



# Injection System Design for Homogeneous and Lean Combustion in Hydrogen Engines

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Akichika Yamaguchi, Jost Weber, Dirk Queck, Jens Zanger

DENSO CORPORATION



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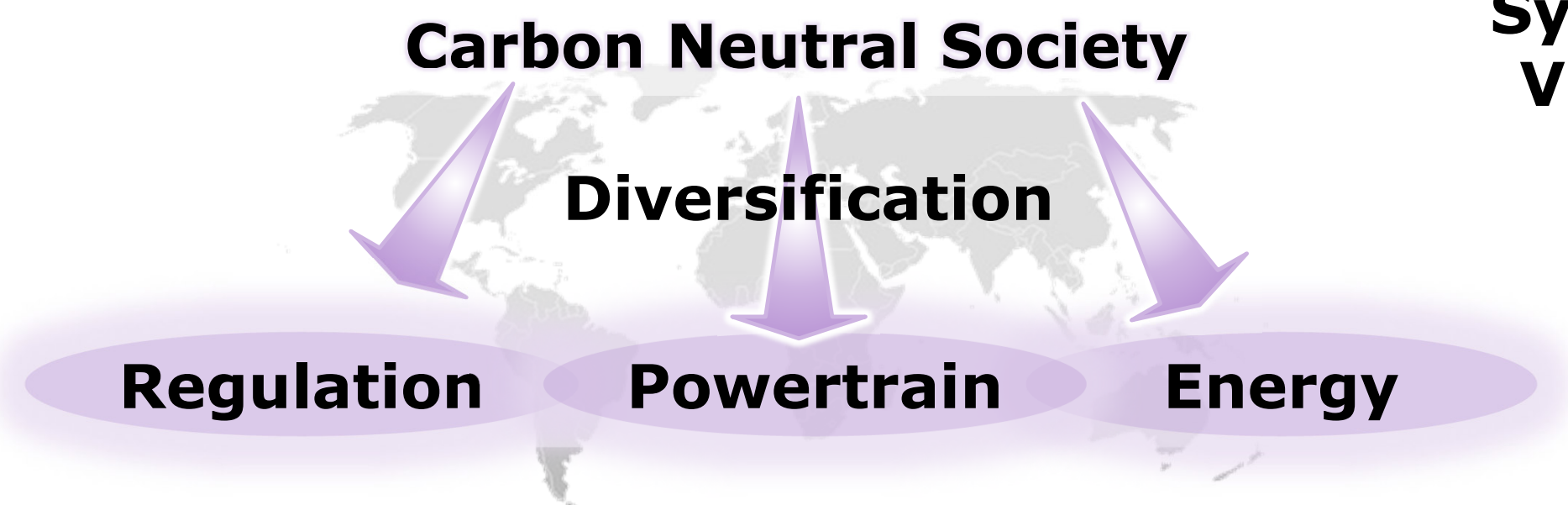


# Agenda

1. Future powertrain trend
2. Injection system for H<sub>2</sub>ICE
3. Concept of high flow rate
4. Validation
  1. Jet
  2. Mixture
  3. Engine
5. Summary

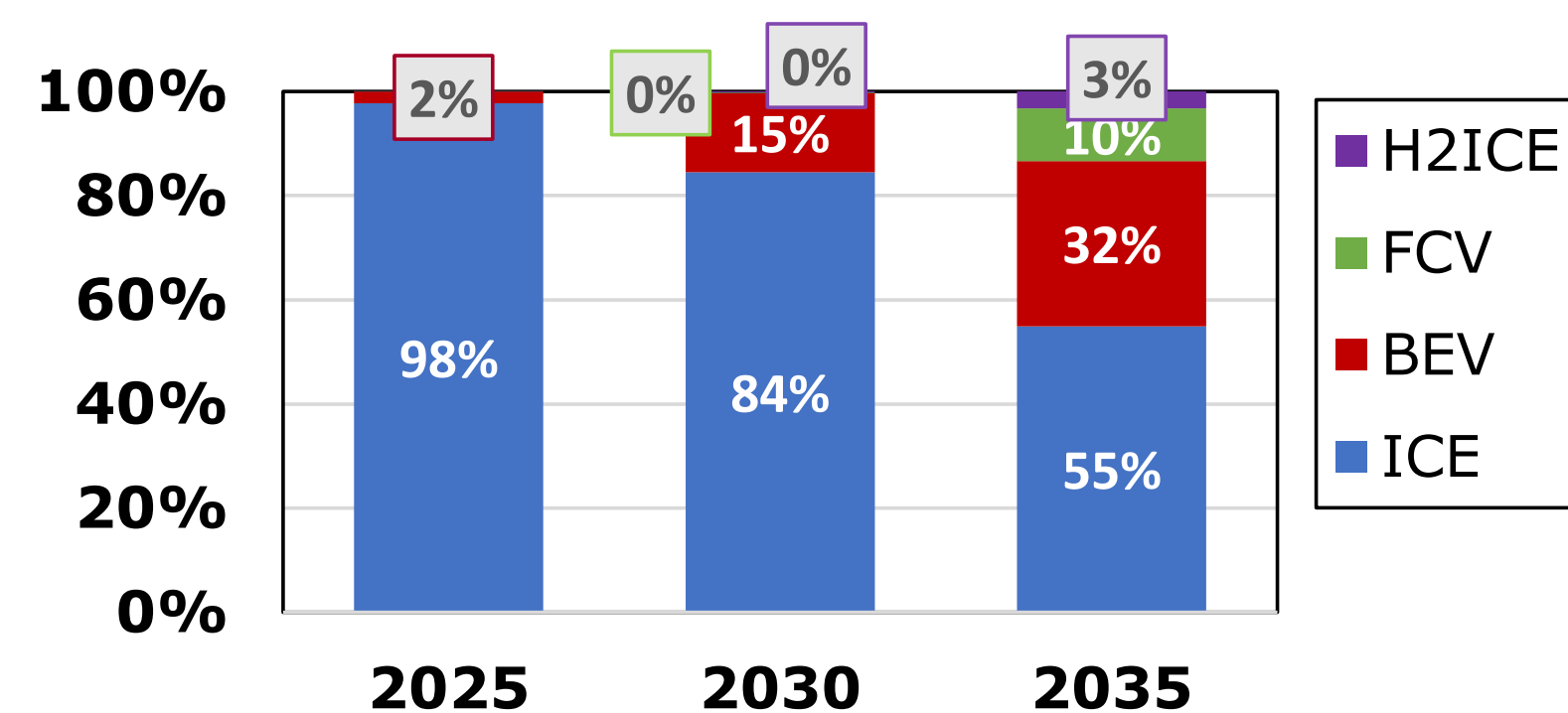
# Powertrain roadmap

## Global Trend



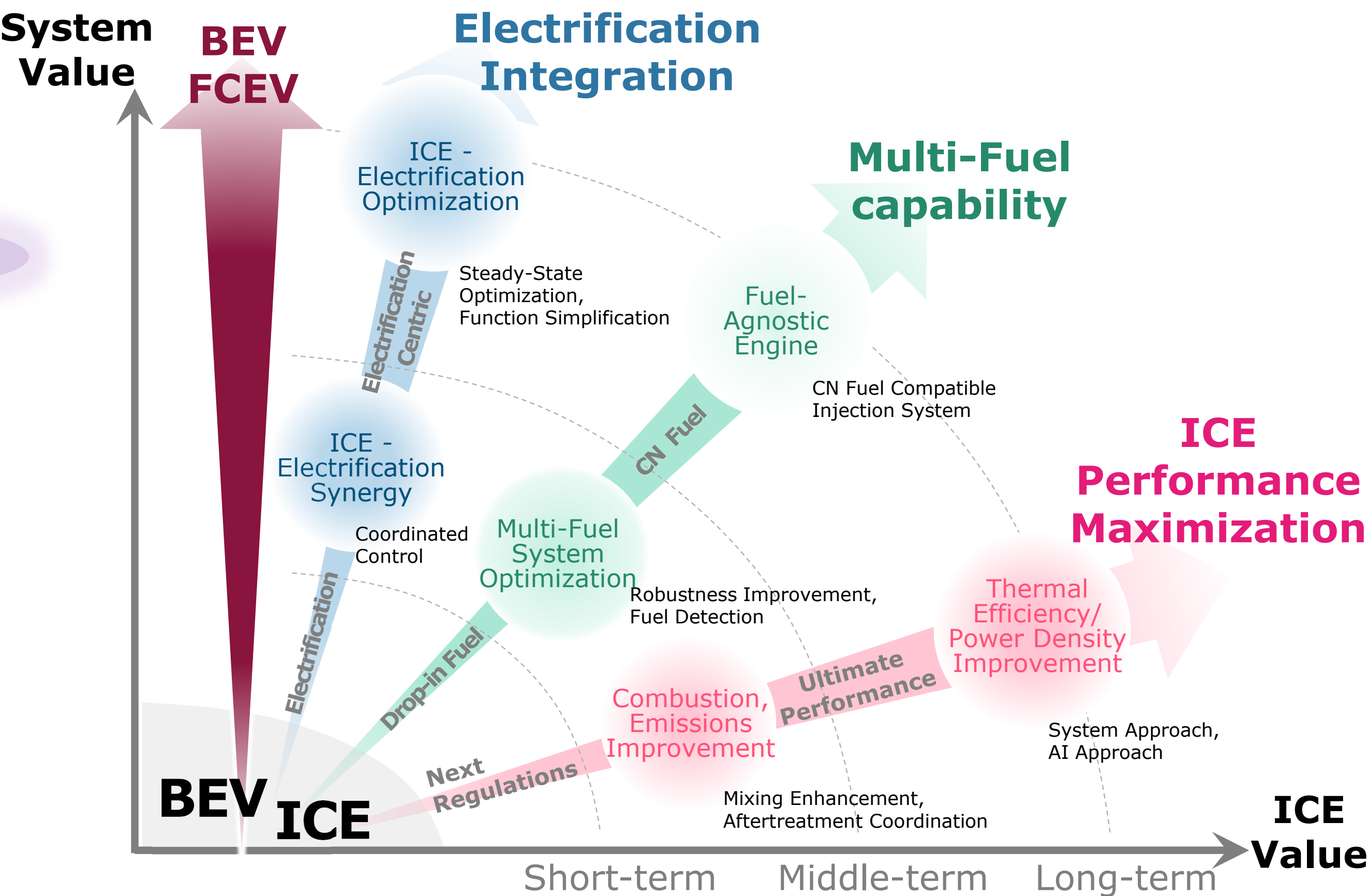
## EU Powertrain

### Production trend of HDV



Reference: DENSO forecast

## Powertrain Roadmap



**DENSO contributes to the evolution of all powertrain technologies**

# Injection system for H<sub>2</sub>ICE

## Requirement of H<sub>2</sub>ICE for HD application:

- Same load performance as diesel engine
- Low emission (NO<sub>x</sub>)
- Same robustness as diesel engine
- Competitive TCO (Total cost of ownership)

## Requirement of injection system:

- Less boost pressure demand
- Lean homogeneous mixture
- Low pressure injection
- Dimension suitable for existing Diesel Engine

## Low Pressure Direct Injection (LPDI)

Provides the optimum balance for HDV

## Type of engine head and port

| Head shape               | Pent-roof head | Flat head   |                 |
|--------------------------|----------------|-------------|-----------------|
| Port shape               | Tumble port    | Tumble port | Swirl/Weak flow |
| Image                    |                |             |                 |
| Mixing                   | Best           | Good        | Poor            |
| NO <sub>x</sub> emission | Low            | Medium      | High            |
| Modification*            | Big            | Medium      | Small           |

\* Assumption: Base engine = HDV engine

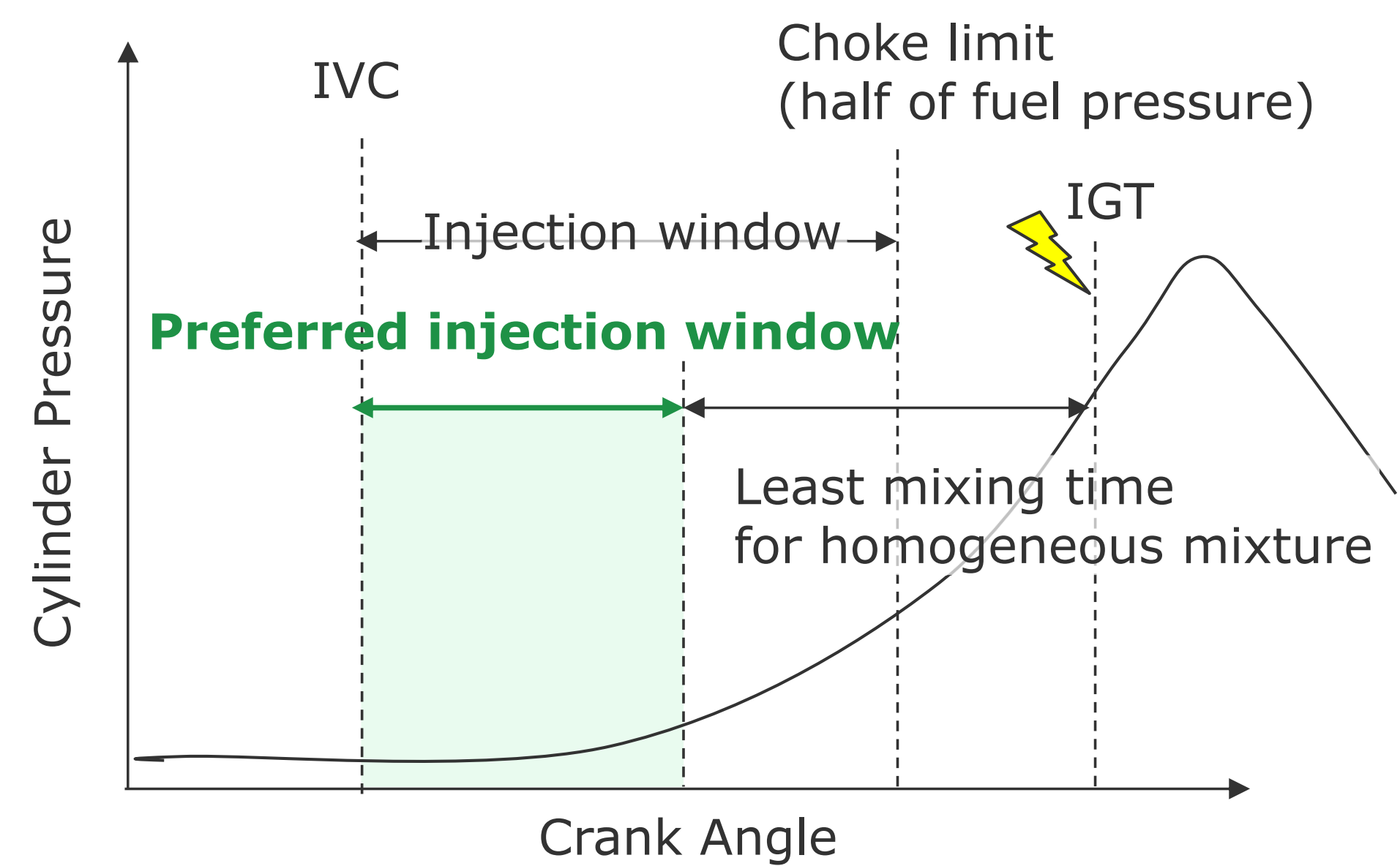
Challenge is how LPDI can meet the requirements with a diesel-based head design

# Concept of High-Flow-Rate Injection

## Challenge

Achieving a homogeneous lean mixture in a diesel-based engine under injection constraints

## Constraint



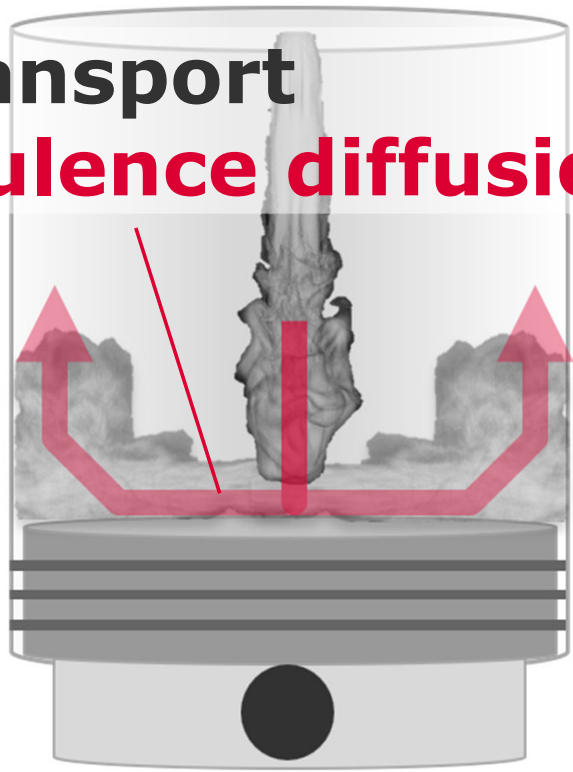
## Solution

**High-flow-rate injection** to enhance in-cylinder turbulence and mixture formation within short time

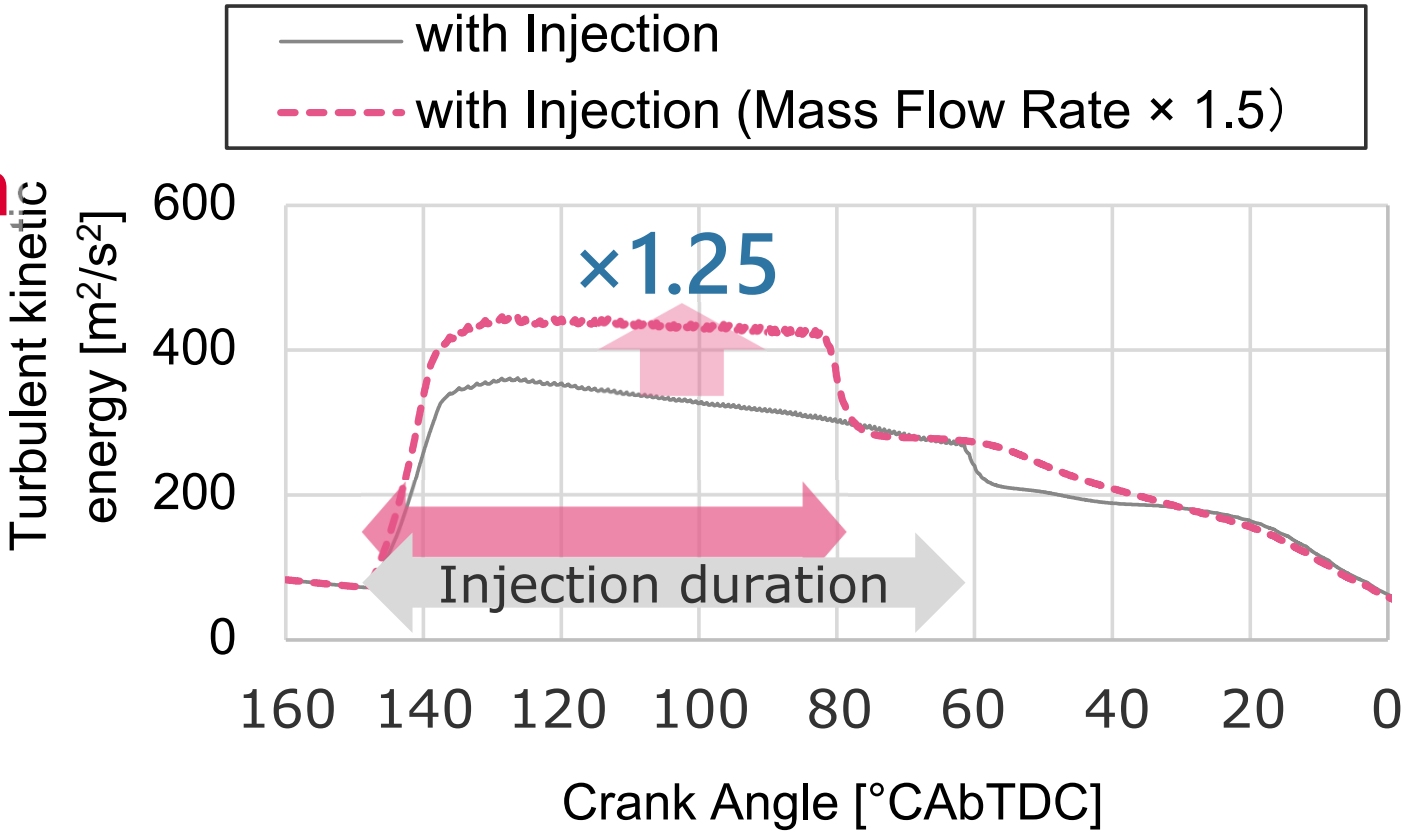
## Feasibility study

Center injection

**Fuel transport + Turbulence diffusion**



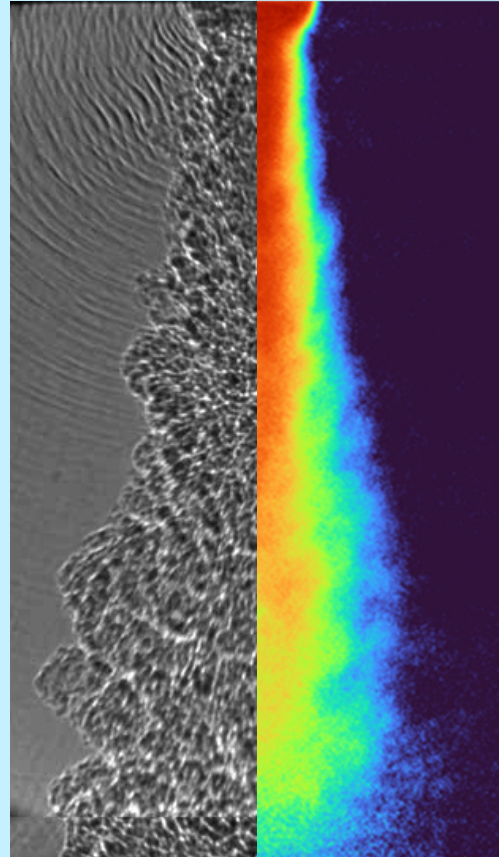
<Evaluated Conditions>  
•CONVERGE 3.0, •Turbulence Model RNG k-ε, •1800rpm-290kPa,  
•CR 14, •S/B 1.07, •2500cc, •Swirl Ratio 1.4@1800rpm,  
•Lambda 2.0, •**Fuel Pressure 3MPa, •SOI -150deg.CA\_ATDC,**



**High flow rate is an enabler to achieve homogeneous mixture under the constrains**

# Validation steps

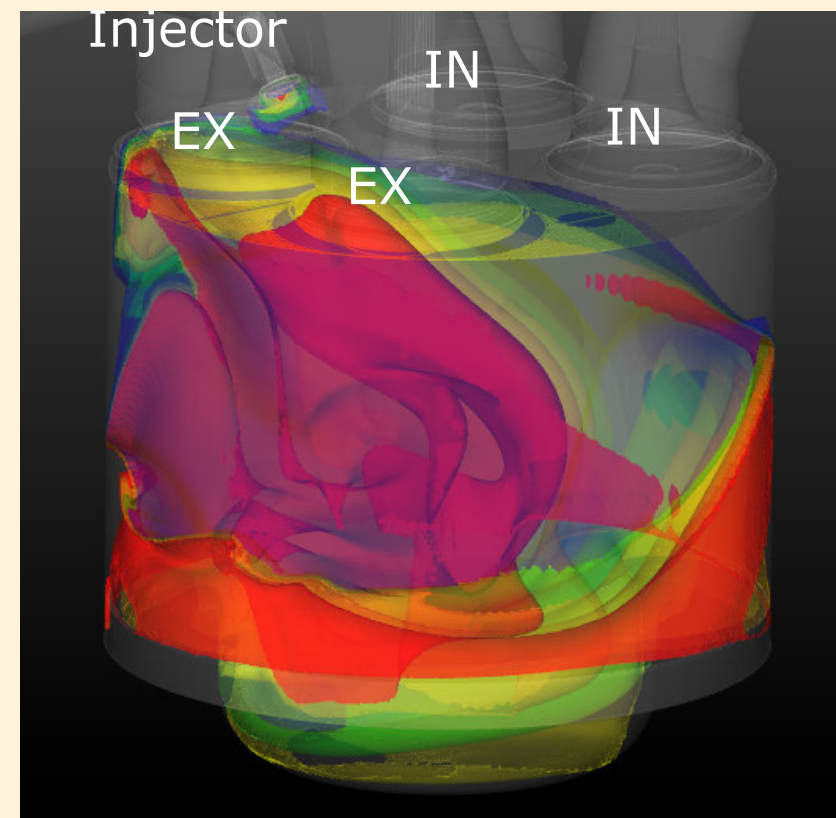
## Jet characterization



### Key Metrics

- Penetration length
- H<sub>2</sub> concentration

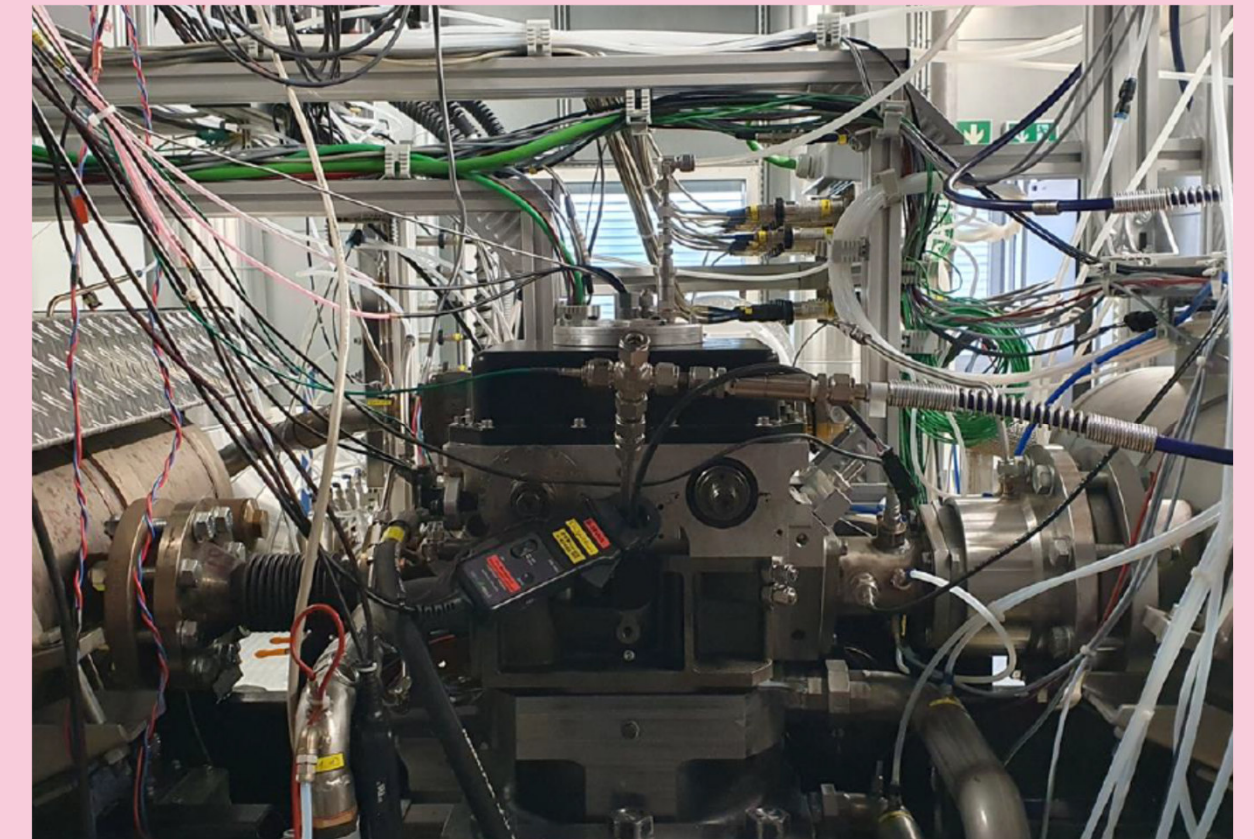
## Mixture formation



### Key Metrics

- Mixture homogeneity
- H<sub>2</sub> concentration distribution
- Turbulence

## Combustion characteristics



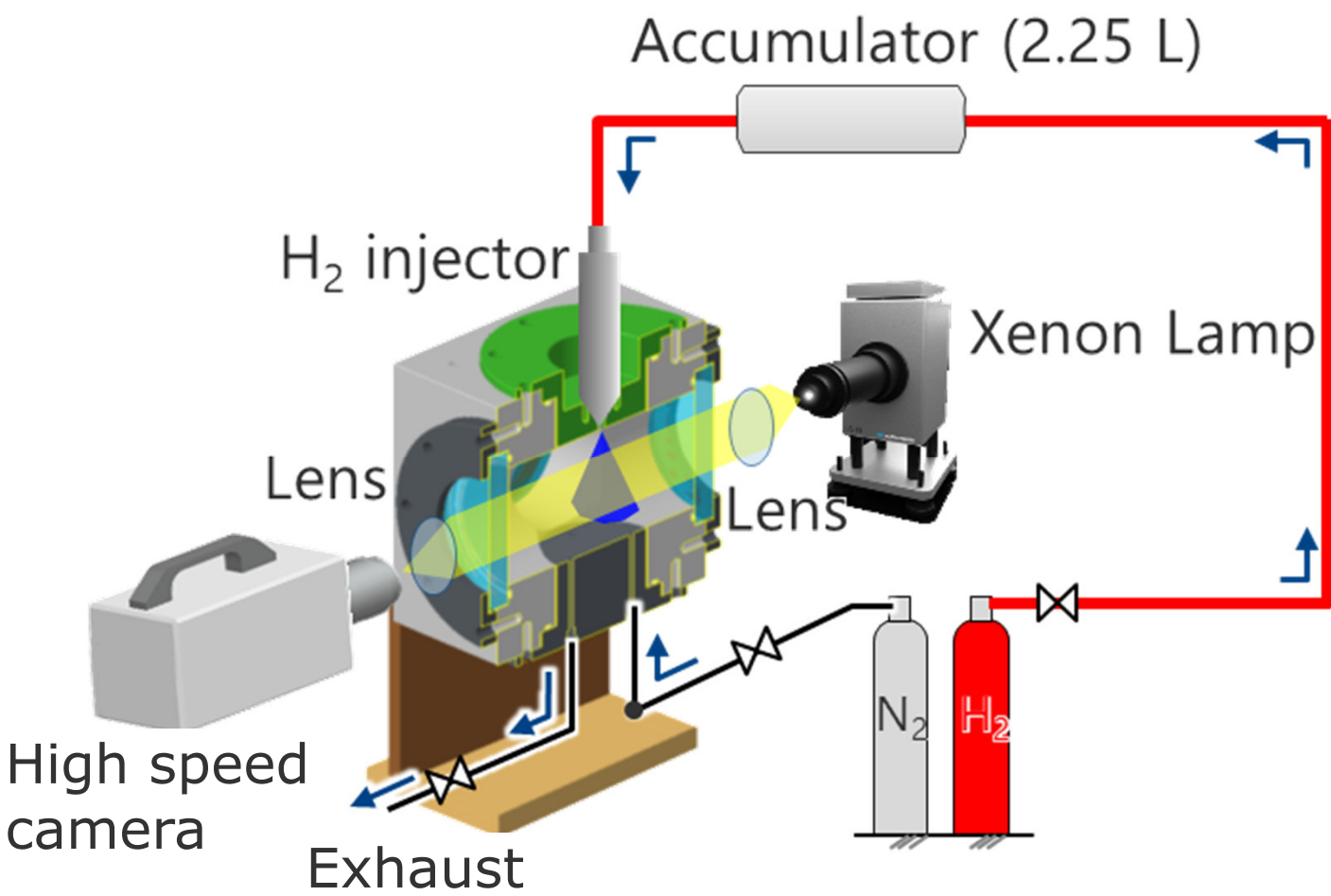
### Key Metrics

- Combustion stability
- NO<sub>x</sub> emission
- Thermal efficiency
- Frequency of abnormal combustion
- High-load capability

# Experimental methods

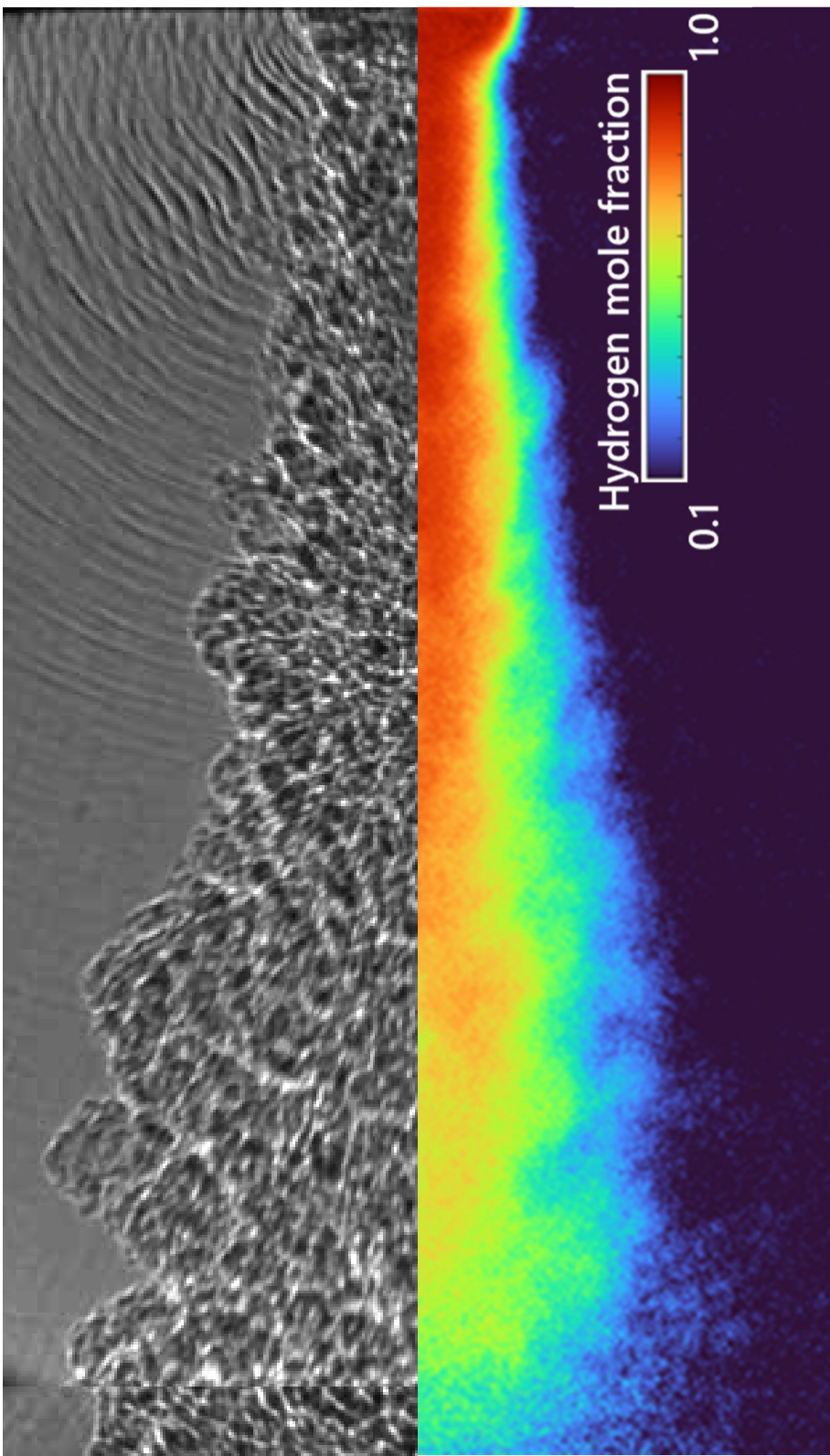
## Shadowgraph Method

Jet structure visualization



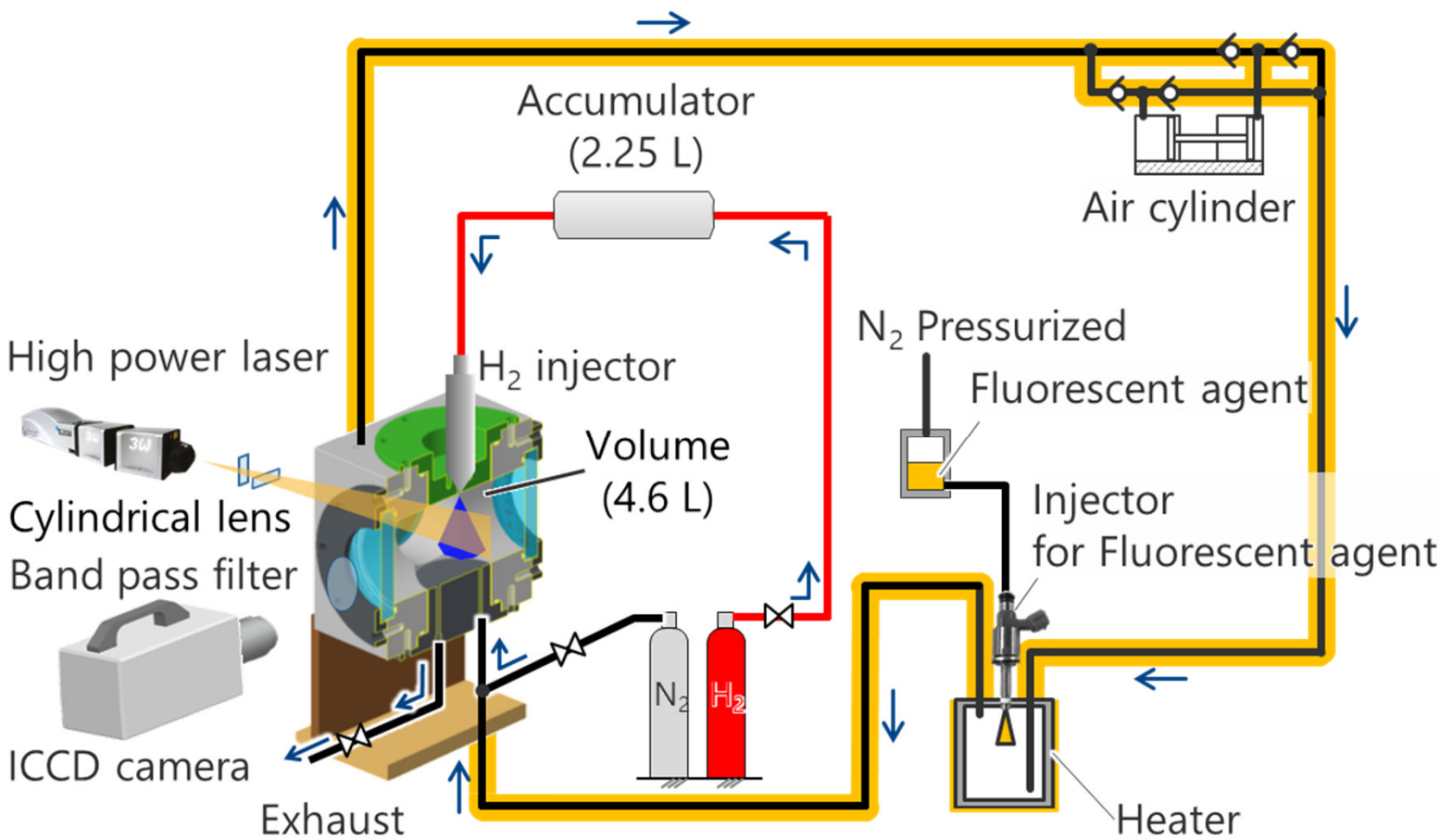
Condition  
 Fuel type: Hydrogen  
 Fuel gas temperature: 293K  
 Injection pressure: 30 bar  
 Ambient pressure: atmospheric  
 Frame rate: 30000 fps  
 Exposure time: 0.2μs  
 Resolution: 640\*640 pixel

Jet structure      Hydrogen mole fraction



## Negative LIF Method

Fluorescent tracer is added to the mixture to measure concentration distribution※2

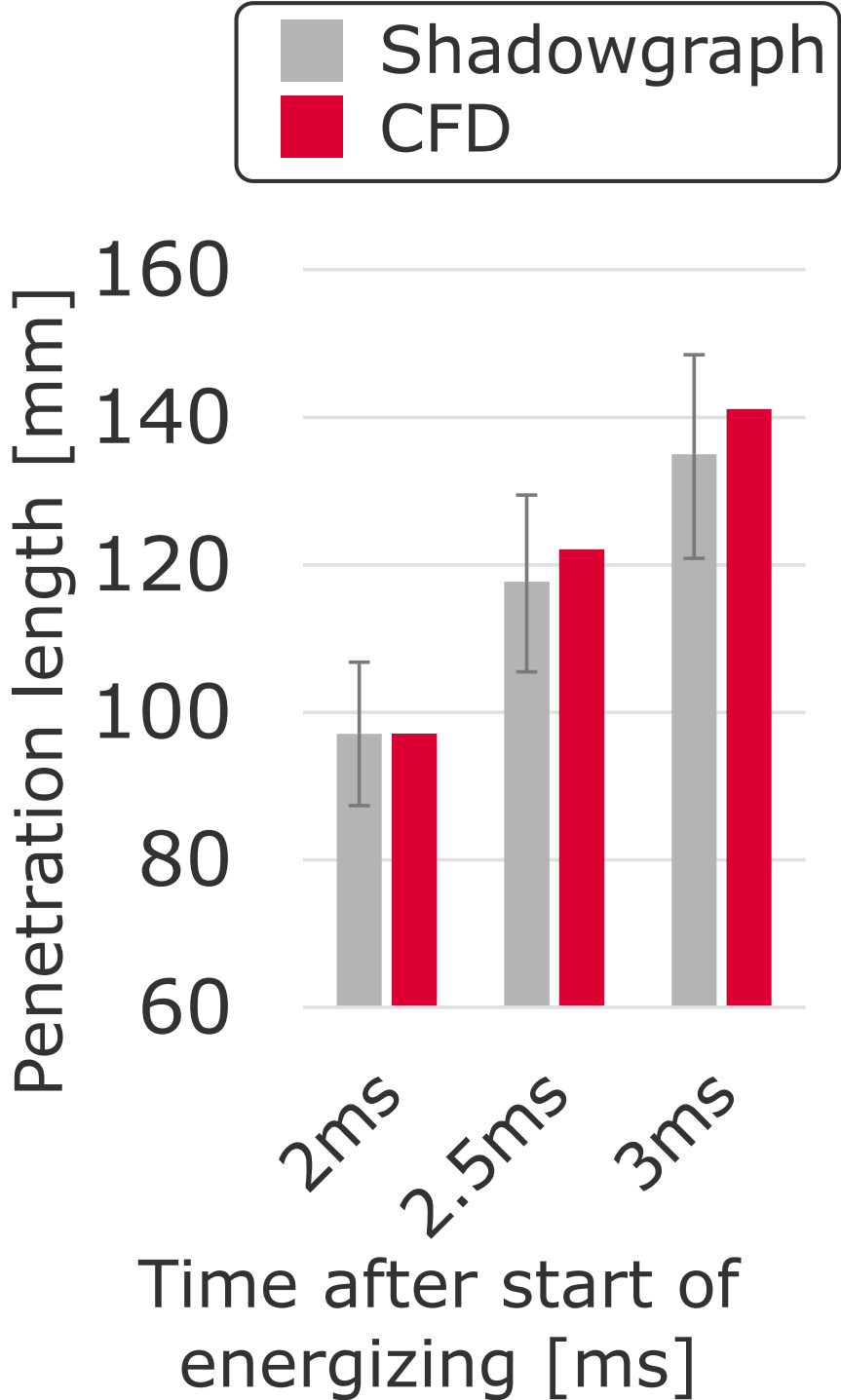
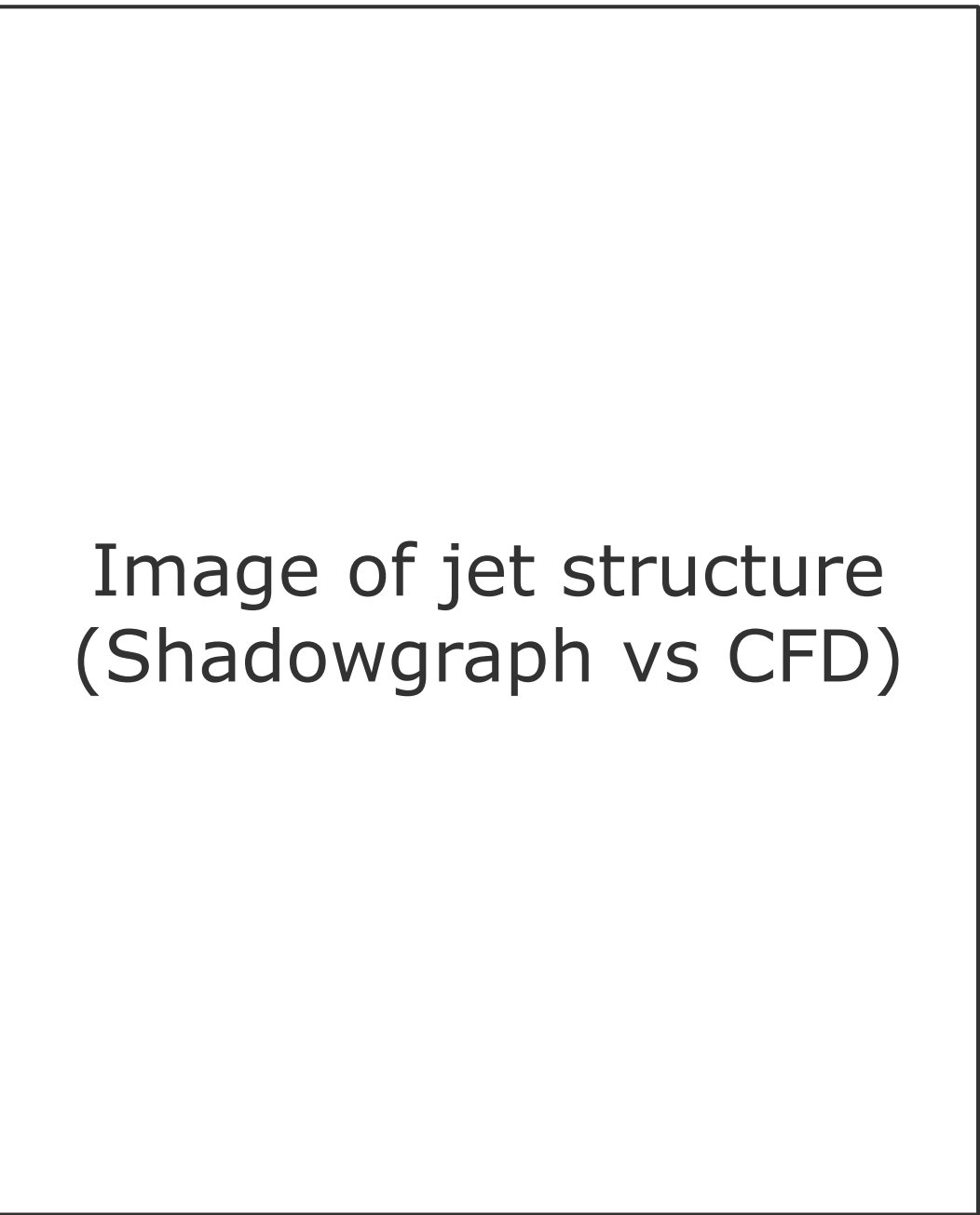


※2 S. Ishida, et al : Visualizing Hydrogen Jet Concentrations with Negative LIF, Proceedings of the 2025 JSAE Annual Congress (Autumn), No. 222, 2025

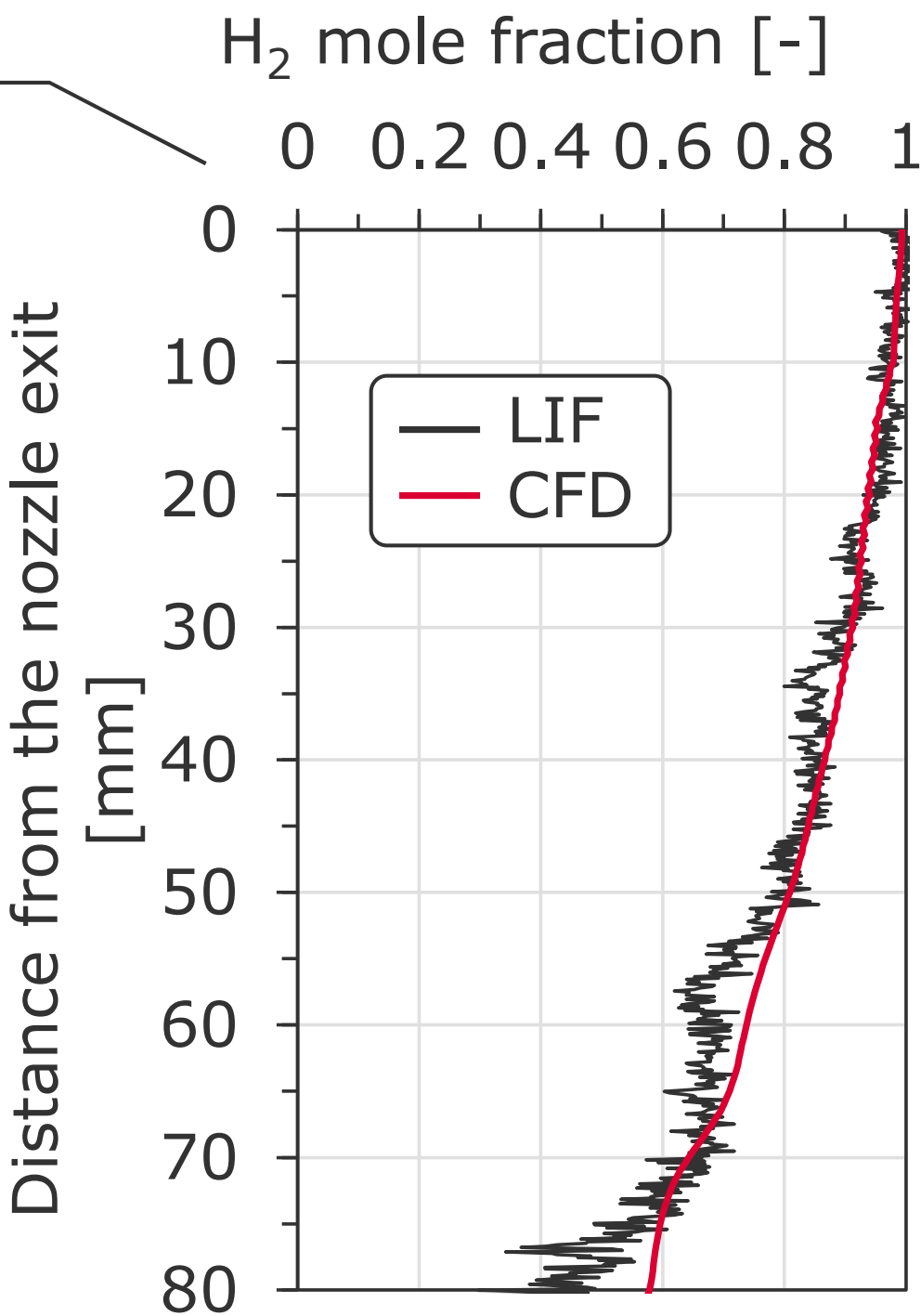
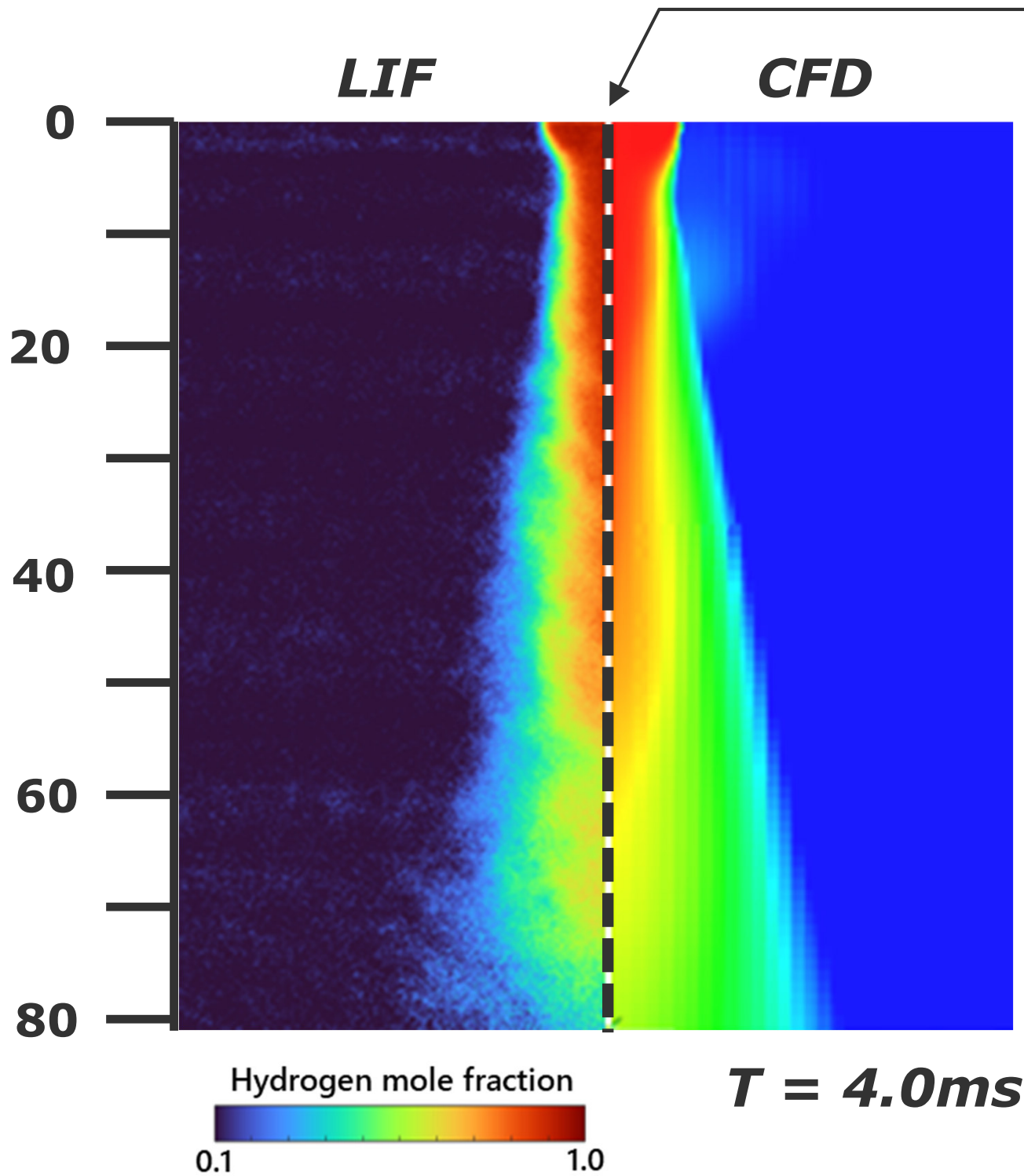
Condition  
 Fuel type: Hydrogen  
 Fuel gas temperature: 293K  
 Injection pressure: 30bar  
 Ambient pressure: atmospheric  
 Fluorescent agent: anisole  
 Laser wavelength: 266nm  
 Band-pass filter: 300±25nm

# Comparison experiment vs CFD

## Jet structure



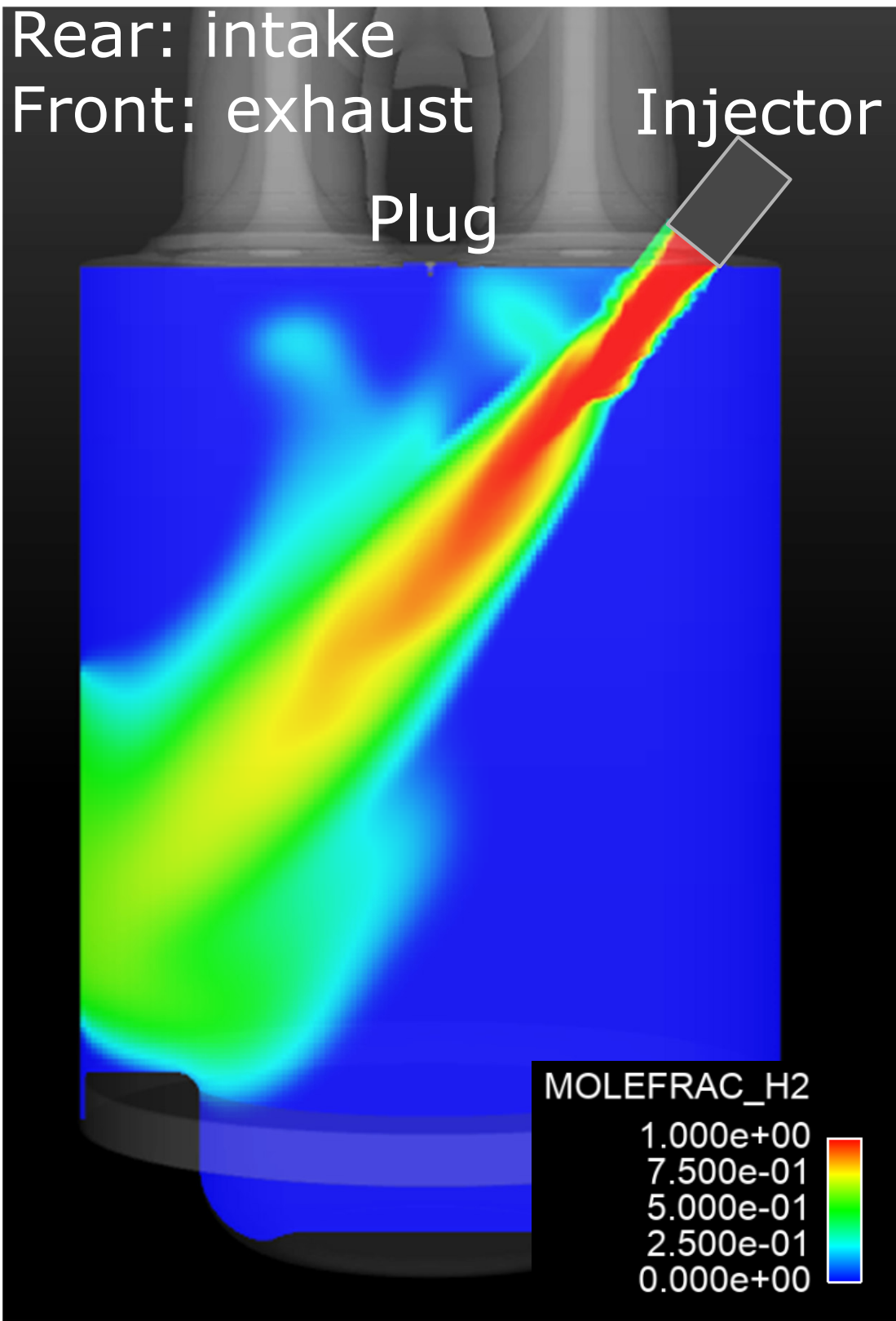
## Hydrogen mole fraction



Hydrogen jet model shows good agreement

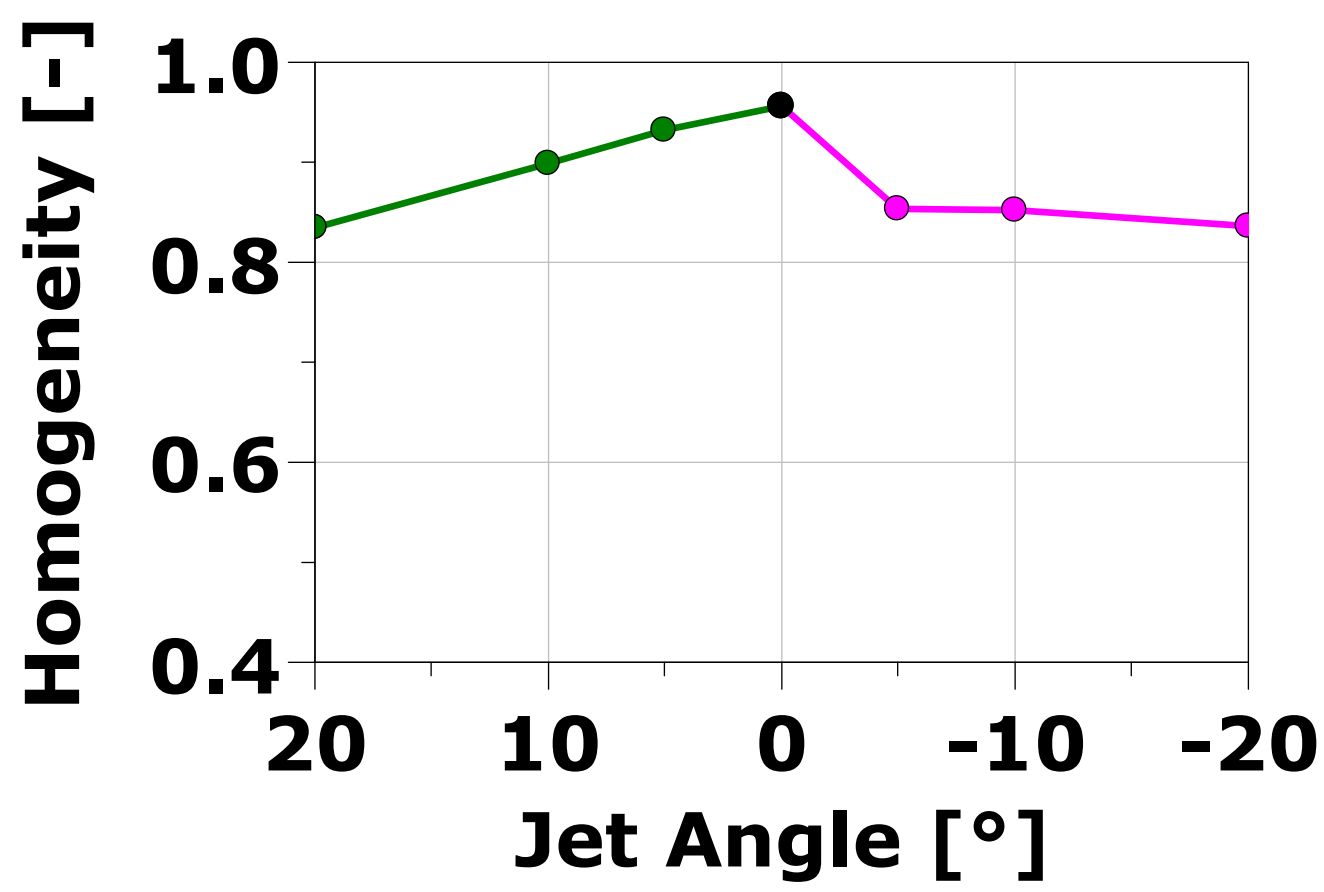
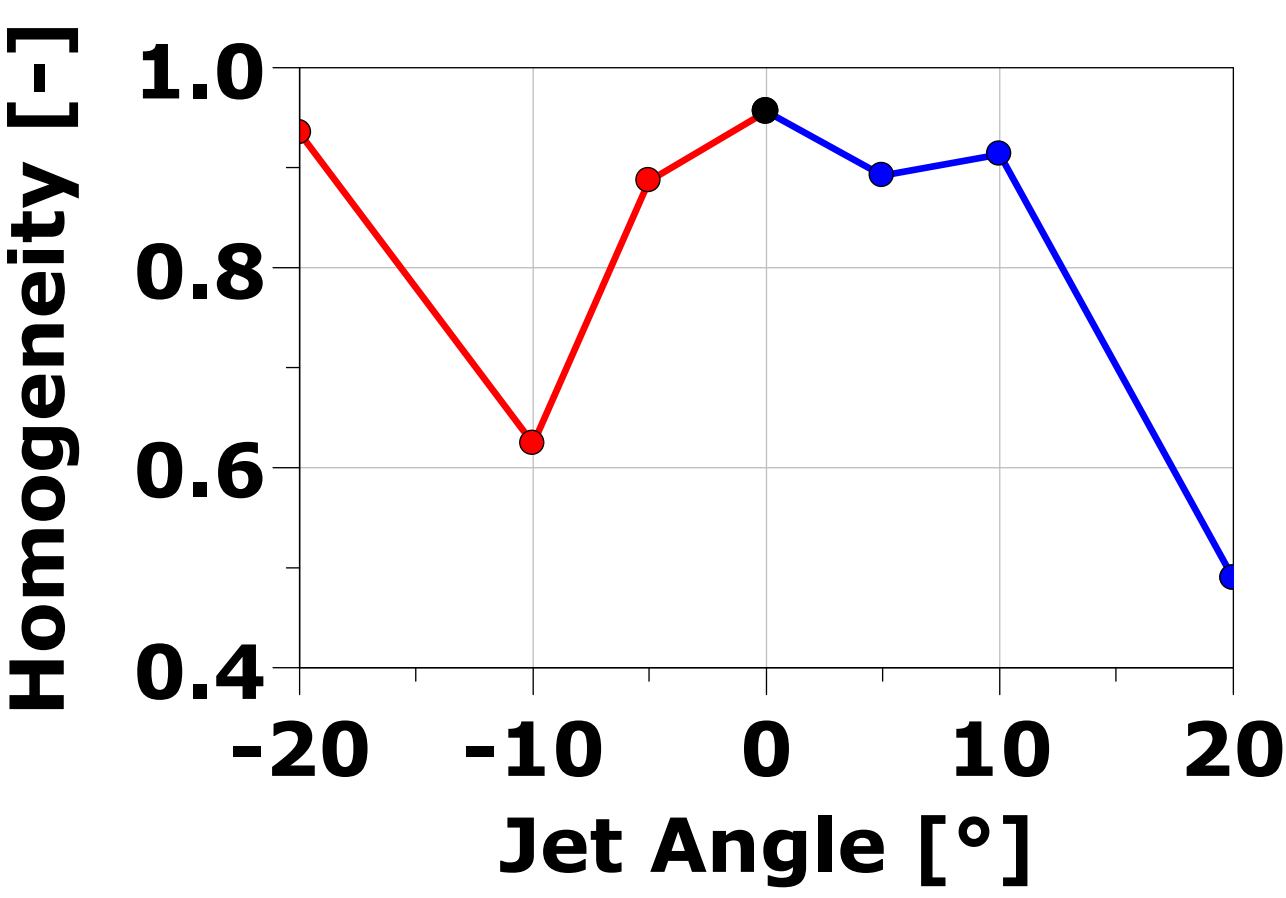
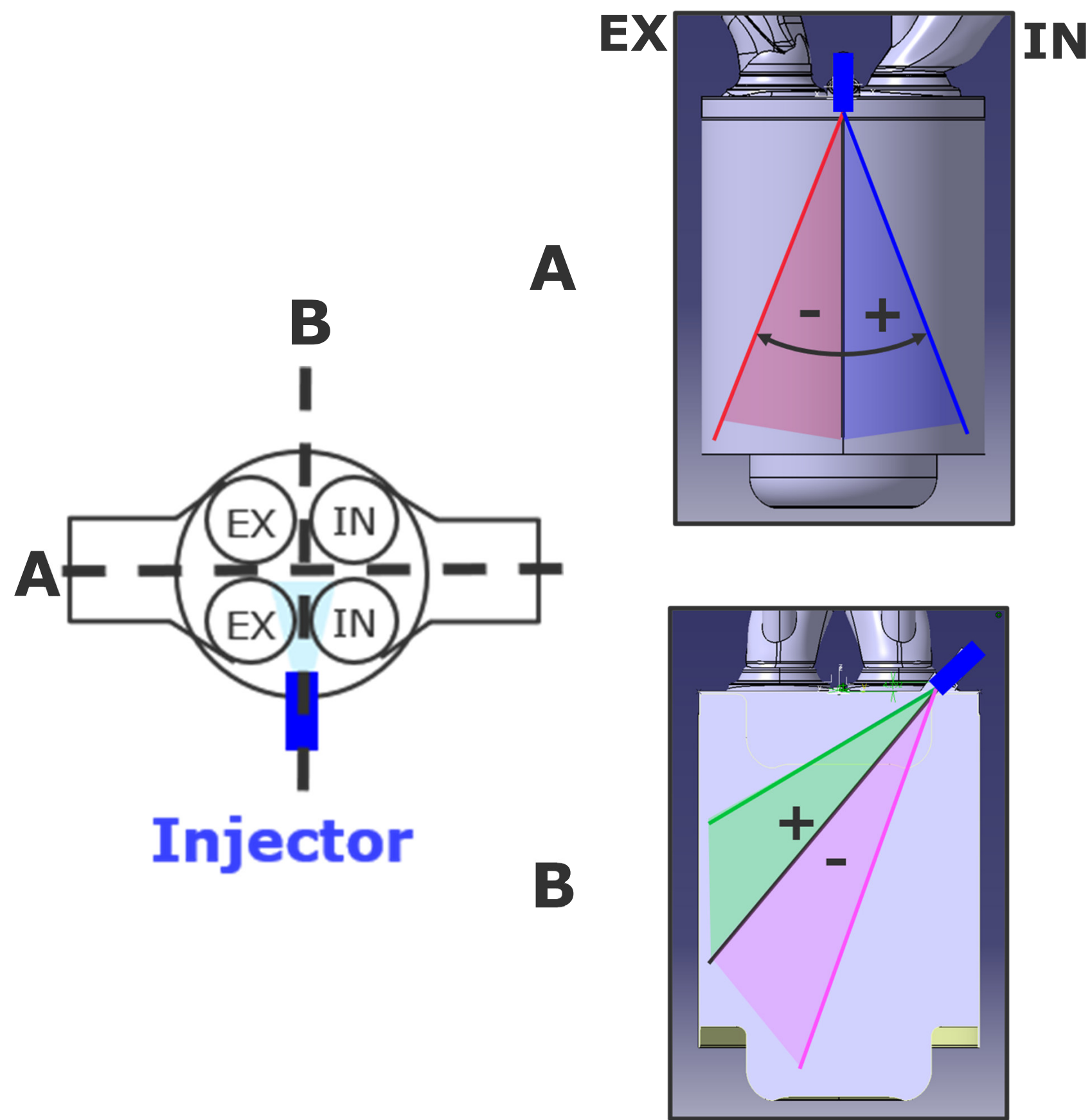
# CFD model for mixture formation

|                       |                  |
|-----------------------|------------------|
| Software, version     | CONVERGE v3.0.24 |
| Turbulence model      | RNG k-ε          |
| Displacement          | 2.13 L           |
| Compression ratio     | 10.6             |
| Lambda                | 2.4 (target)     |
| Mesh size in cylinder | 1 mm             |

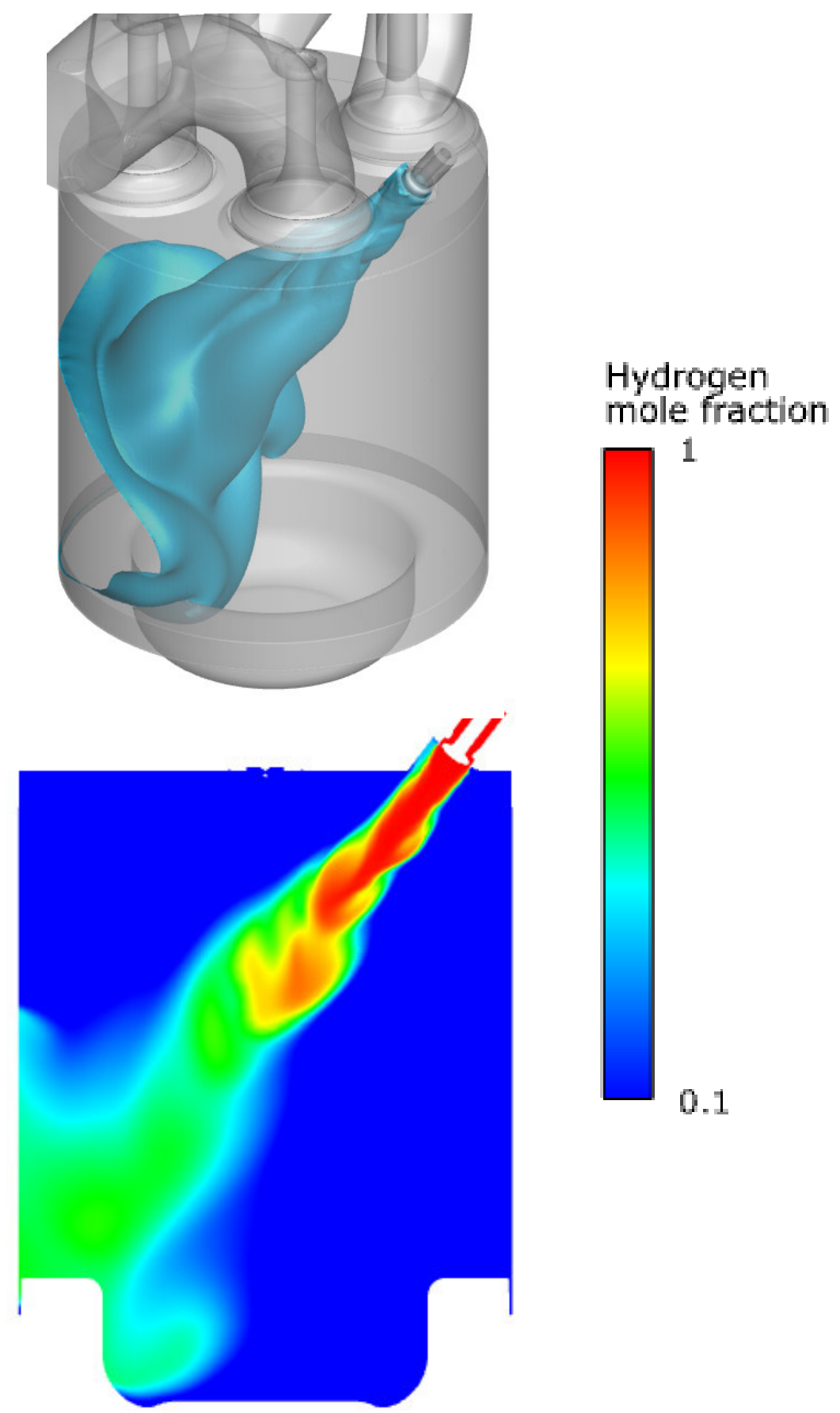


# Optimization of injection direction

## Injector Jet Angle Variation in CFD



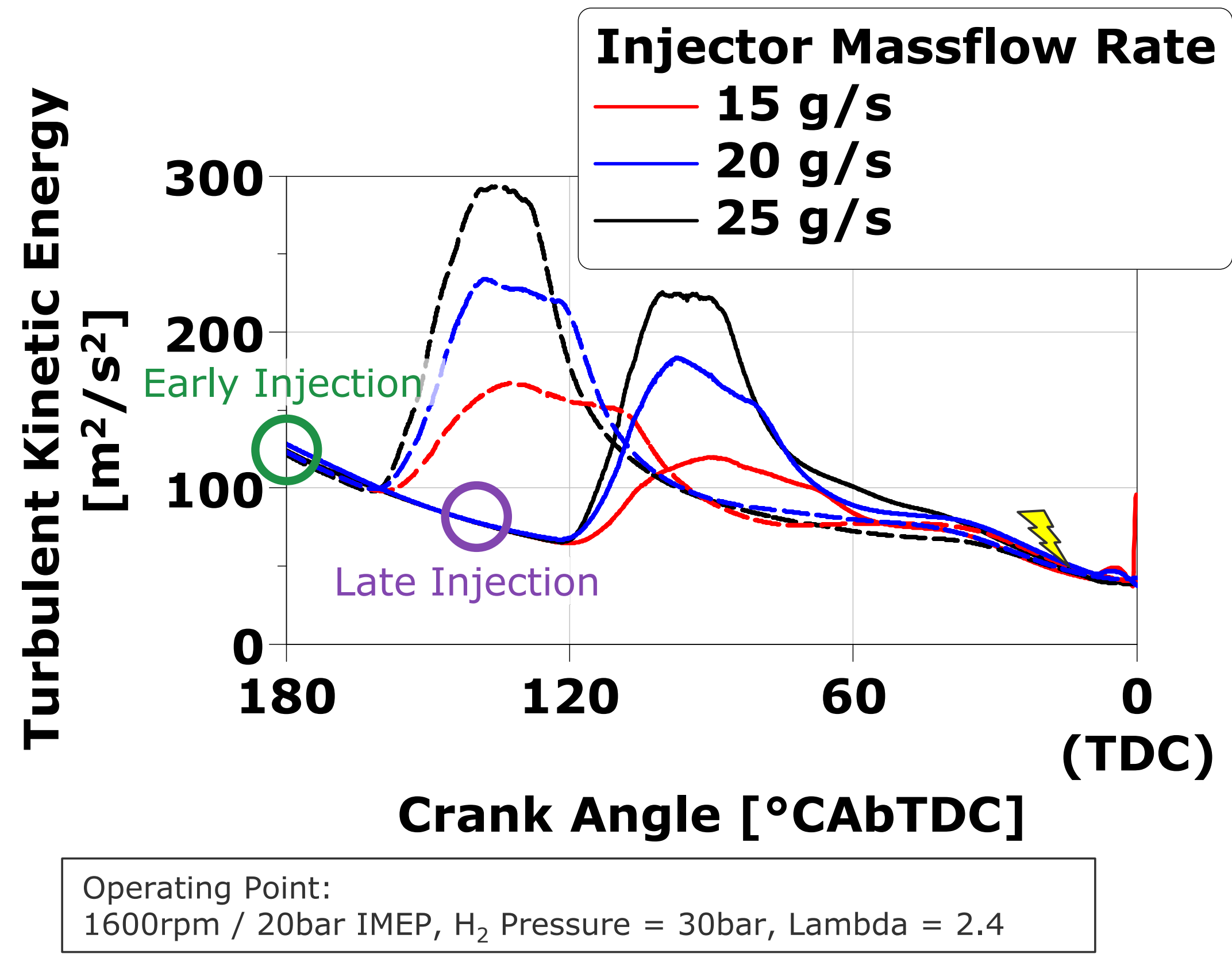
Jet behaviour at 0°



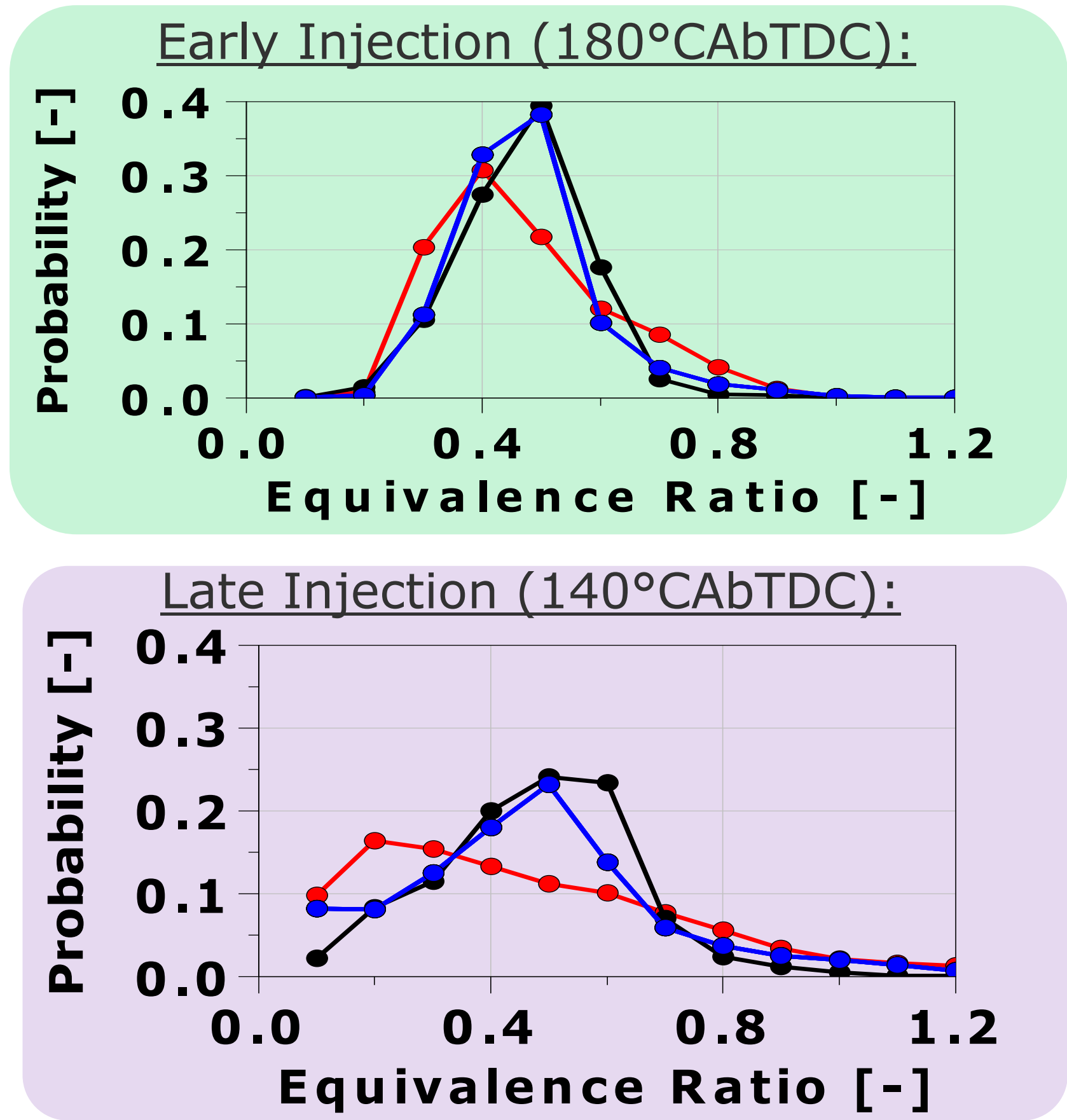
**Optimum Jet Direction for maximum Homogeneity identified**

# Effect of high-flow-rate injection

## Turbulent Kinetic Energy



## Equivalence Ratio Distribution before Ignition



**High-flow-rate injection enhances mixture formation, particularly under late injection conditions.**

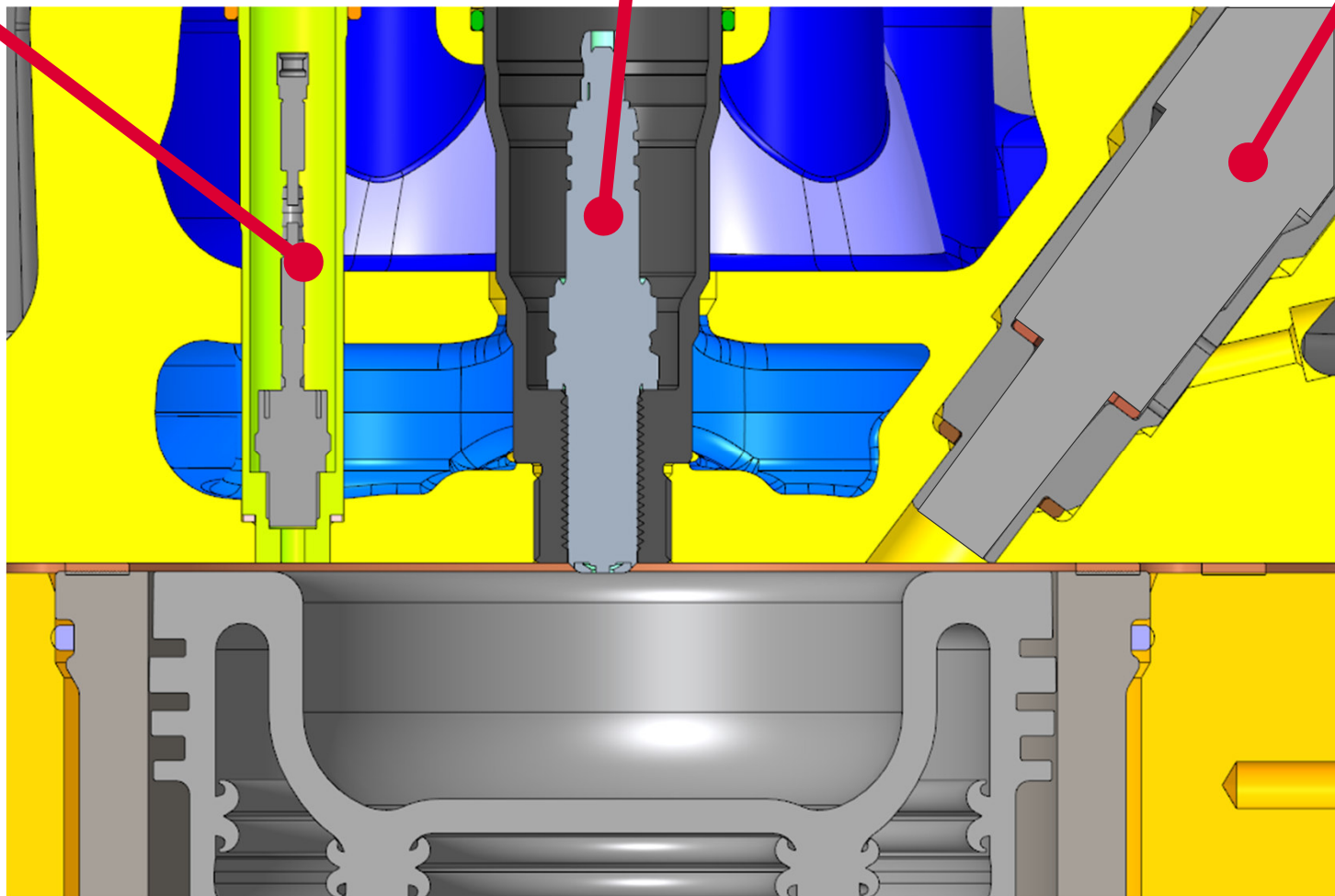
# Proof of Concept with HDV engine

|                        |                 |
|------------------------|-----------------|
| Cylinder               | Single cylinder |
| Displacement           | 2.13 l          |
| CR                     | 10.6            |
| Intake air temperature | 25 °C           |
| Lambda                 | 2.4             |
| Fuel pressure          | 30 bar          |

Cylinder Pressure  
Sensor

Spark Plug

LPDI Injector

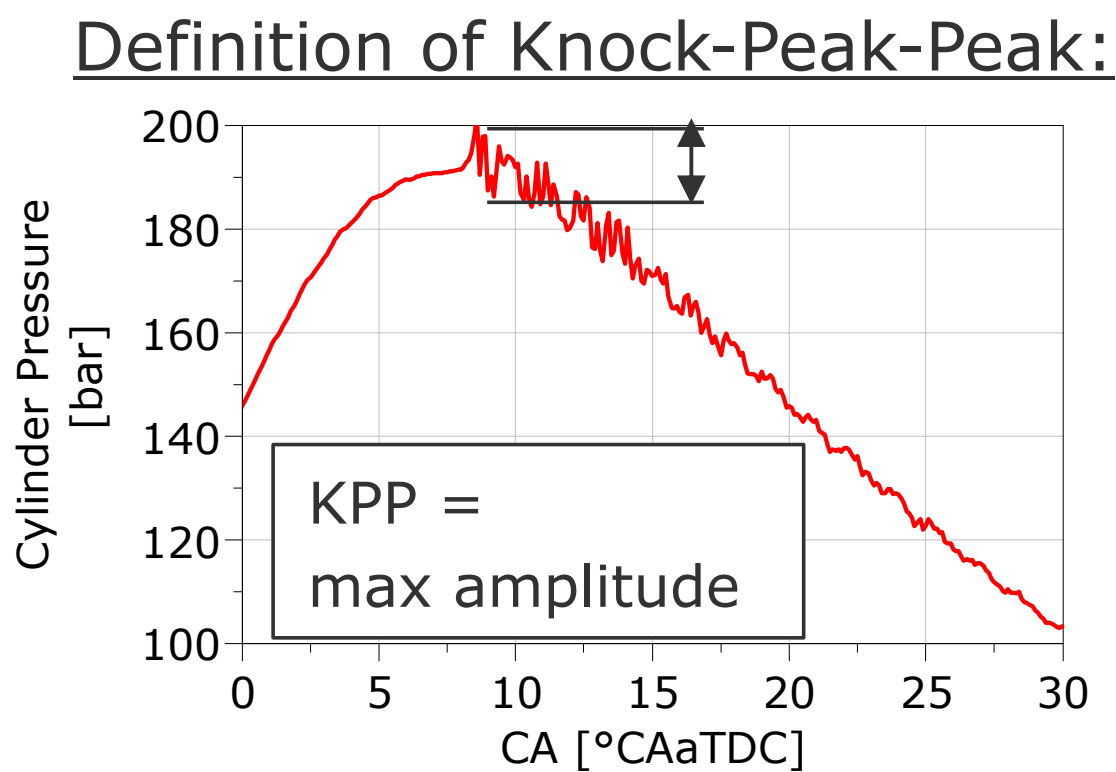
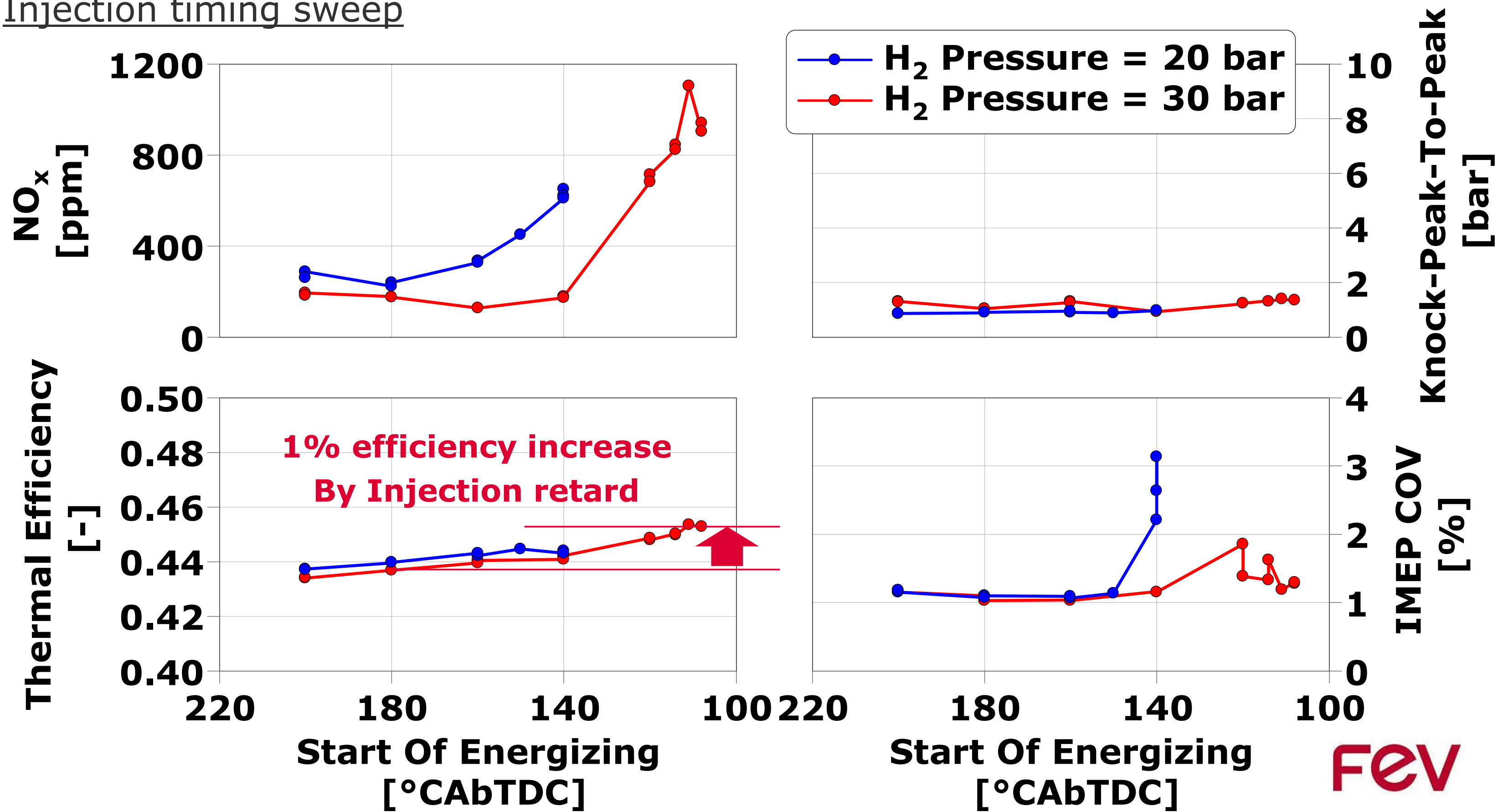


FEV

Potential of high-flow rate injector was investigated with HDV engine

# Engine Results of HDV Single Cylinder Engine

Injection timing sweep

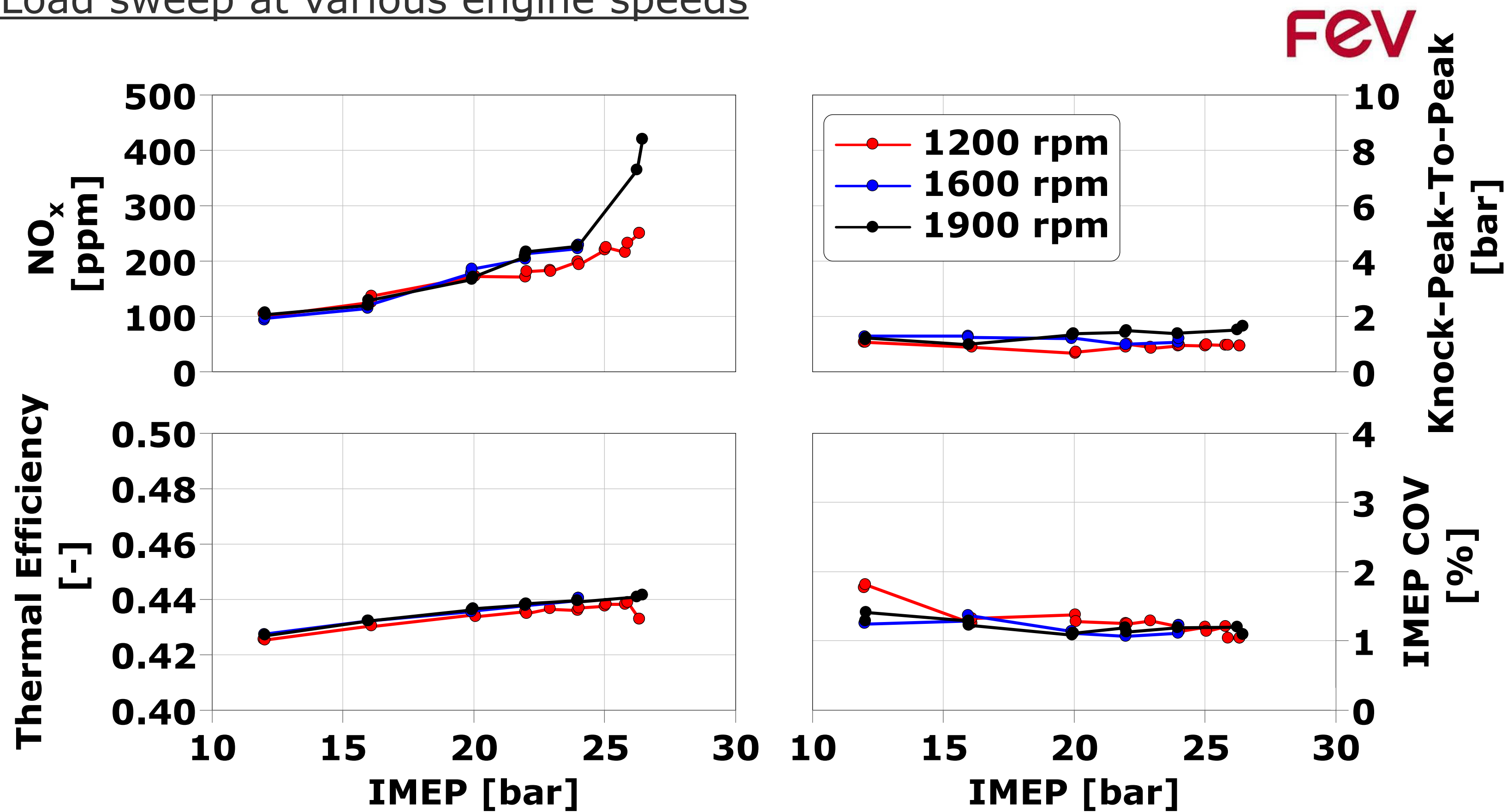


Engine type: Single cylinder  
Displacement: 2.1 L  
CR: 10.6  
Engine Speed = 1600rpm  
IMEP = 20 bar  
Lambda = 2.4  
Center of Combustion = 8°aTDC

Efficiency benefit of retarded injection confirmed on Engine

# Engine Results of HDV Single Cylinder Engine

Load sweep at various engine speeds



Engine type: Single cylinder  
Displacement: 2.1 L  
CR: 10.6  
SOE = 180°CAbTDC  
Lambda = 2.4  
Center of Combustion = 8°aTDC

IMEP of 26 bar achieved on Engine.

# Summary

**DENSO contributes to a sustainable mobility future by advancing all powertrain pathways**, from highly efficient internal combustion engines to electrified solutions.

For heavy-duty hydrogen engines, **DENSO has selected LPDI** as the optimal injection strategy, leveraging high-flow-rate injection to deliver superior mixture formation and engine performance.

The benefits of high flow rate injection are:

- Stronger jet-induced turbulence improves mixture formation and promotes a more homogeneous air-fuel mixture, which enables higher load operation with better combustion stability and reduced abnormal combustion tendency.
- Shorter injection duration provides more mixing time, especially for late injection after IVC.
- Greater injection timing flexibility allows a better balance between NO<sub>x</sub> emissions and thermal efficiency

***DENSO***

Crafting the Core