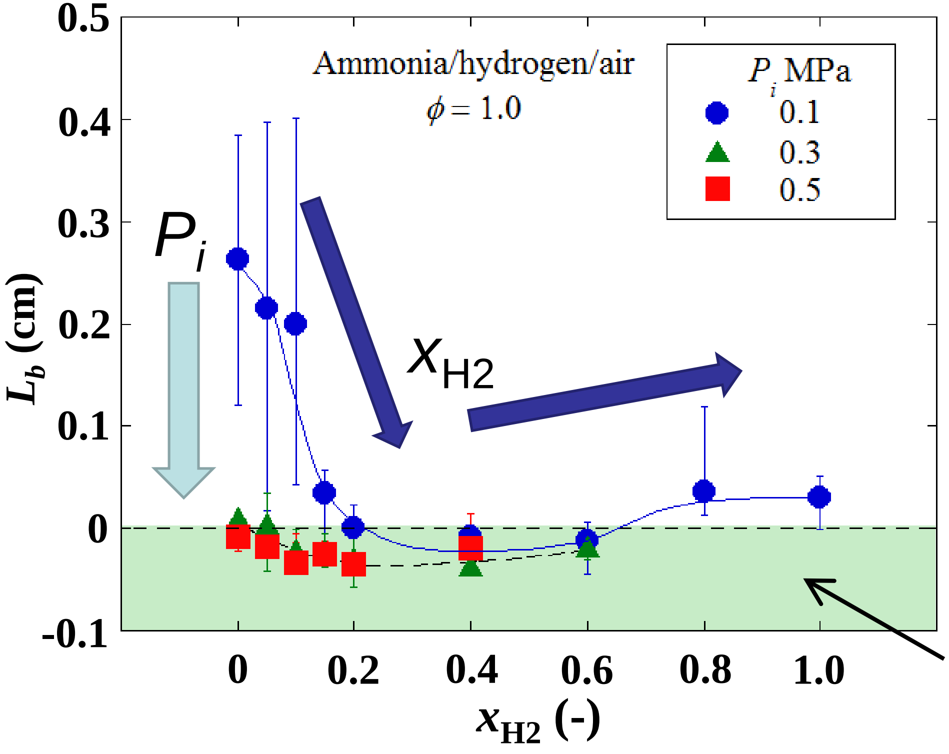


Further improvement of reaction mechanism is required.

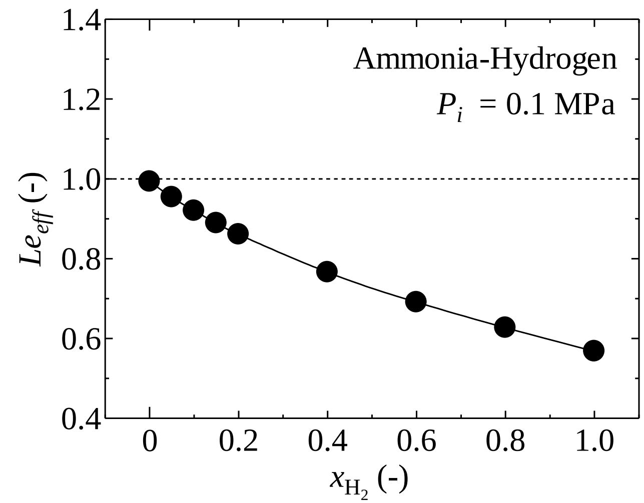
Markstein length, L_b

Markstein length, L_b : Sensitivity of laminar burning velocity to flame stretch

$L_b < 0$: Burning velocity increases
$L_b > 0$: Burning velocity decreases
for positive stretched flames.



- As initial mixture pressure increases, L_b at $x_{H2} = 0$ decreases to around 0.
- L_b changed non-monotonically with the increase in hydrogen ratio.



Non-monotonic change in L_b cannot be explained from view point of effective Lewis number, Le_{eff}.

Negative L_b is good for turbulent combustion because local burning velocity is increased by flame stretch.

Conclusions

Reaction enhancement by the hydrogen addition

- Laminar burning velocity of the ammonia/hydrogen/air premixed flame exponentially increases with the increase in the hydrogen ratio.
- Laminar burning velocity decreases as the initial mixture pressure increases.
- Markstein length varies non-monotonically with the hydrogen ratio.

Stability enhancement by the swirling flow

- Please refer the proceedings below:

Reference:
Y. Arakawa, A. Hayakawa, K.D.K.A. Somarathne, T. Kudo and H. Kobayashi, Flame characteristics of ammonia and methane flames in a swirl combustor, *Proceedings of 12th International Conference on Flow Dynamics (12th ICFD)*, Sendai, Japan, October 27 - 29, 2015.

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