KAIST Korea Advanced Institute of Science and Technology

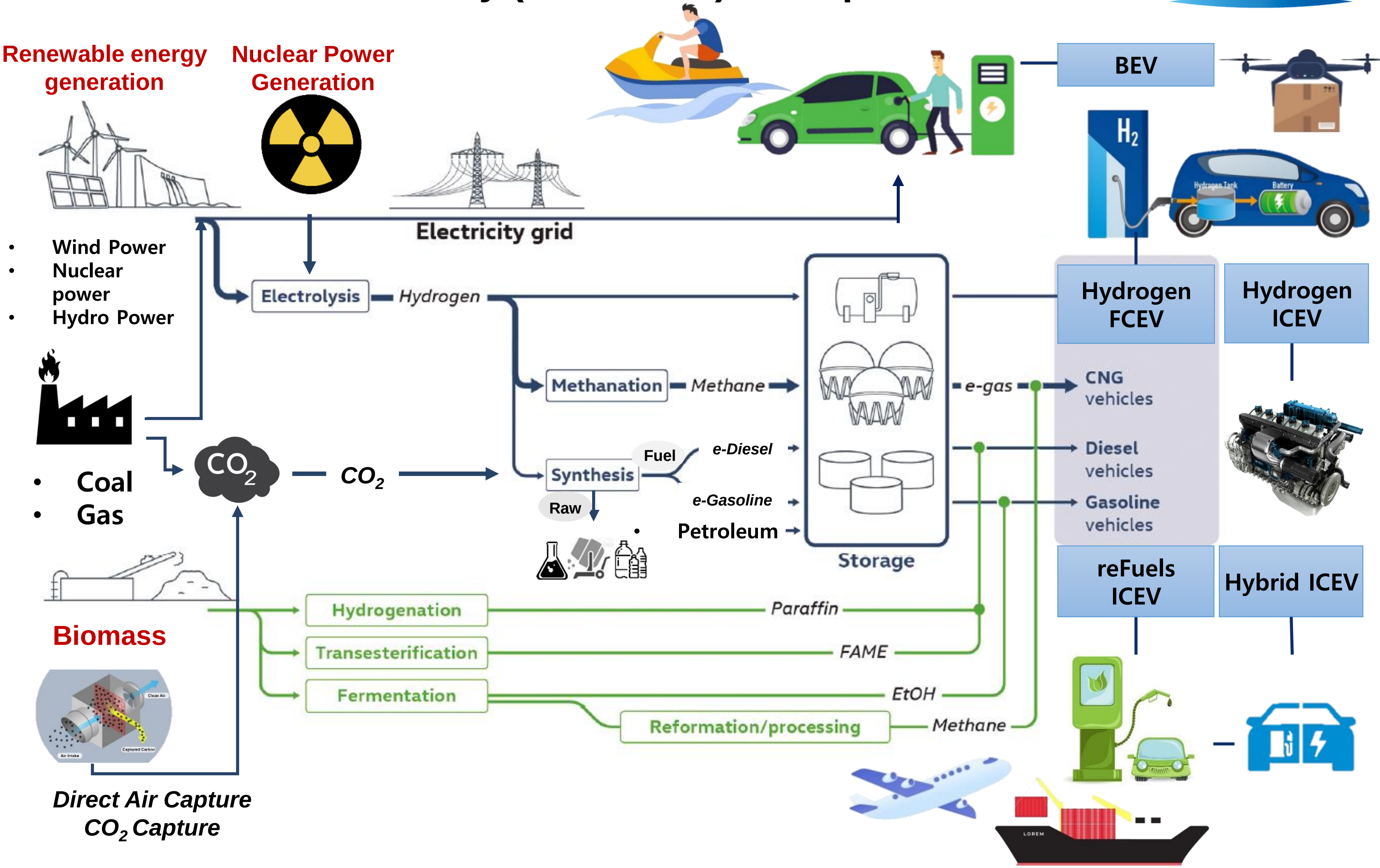
Lean Stratified Charged Hydrogen Combustion and Pollutant Formation

13 December 2023

Choongsik Bae

Future Transport Power Laboratory,
Dept. Mechanical Engineering, KAIST

Active Carbon Neutrality (Reduction) Transport Power



reFuel = Carbon-neutral fuel = Carbonless fuel+Bio-fuel+e-fuel

Source: *Vienna motor symposium, 2018*

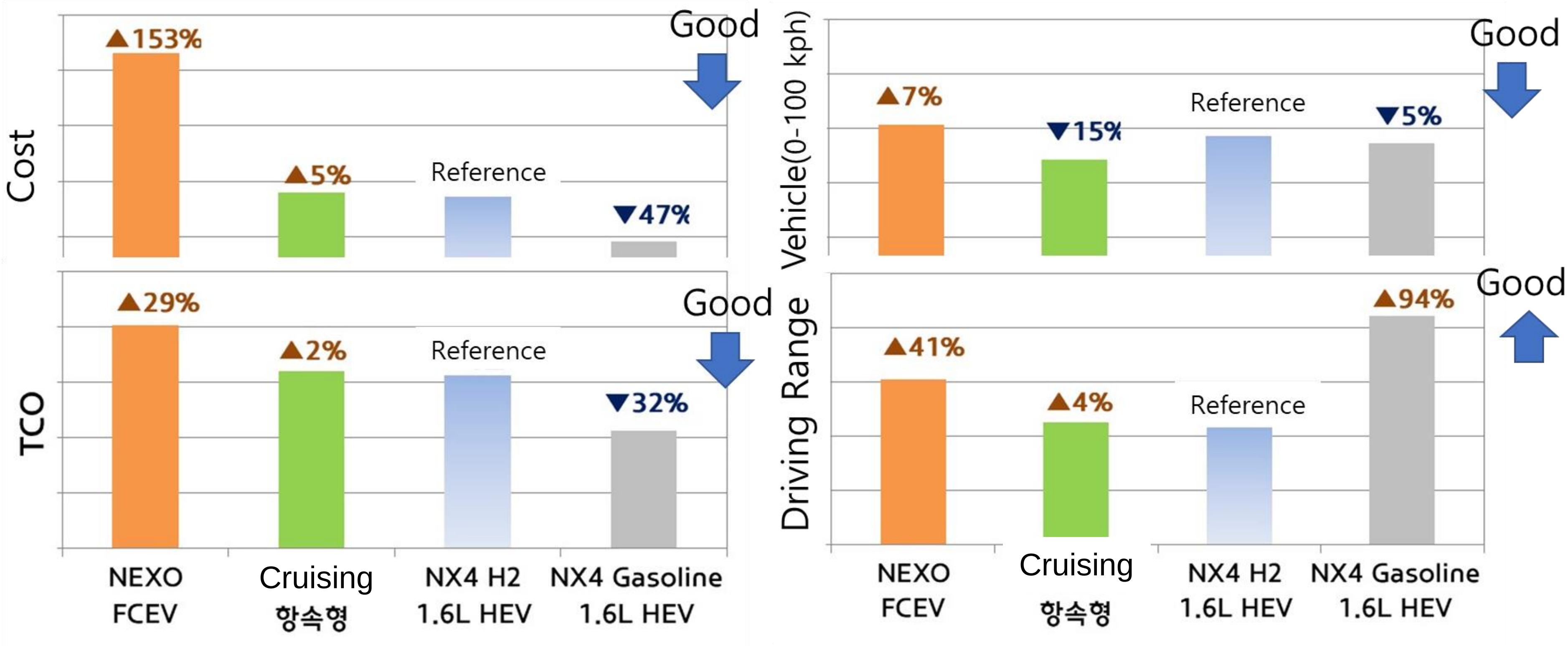
Source: *Position paper, IASTEC, 2021*

Hydrogen Engine Competitiveness

- Competitive H2 ICE in aspect of value for money (5% ↑over BEV, 153% ↑over FCEV)
- Driving range 4% disadvantage over BEV, 41% disadvantage over FCEV

→Need to maximize H2 engine efficiency and develop innovative technology for H2 fuel tank

- H2ICE allows more sustainable supply chain independent from rare earth material needed for BEV & FCEV



Source: *R&D Technology Forum : Sustainable Carbon neutral ICE, Hyundai Motor Company, 2023*

Contents

*LIBS = Laser - Induced Breakdown Spectroscopy

1. Mixture formation with hydrogen injection in a constant-volume chamber
   - Visualization of mixing process with Schlieren
   - *LIBS measurement on hydrogen-nitrogen mixture strength
   - OH Chemiluminescence on hydrogen combustion with single injection
   - Characterization of double hydrogen injection

2. Lean stratified charge combustion in a hydrogen engine
   - Combustion stability and NOx emission measurement in single-cylinder engine
   - Effects of EGR and post-injection on NOx emission reduction in prototype multi-cylinder engine

LIBS measurement on hydrogen mixing process

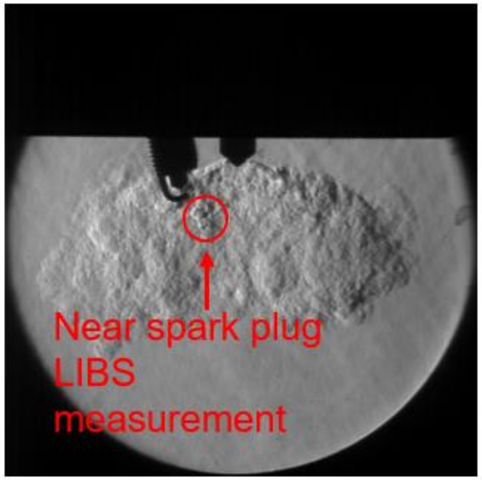
* LIBS = Laser - Induced Breakdown Spectroscopy

1. Measure the local equivalence ratio of homogenous/stratified hydrogen mixture using *LIBS methodology

2. Define hydrogen jet shape created by hollow-cone injector

3. Obtain mixture flammability by examining local equivalence ratio

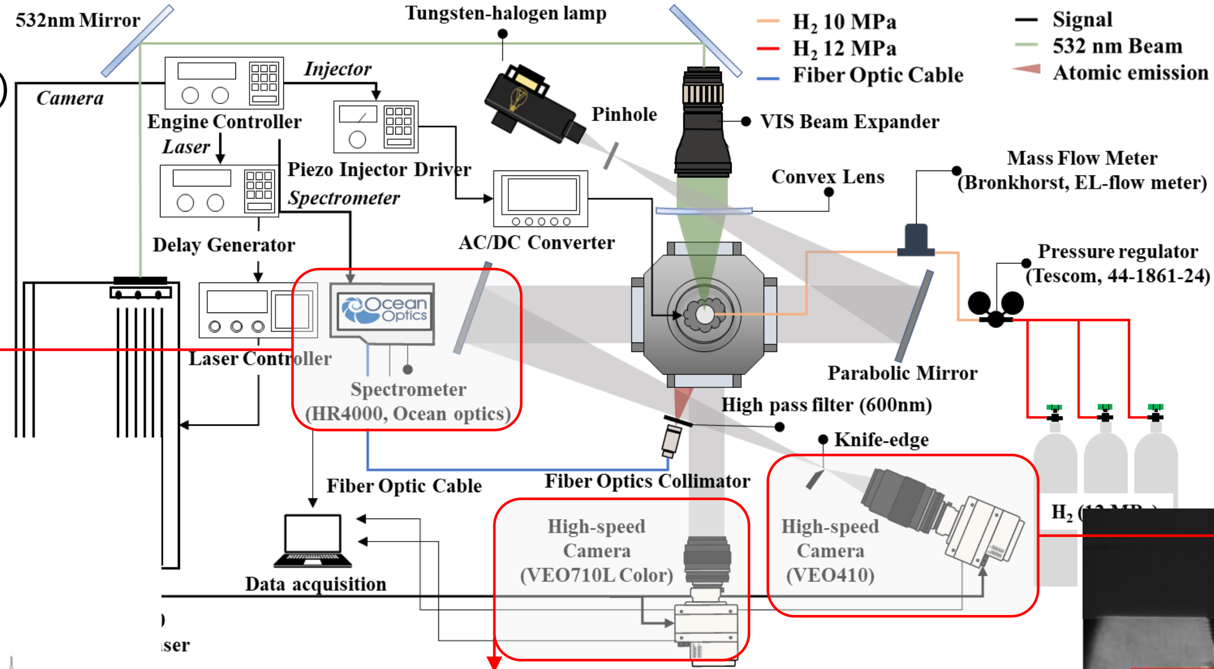
4. Observe spark plug arc discharge channel ignitability.

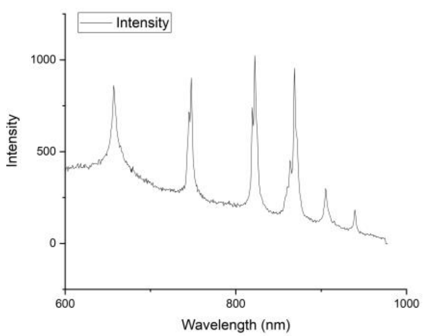


Experimental Setup (Schlieren & LIBS) in CVCC

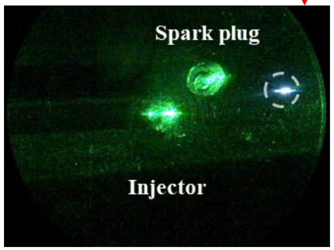
*CVCC: Constant Volume Combustion Chamber

*CVC size: 1.4L
(Cube hexahedron)





<Laser-induced breakdown spectroscopy>



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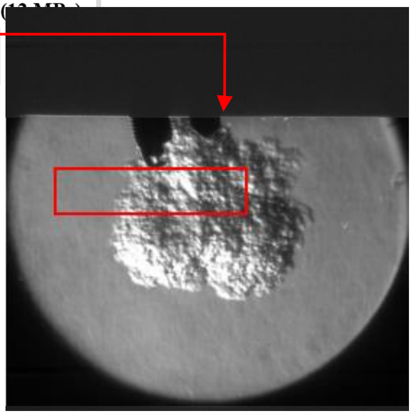
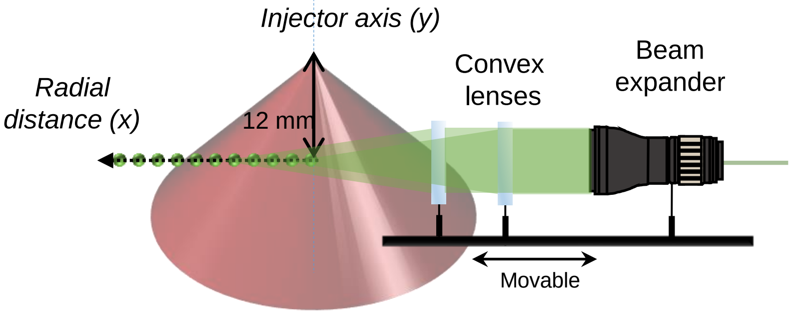


<High-speed schlieren jet structure>

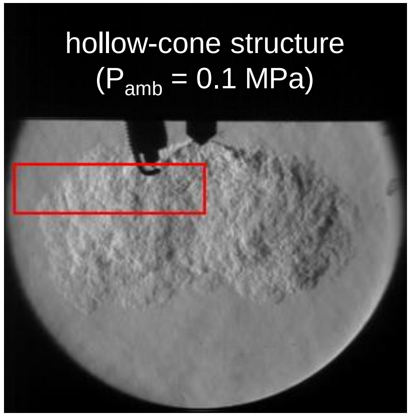
Experiment Conditions

- LIBS under different ambient pressure / measurement location

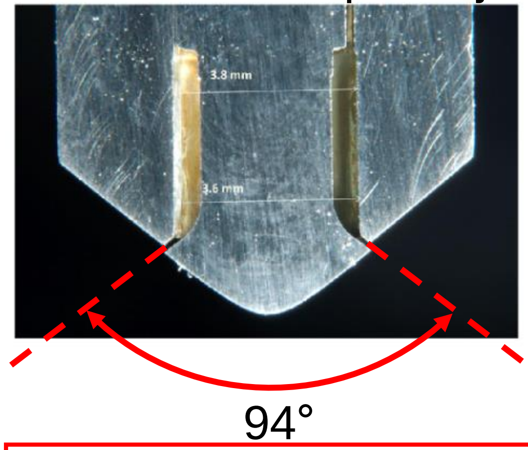
Parameters	Values
Injection duration [ms]	1
Ambient / hydrogen temperature [K]	323.0
Injection pressure [MPa]	10.0
Ambient pressure [MPa]	0.1, 0.5, and 1.0
Measurement location from injector tip (x) [mm]	3 – 32 (non-linear) *Fixed vertical location



By moving the convex lenses, measurement location can be varied (**Focal point**)



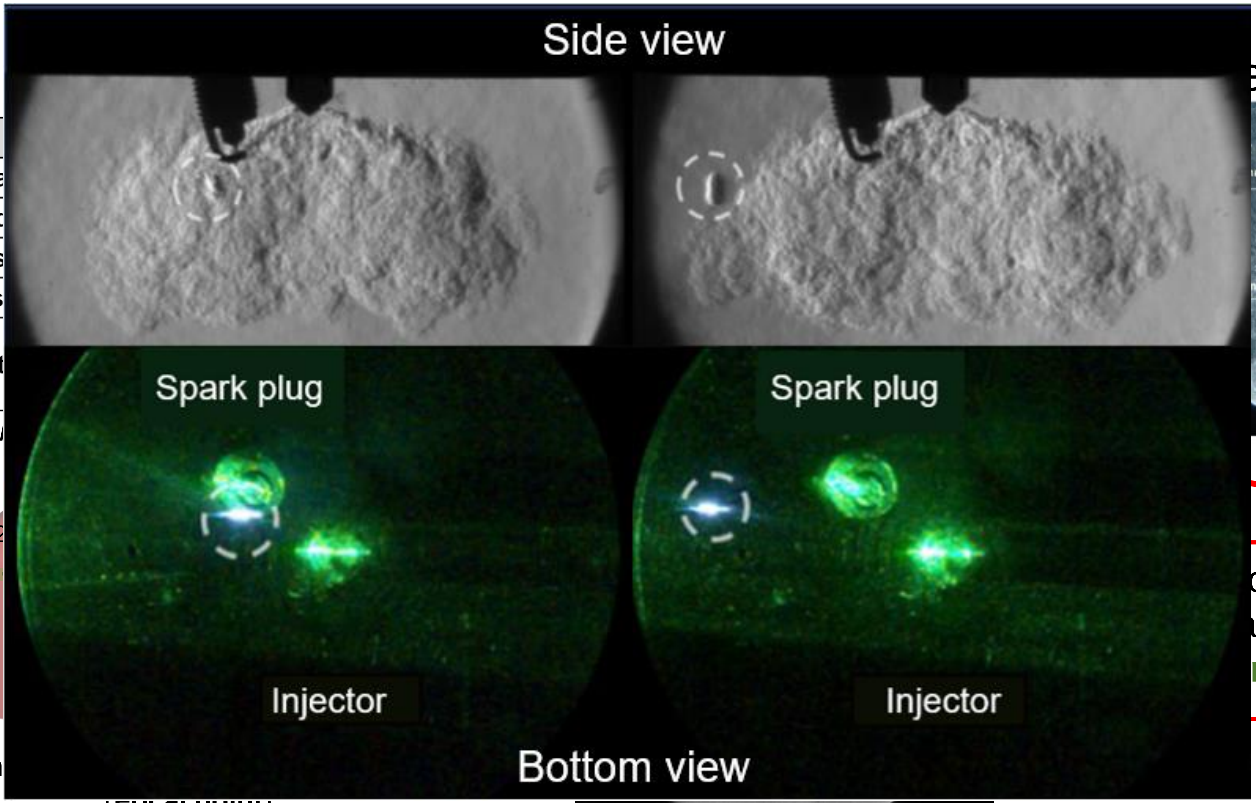
Hollow-cone shaped Injector



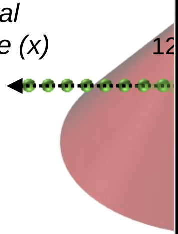
- Hollow-cone shaped injector creates a **hollow-shaped hydrogen jet**

Experiment Conditions

- LIBS under different ambient pressure / measurement location



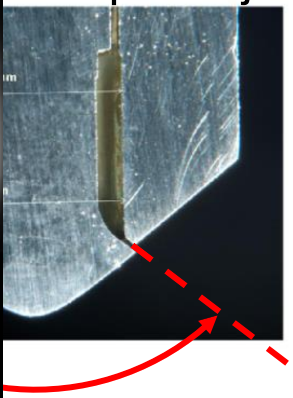
Injection dura
Ambient / hyd
Injection pres
Ambient pres
Measurement



By moving the con

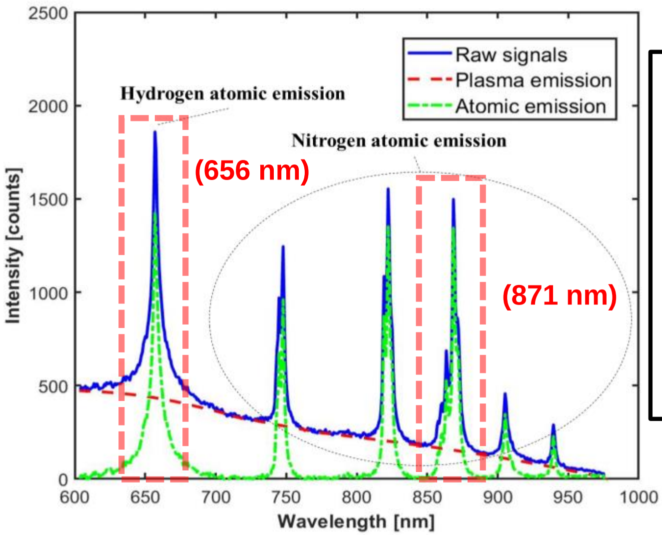
(Focal point)

e shaped Injector



one shaped injector
hollow-shaped
n jet

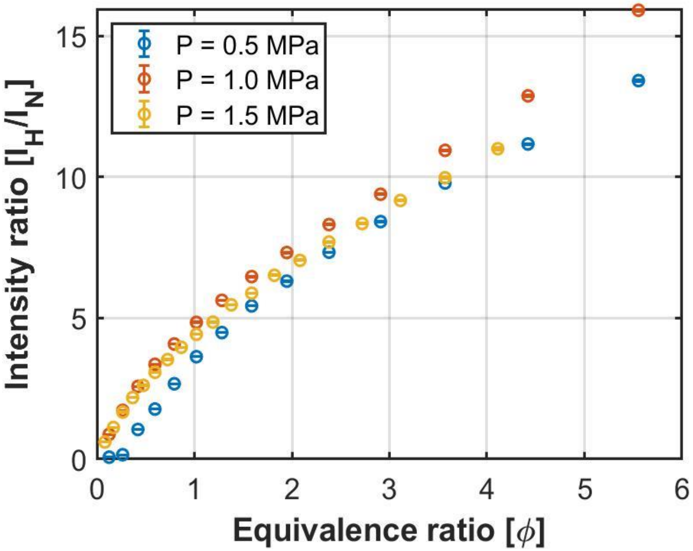
LIBS Calibration Post Processing



<Post-processed spectrometer signals>

- Post-Processing data
  = Raw Data – Background
- Removing background
  ➔ improve the SN ratio
- **Hydrogen and Nitrogen Intensity ratios are constant**
- Calibration process
  (based on the ideal gas law)

With 200 times repetition



$$\boldsymbol{Equivalence\ ratio\ (\Phi) = \alpha\ [\frac{I_H}{I_N}]^2 + \beta\ [\frac{I_H}{I_N}]}$$

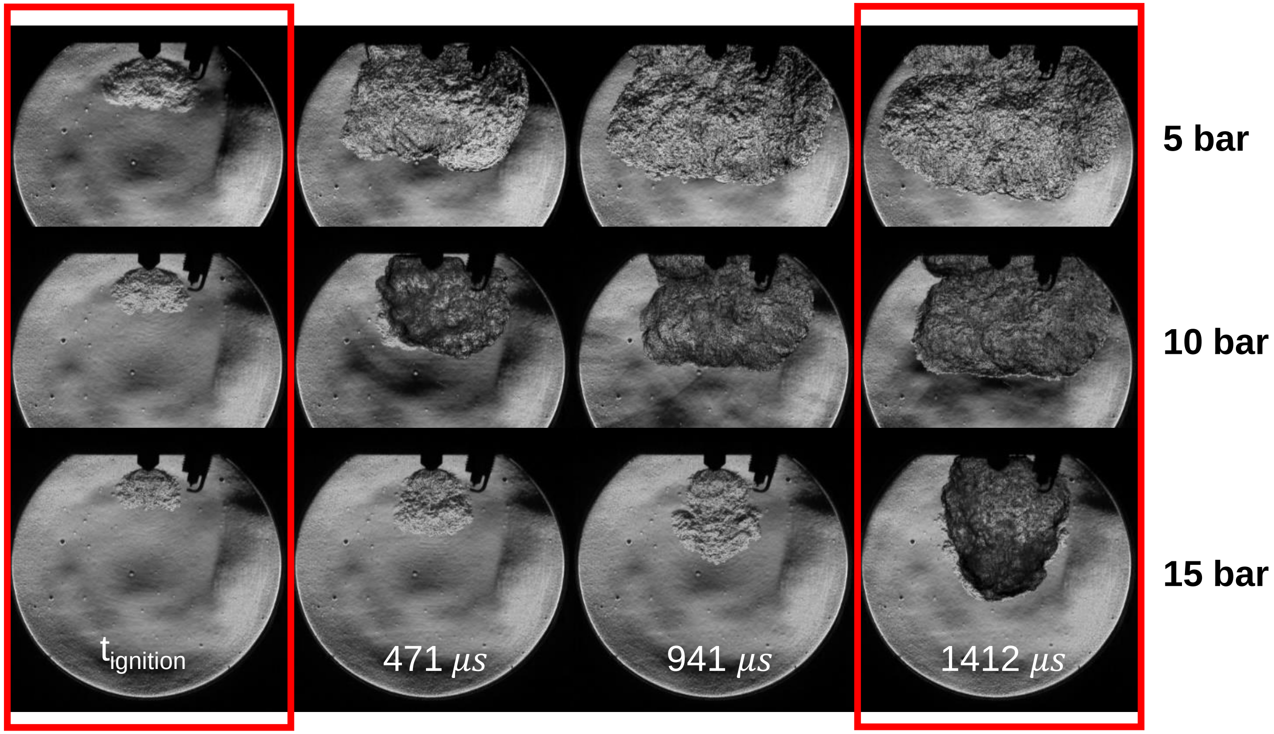
Where, $\boldsymbol{\alpha, \beta}$ = empirical constant,

I_H = Intensity of hydrogen atomic emission [counts]

I_N = Intensity of nitrogen atomic emission [counts]

Hydrogen Jet at Various Ambient Pressure

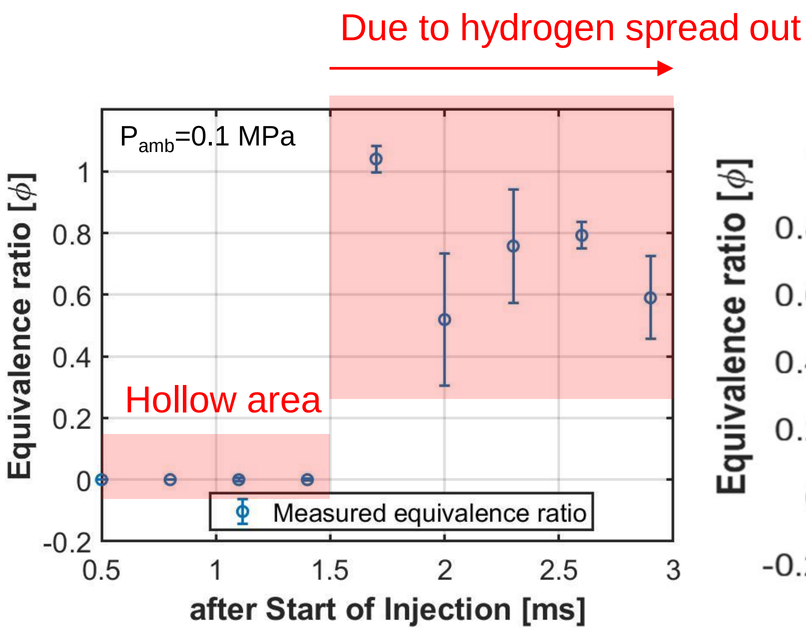
Hydrogen Stratified Combustion: Local equivalence ratio varies combustion characteristics

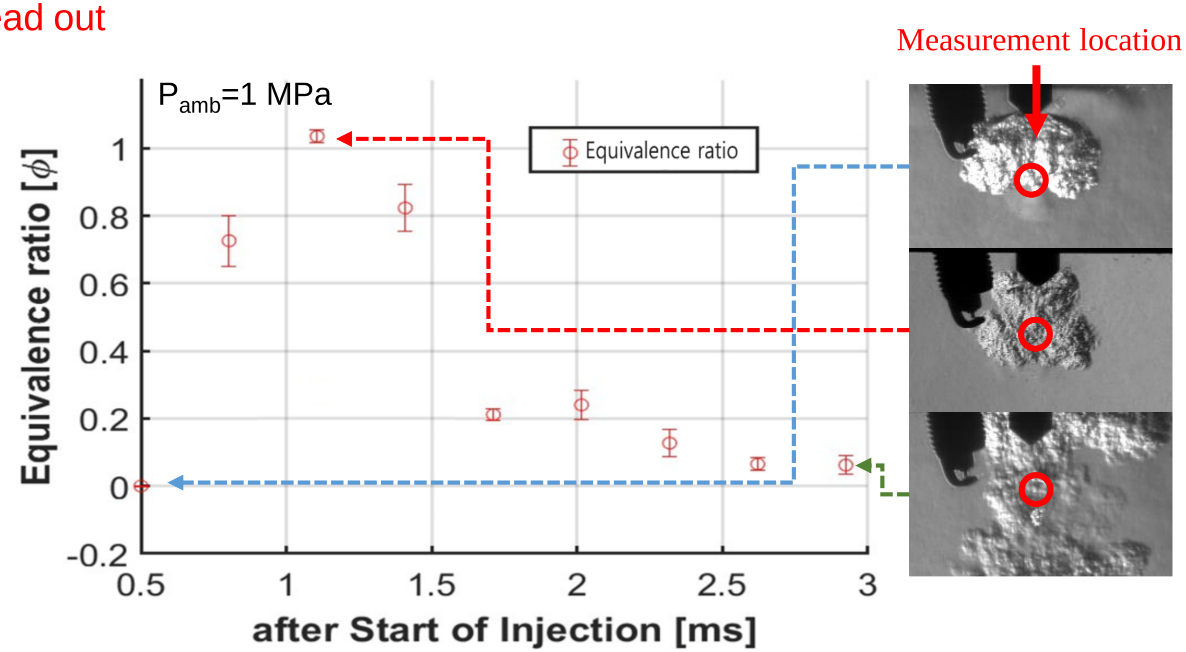


- At high atmospheric pressure, **jet is contracted** so that hydrogen does not reach the spark plug directly .
- It is assumed that the increase in the atmospheric pressure is the main cause for the contracted jet shape (Spatial effect)
  - Atmospheric Pressure Increase ➔ **Flame Area Reduction**

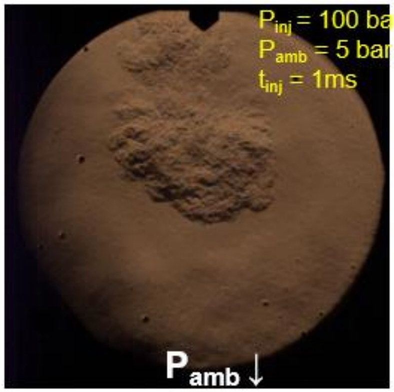
Effect of Ambient Pressure on Jet Structure

- High ambient pressure makes the hydrogen move toward inner side of the jet structure
  ➔ jet collapse

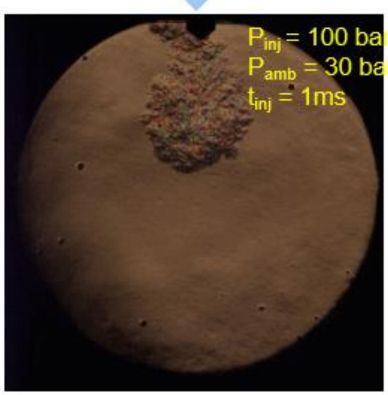




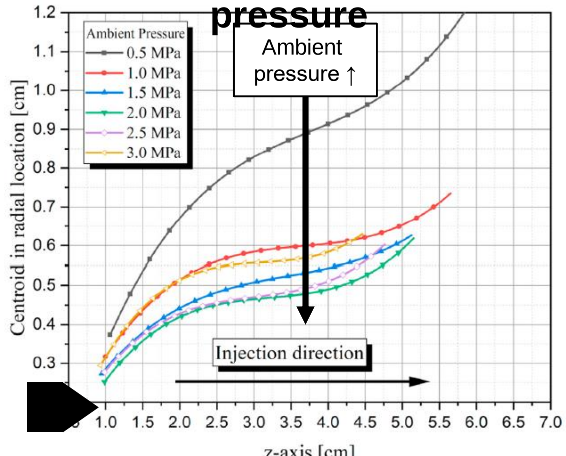
Jet Structure: Reconstructed Hydrogen Jet Growth



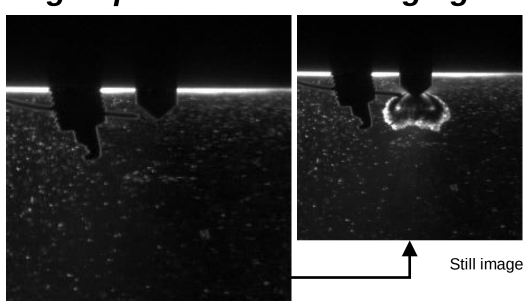
Ambient pressure ↑



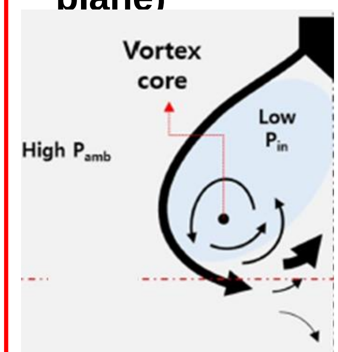
Hydrogen jet contraction according to atmospheric pressure



- ***High-speed schlieren imaging***



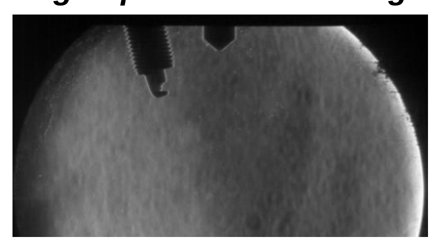
Hydrogen Jet Collapse (2D plane)



Shear layer
↓
vigorous momentum exchange
High P_{amb} & Low P_{in}

Pressure difference
↓
Jet contraction

- ***High-speed shadow imaging***

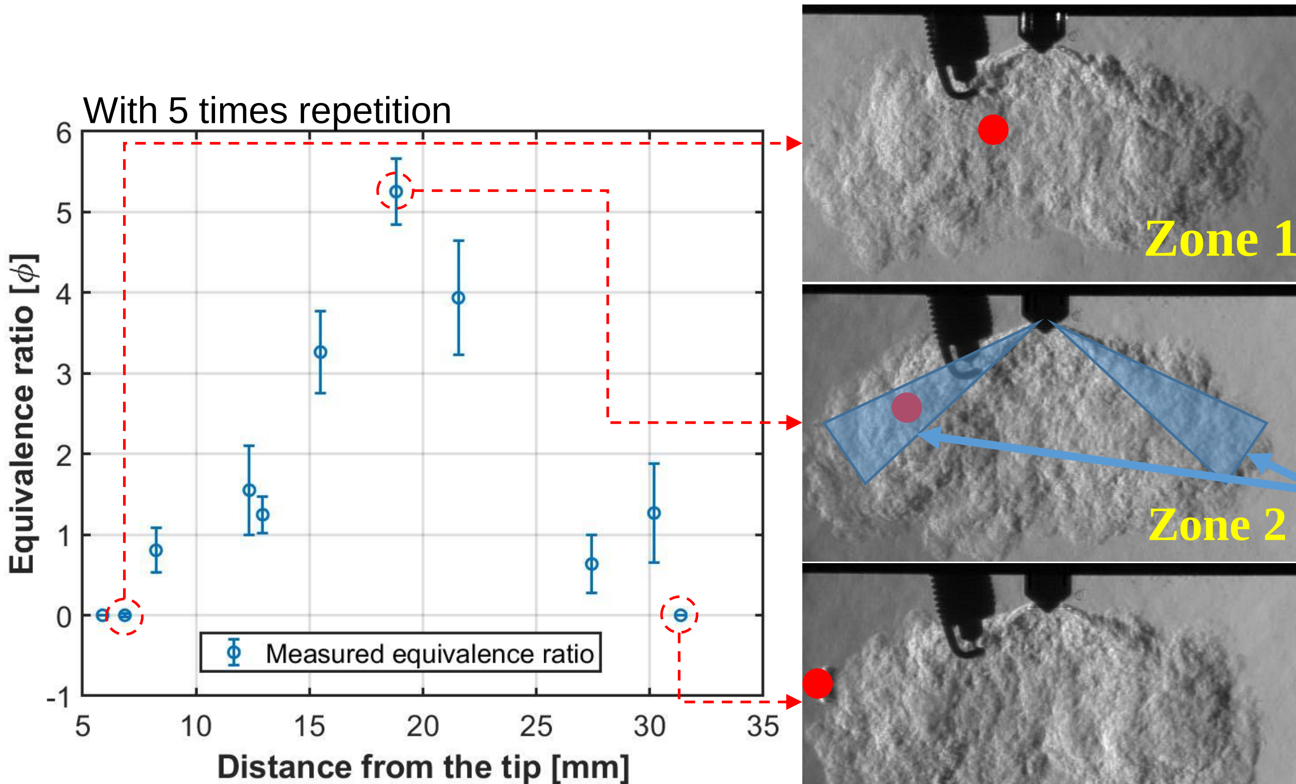


Toroidal vortex (ring)

Despite hydrogen having a high diffusion rate, it is observed that **jet shape collapses and contracts** easily under high atmospheric pressure conditions due to **low jet stiffness**.

Mixture Strength Distribution

- Measurement location



P_{amb} = 0.1 MPa, T_{laser} = aSOI 2.1 ms

Zone 1:
Due to the hollow area, hydrogen was not detected

Zone 2:
Max equivalence ratio was observed;
Jet center core region

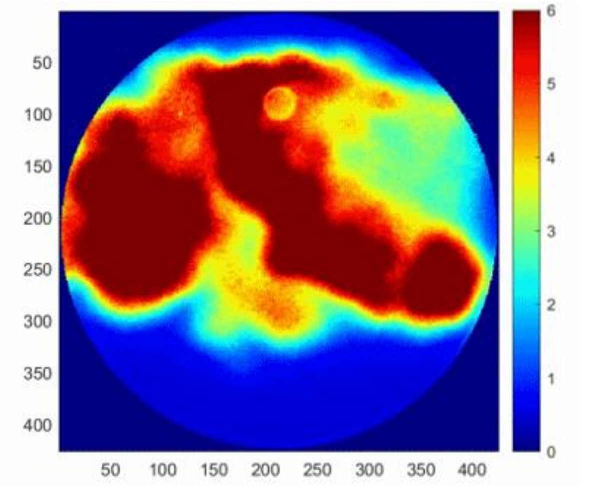
Zone 3:
Hydrogen was not detected at the outer side of hydrogen jet structure

- Measured Equivalence Ratio Corresponds to the Results of Captured Hydrogen Jet Images

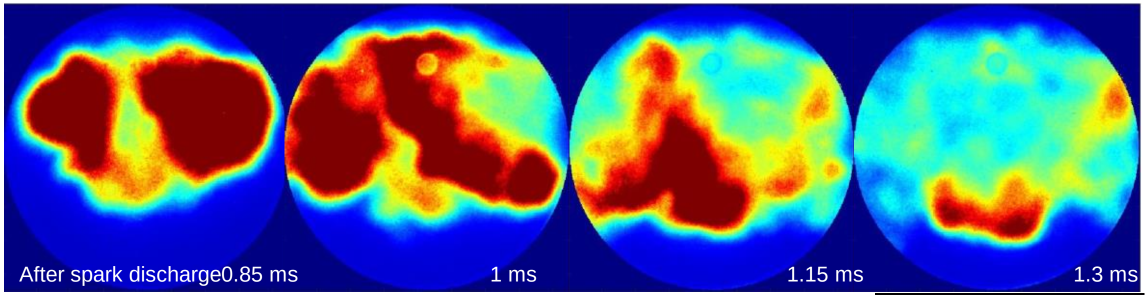
Hydrogen Energy Conversion (Pamb=0.1 Mpa, pinj=10Mpa)

- OH chemiluminescence indicated local-rich mixture when the ignition discharged during the injection

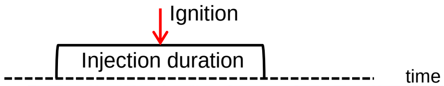
*ignition discharge during injection



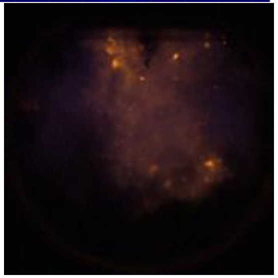
OH chemiluminescence results (ASOI: 1024 μs)



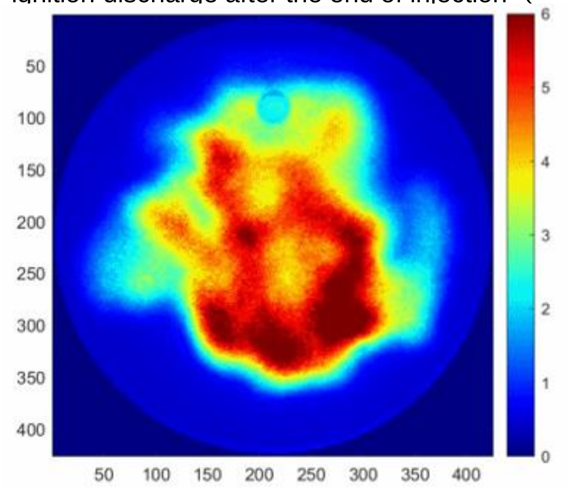
: Because the injection was still made after the ignition discharge, high OH intensity was measured at the center of optical window.



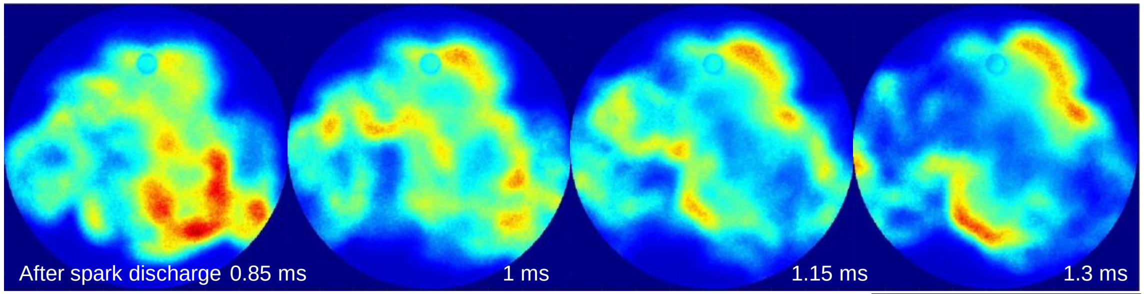
*Direct flame visualization



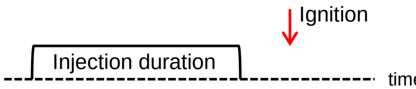
*ignition discharge after the end of injection



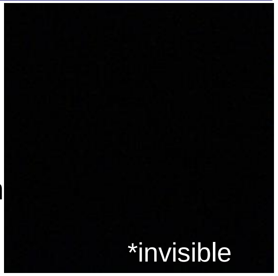
OH chemiluminescence results (ASOI 2560 μs)



: Mixture is rather lean and more distributed, but the local-rich area still exists



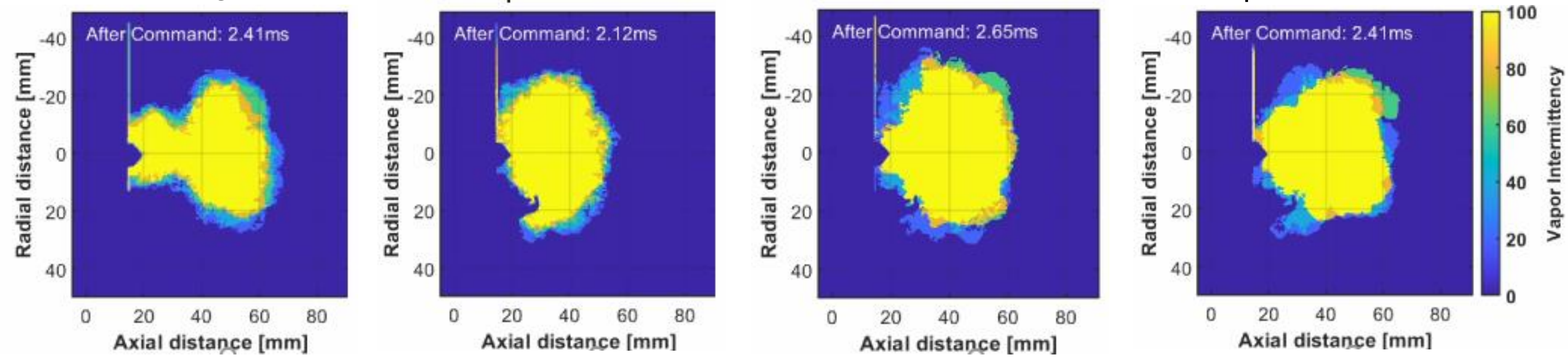
*Direct flame visualization

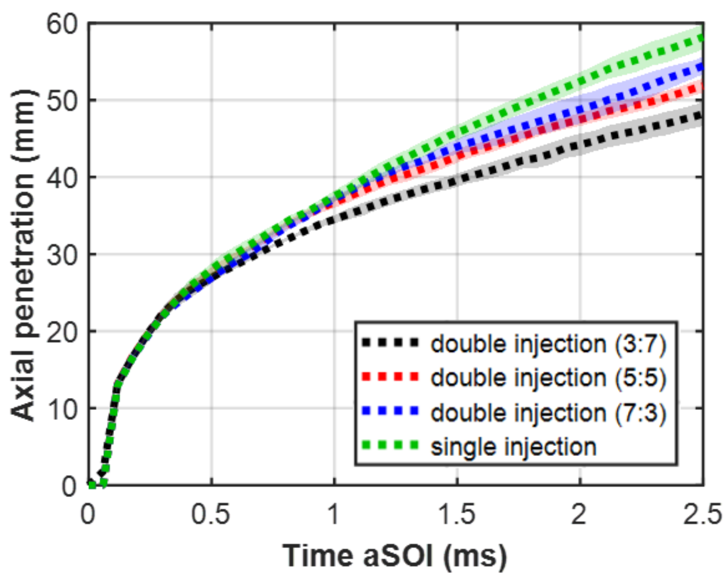


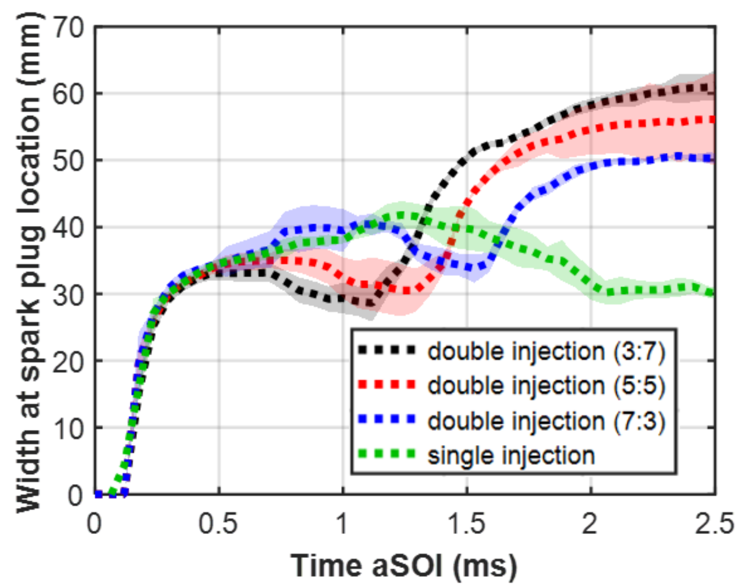
Double injection w.r.t. split ratio

- Jet structure change depending on split ratio (P_{amb} = 5 bar, dwell time = 600μs)

Single | Split ratio 3:7 | Split ratio 5:5 | Split ratio 7:3



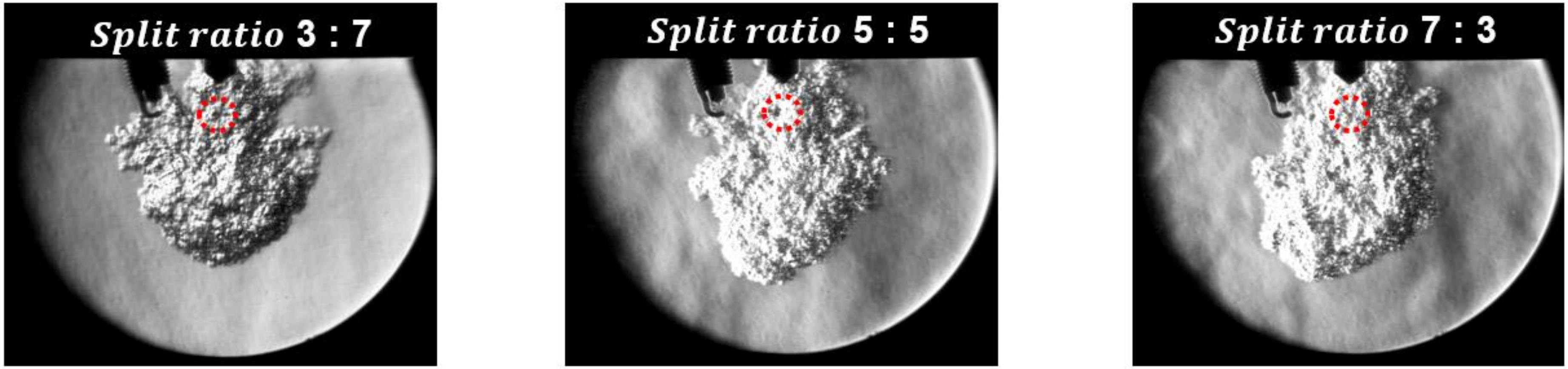


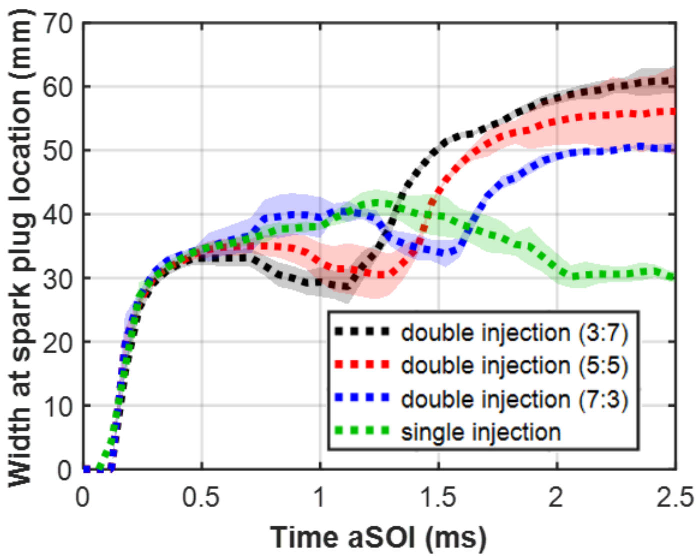


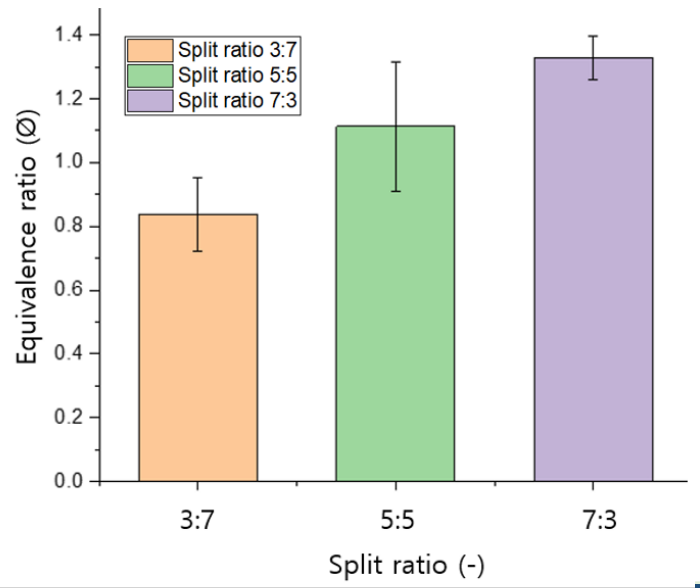
For double injection, hydrogen jet spread out to spark plug penetration, but penetration was decreased
→ Increases in 2nd injection portion caused jet dispersion after end of the 2nd injection

Double injection w.r.t. split ratio
- Local equivalence ratio measurement

- Changes in local equivalence ratio depending on split ratio (P_{amb} = 5 bar, dwell time = 600μs)



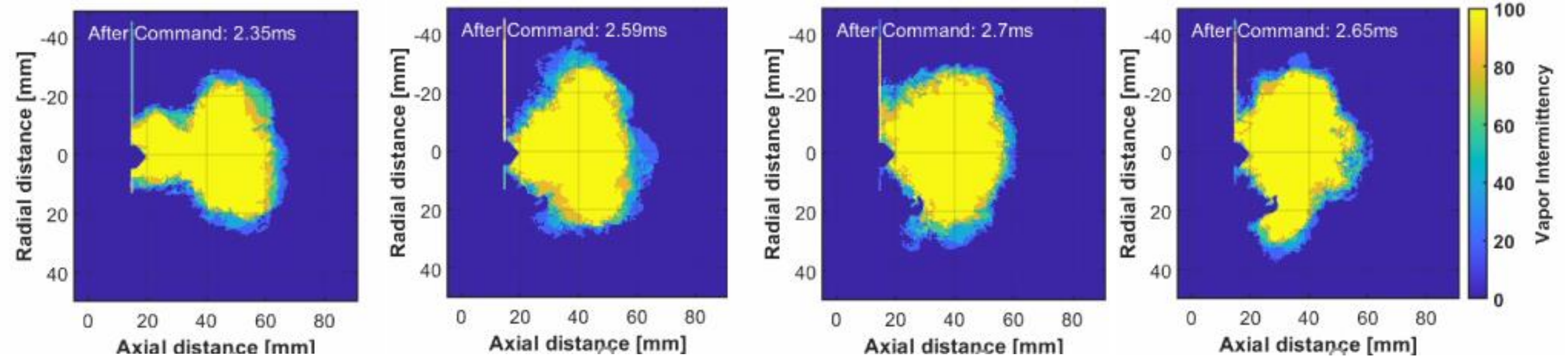


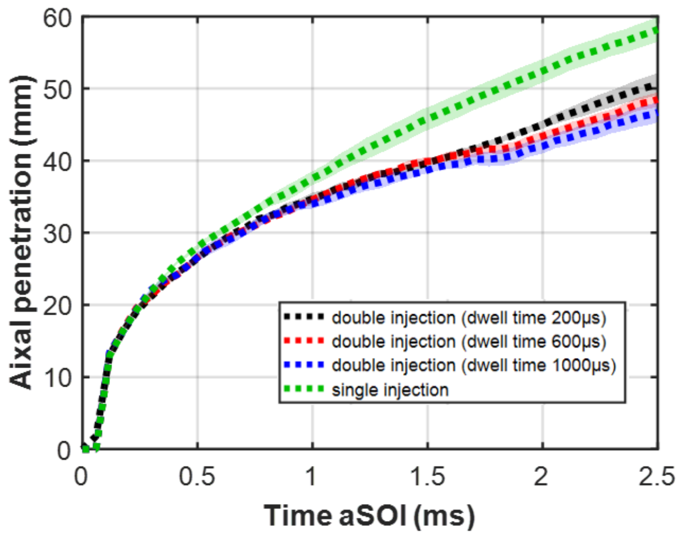


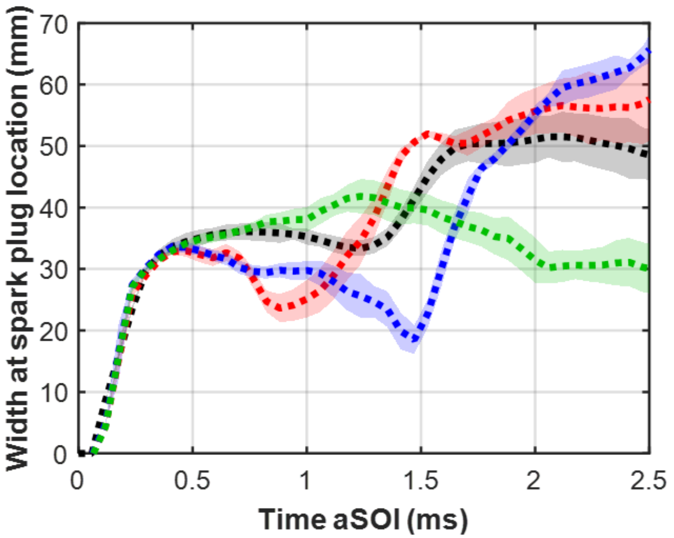
Dispersion of jet meant that jet was moving outward → Low hydrogen concentration at jet center
→ Lower local equivalence ratio measurement at the center

Double injection w.r.t. dwell time

- Jet structure change depending on dwell time (P_{amb} = 5 bar, split ratio = 3:7)



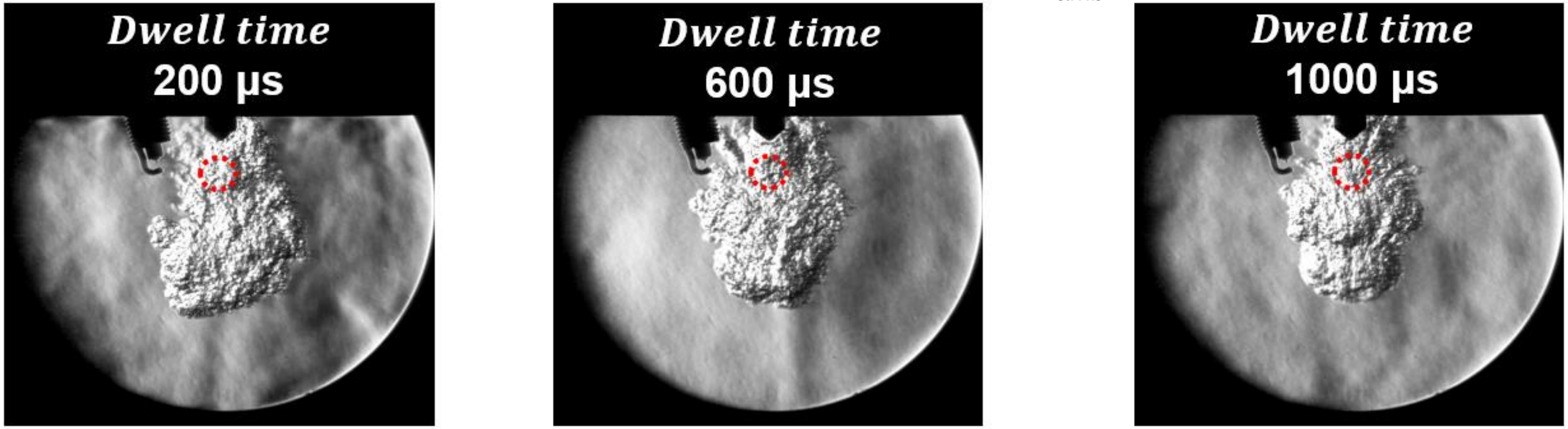


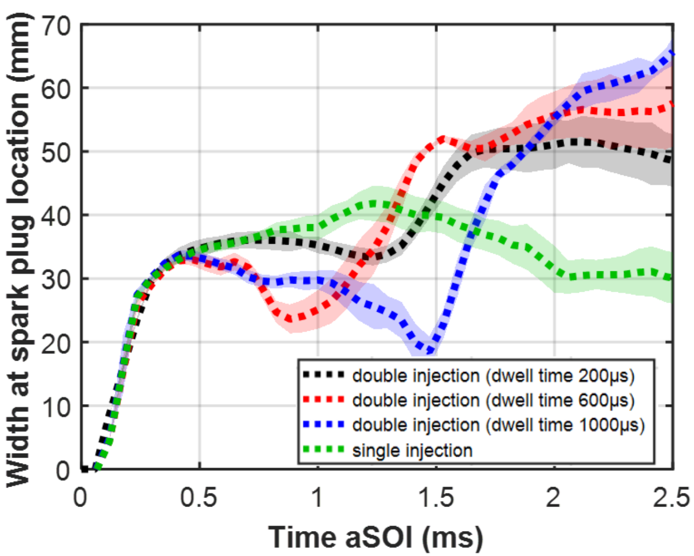


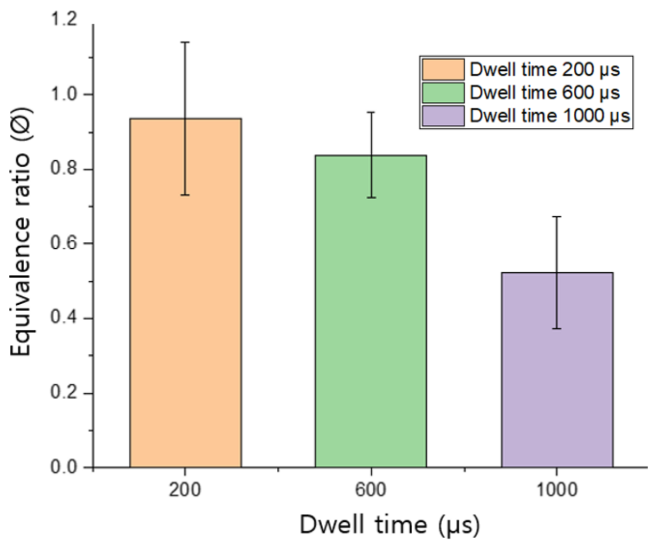
Although the change in penetration was limited depending on dwell time, jet width changed substantially
➔ Increases in dwell time caused higher hydrogen dispersion

Double injection w.r.t. dwell time
- Local equivalence ratio measurement

- Effect of dwell time on the hydrogen jet equivalence ratio (P_{amb} = 5 bar, Split ratio = 3:7)





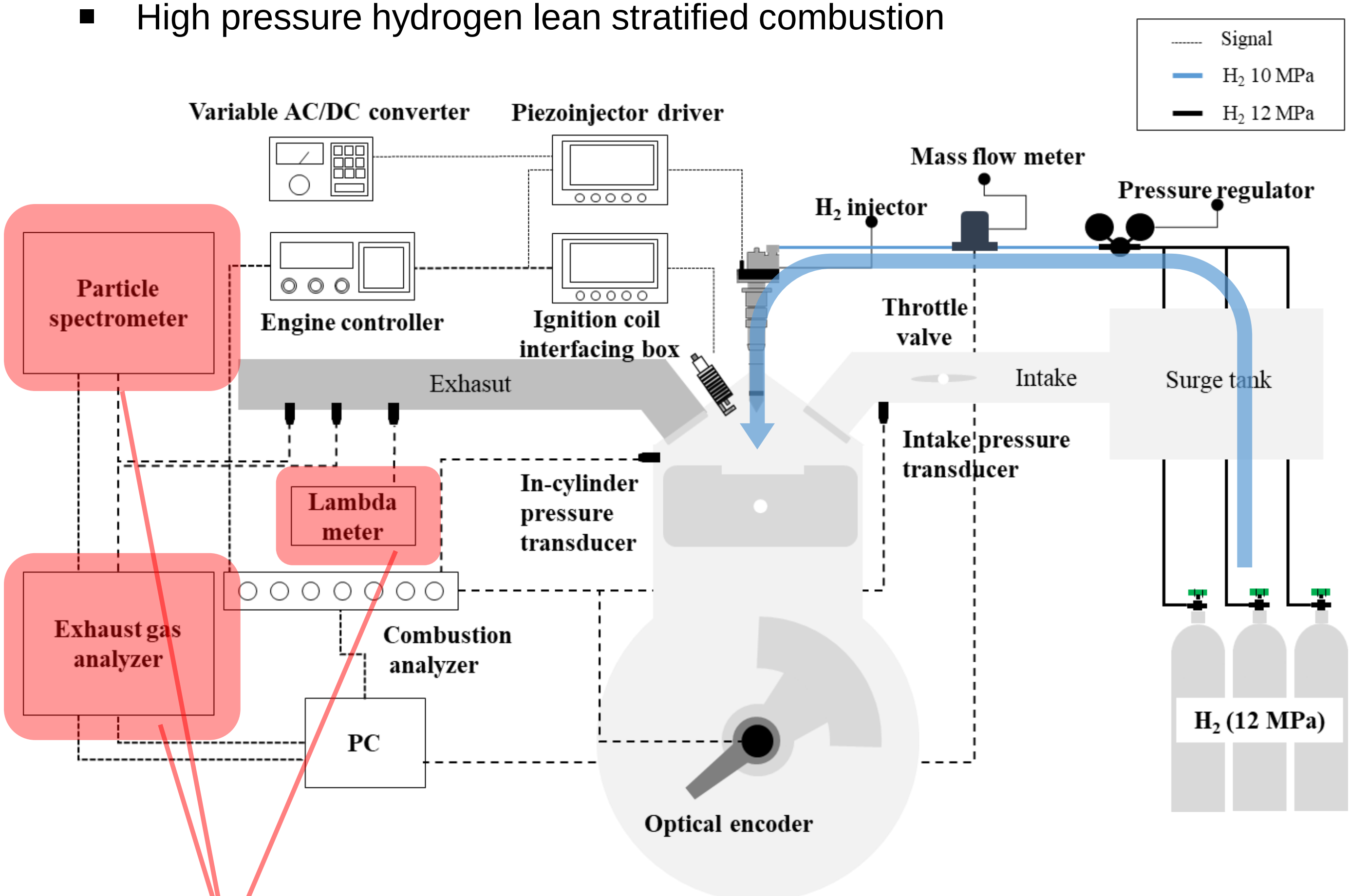


At dwell time = 200 µs, hydrogen concentration at the jet center was increased (higher Ø)
At dwell time = 1000 µs, hydrogen dispersion was increased and concentration at the center was decreased (Lower Ø)

*SG DISI: Spray-guided direct injection spark ignition

Experimental Setup for Single Cylinder Engine

- High pressure hydrogen lean stratified combustion

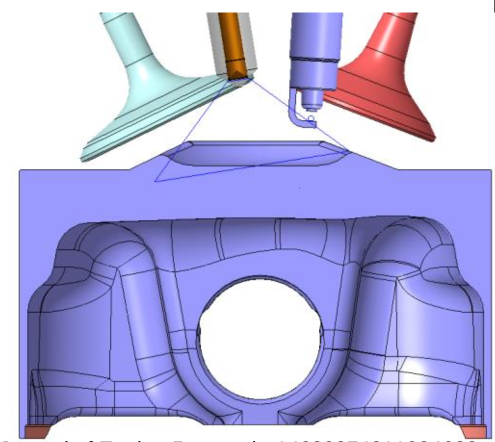


- *Experiment chematic of hydrogen reciprocating engine*

- PM & NO_X emission
- Air ratio(λ)

Parameters	Values
Engine type	Spray guided Spark ignition DI engine
Bore X Stroke	85 X 88 mm
Compression ratio	12: 1
Intake valve	11 aTDC – 22 aBDC
Exhaust valve	34 bBDC – 10 aTDC
Injector	Outwardly opening piezo injector

*Reciprocating engine head



Lee, S., Kim, G., & Bae, C. (2021). Effect of injection and ignition timing on a hydrogen-lean stratified charge combustion engine. International Journal of Engine Research, 14680874211034682.

Experimental Conditions

- Experimental conditions for single-cylinder research engine

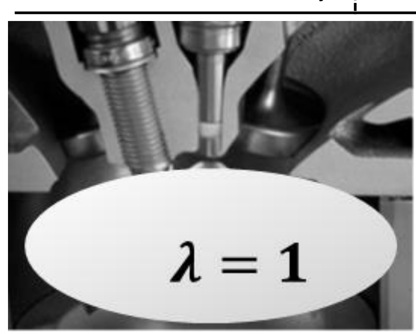
- *Effect of ignition timing on hydrogen SCC*

Parameters	Value
Engine speed	1300 rpm
Injection pressure	10 MPa
Injection quantity	160 g/h
Throttle valve position	0 % (WOT)
Air excess ratio (λ)	2.5
Injection timing (t_{inj})	32 bTDC*
Ignition timing (t_{ig})	**-12 – 18 aTDC**

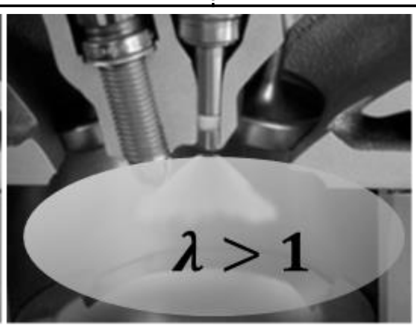
Lean-stratified charge
(λ = 2.3)

- *Effect of mixture formation mode on the combustion and emission characteristics*

Parameters	Homogeneous charge	Lean homogeneous charge	Lean-stratified charge
Engine speed	1300 rpm		
Injection pressure (P_{inj})	10 MPa		
Injection quantity	188 g/h		
Throttle valve position	98 %	92 %	0 % (WOT)
Air excess ratio (λ)	1	1.7	2.3
Injection timing (t_{inj})	158 bTDC	158 bTDC	26 bTDC



Homogeneous charge
(λ = 1)

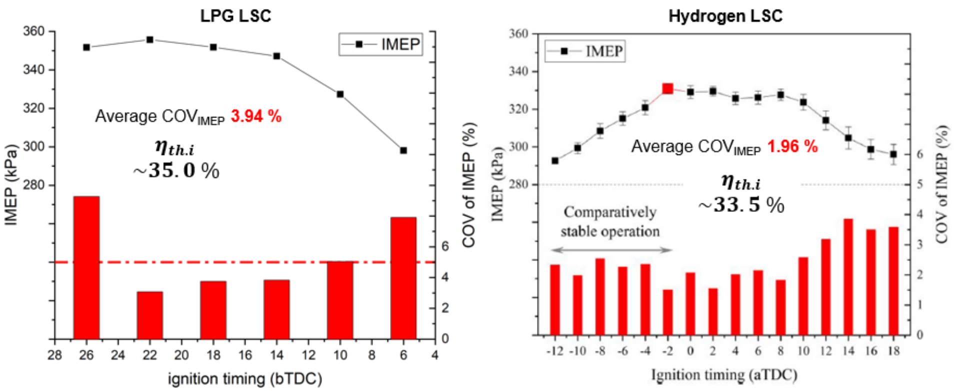


Lean homogeneous charge
(λ = 1.7)

Lean-stratified charge
(λ = 2.3)

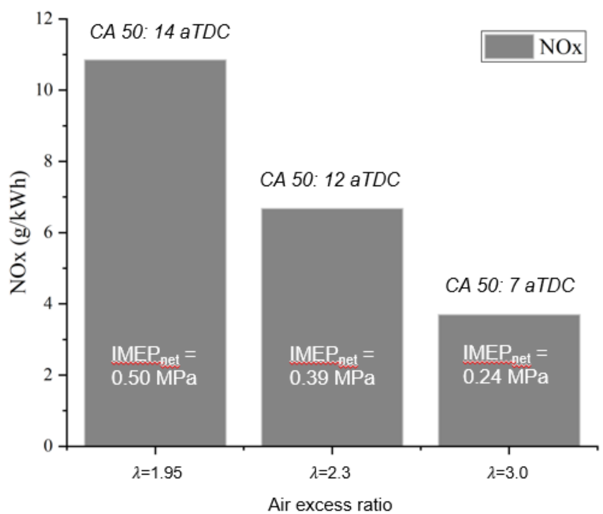
*Average value of 300 cycles *Use only under COV_{IMEP} 5 % data

Results – Combustion stability (COV_{IMEP}), NOx



< IMEP and COV at different ignition timing >

- In the case of hydrogen, **Stable operation within wide mixture area** (Overall low COV_{IMEP} measured)
- In the case of hydrogen, the process required for phase change such as atomization and evaporation is not required, so **stable ignition is possible** immediately after injection is terminated
- **Low indicated thermal efficiency** result than LPG stratified combustion (Estimated to be due to heat transfer loss)

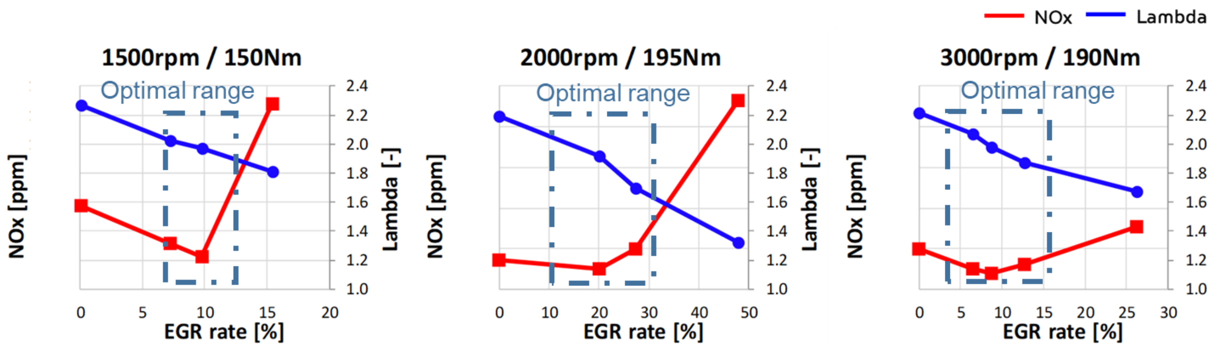


< Results of NOx emission by air excess ratio (MBT timing) >

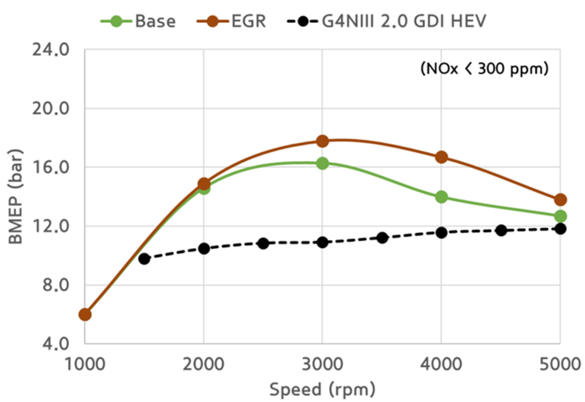
- Lower NOx emissions as air excess ratio increases
- Confirm the possibility of reducing NOx emissions through stratification (ex. Lean-boosting, e-turbo)

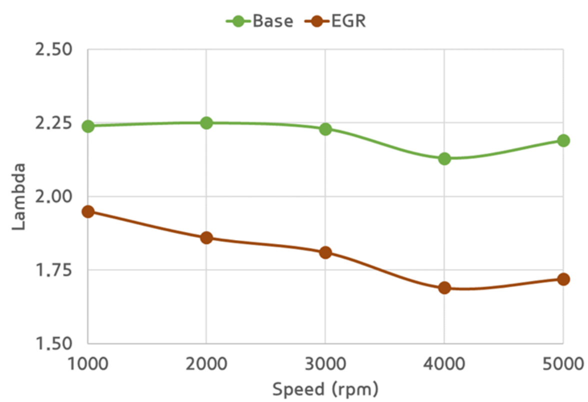
Effect of EGR in a hydrogen prototype engine

■ NOx Trend and AFR Changes



■ WOT Performance with EGR





- **NOx reduction by increasing EGR supply** → Increasing H2 amount
  → possible to improve engine performance

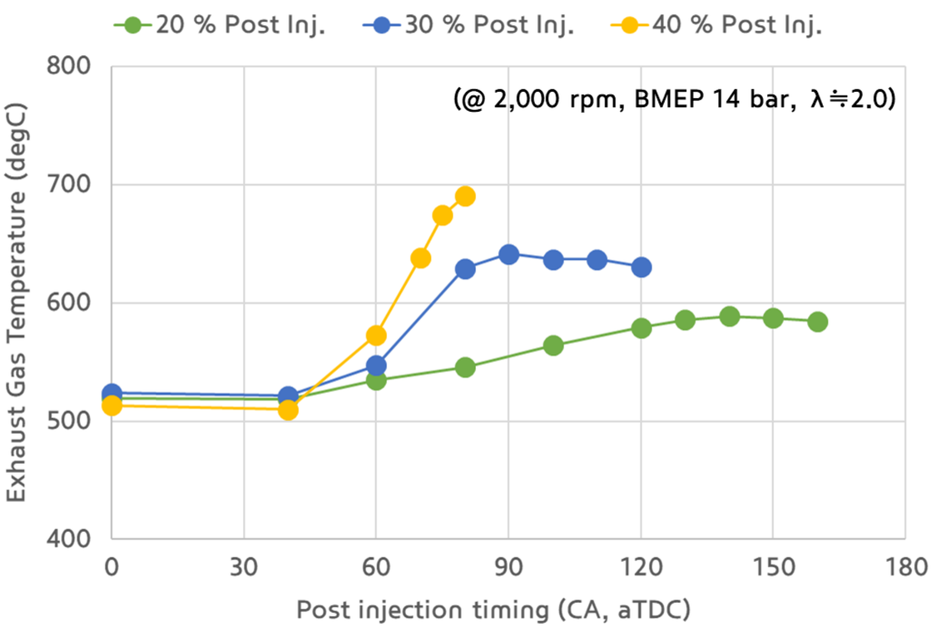
- Optimal EGR rate for each engine operating condition
  - **Maximum NOx reduction when 10 ~ 20 % of EGR**
  - NOx increased when more EGR rate than optimal rate

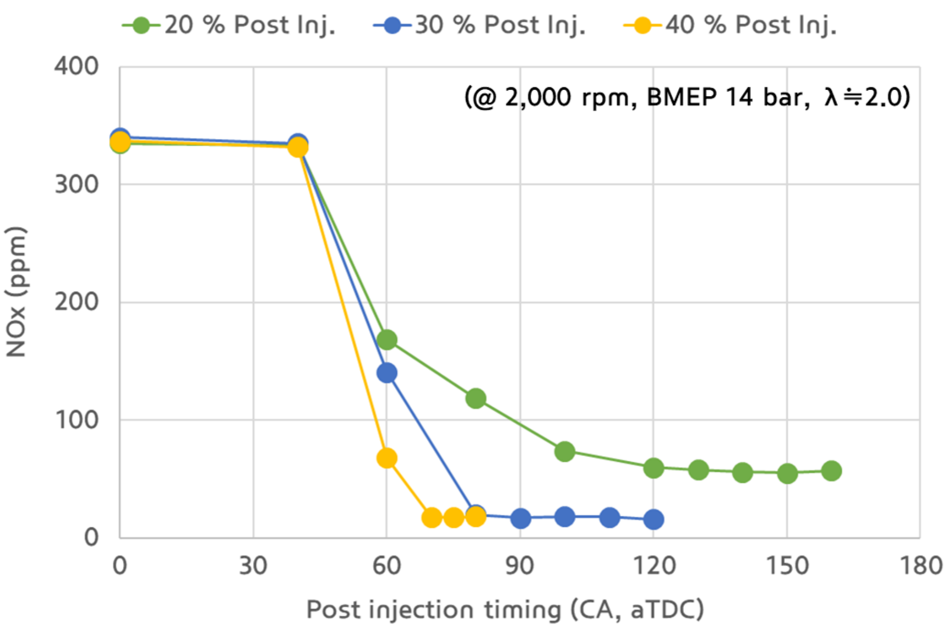
- **AFR could be reduced by supplying EGR while maintaining NOx limit**
  → Increasing the amount H2 supply
  → Better WOT performance (Max. 13 % under mid-high speed range)

Source: *R&D Technology Forum : Sustainable Carbon neutral ICE, Hyundai Motor Company, 2023*

Effect of Post-Injection with ATS

- Exhaust Gas Temp. and NOx Trend (@ 2,000 rpm/BMEP 14 bar)





- The more injection amount and the later injection timing of post-injection, the **higher exhaust gas temperature and the lower NOx** (@ same AFR, same BMEP)

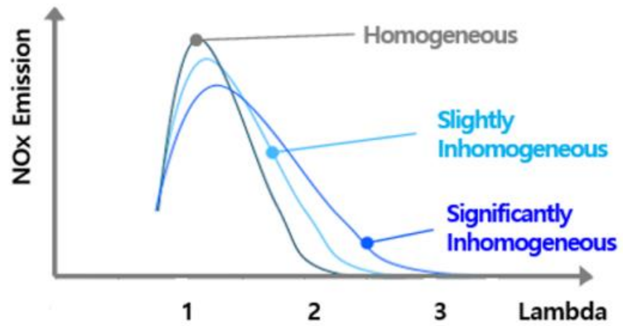
  → Possible to improve engine power by lower AFR or reduce of aftertreatment system complexity when post-injection is applied

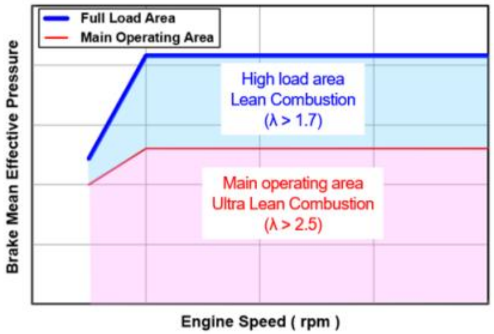
Source: *R&D Technology Forum : Sustainable Carbon neutral ICE, Hyundai Motor Company, 2023*

Target engine and development concept
Boosting System

Source: *Hydrogen IC Engine: Zero-Impact Emission Technology for Sustainable Mobility, HMC, Aachen Colloquium, 2022*

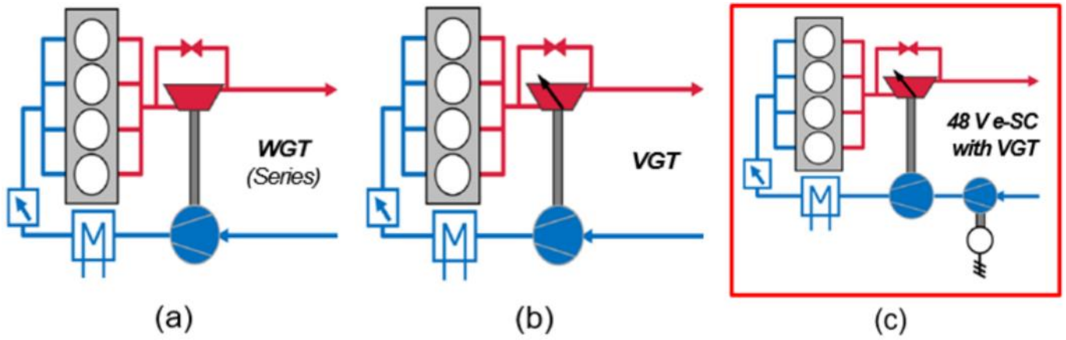
- It was found through previous researches that near zero NOx emission is possible when λ > 2.5, but NOx emission is highly dependent on mixture homogeneity.
- For high load, target is to achieve λ > 1.7 to prevent abnormal combustion.





NOx emission ratio (left), excess air ratio target

- Two-stage boosting system combining 48 V driven electric supercharger & VGT is implemented.



WGT (a), VGT (b), 2-Stage boosting system (c)

Summary

- Hydrogen ICEV has a better feasibility than BEV or FCEV because of its lower TCO and low dependence on rare earth material.
- Hydrogen ICE has a similar engine performance to conventional fossil fuel while maintaining lower NOx emission.
- LIBS can measure the local equivalence ratio of the hydrogen mixture.
- Delaying ignition timing increased the homogeneity of the stratified mixture.
- Double injection can modify the hydrogen jet behavior in terms of penetration and width ➔ reduce the jet contraction at high ambient pressure.
- Hydrogen ICE is free from CO2 and has a wider flammable range compared to fossil fuel.
    - Air boosting systems such as WGT, VGT, and e-Turbo can improve performance and thermal efficiency.
- EGR should be considered to reduce NOx emission when produced more while operating an engine under lean stratified charge mode compared to lean homogeneous charge mode.

KAIST

Thank you for your kind attention.

Contact

Choongsik Bae
Professor, PhD, FSAE

Future Transport Power Laboratory
Dept. Mechanical Engineering
KAIST

Tel.: +82 (0)42-350-3044
E-mail: csbae@kaist.ac.kr
Web: ftpl.kaist.ac.kr