Effects of 2-EHN additive's volume fraction and injection parameters on methanol auto-ignition combustion

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Contents

Strengthened IMO strategy on GHG reductions (Jul. 2023. – MEPC 80)

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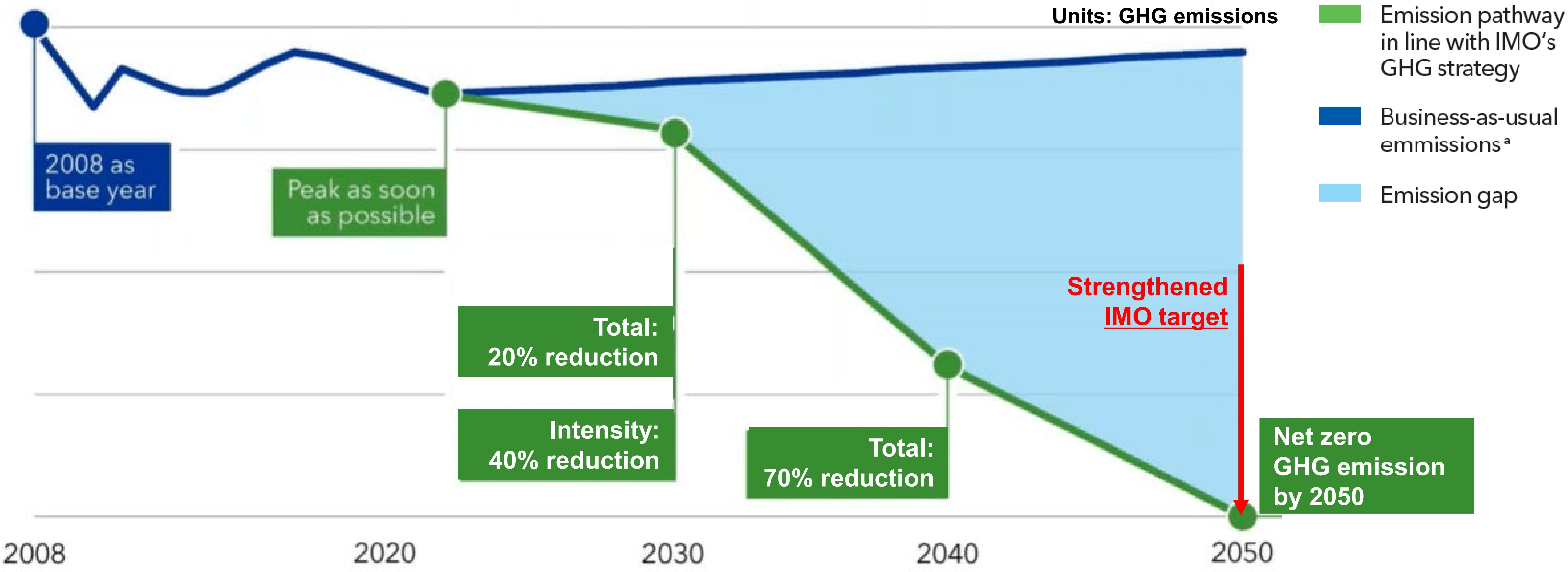


(Total: Well-to-wake GHG emission; Intensity: CO_2 emitted per transport work)

<MEPC 80: Increased emission reduction ambitions in revised IMO GHG strategy (DNV, July 2023)>

- **IMO has drastically tightened regulations on Greenhouse Gas from 50% to 100% by 2050.**

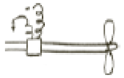
The need for alternative fuels in marine powertrains

- Applicable tech.

HYDRODYNAMICS

10-15%

- Hull coating
- Hull form optimization
- Air lubrication
- Cleaning

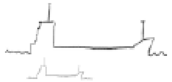


FUELS AND ENERGY SOURCES

0-100%

- LNG/LPG
- Electrification
- Biofuel
- Synthetic/hydrogen etc.

Alternative tech needed



LOGISTICS & DIGITALIZATION

>20%

- Speed reduction
- Vessel utilization
- Vessel size
- Alternative routes

- The need for alternative fuels in marine powertrains

Alternative fuels & tech.		GHG Reduction Potential	Feasibility (term)		
Low carbon fuels	LNG, LPG, CNG	20-30 %	Short	Mid	long
Zero carbon fuels	Hydrogen (Engine)	0-100 %	Short	Mid	long
	Methanol (e-Fuel)	20-100 %	Short	Mid	long
	Ammonia	20-100 %	Short	Mid	long
	Biofuel	20-100 %	Short	Mid	long
Sustainable energy sources	Electric propulsion(Battery)	0-100 %	Short	Mid	long
	Fuel cell	0-100 %	Short	Mid	long
	Wind power	1-32 %	Short	Mid	long
	Solar energy	0-12 %	Short	Mid	long
	nuclear energy	0-100 %	Short	Mid	long

<Maritime Greenhouse Gas (GHG) Reduction Strategy Technology and Prospect, 2019, KRISO>

- **Applicable technologies for reducing greenhouse gases in the shipping sector**

➔ To achieve the ultimate 100% reduction goal, it is essential to apply alternative propulsion technologies including **alternative fuel**

- the fuel and propulsion technologies to achieve the emission goals:
  carbon-free fuel applications: hydrogen, **methanol(green)**, ammonia, and biofuels

Alternative fuels for marine powertrains

■ Alternative fuels for marine powertrains

*	Fuel types	Condition for storage	Tank size (compared to MDO)	Price (compared to MDO)	Pros.	Cons.
LNG	Fossil fuel	-162°C	2.3	1.3	• Low price • Abundant production	• Limited carbon reduction • Methane slip • High price
LPG		47°C	1.74	1.2	• Low price • Abundant production	• High carbon content
Bio-Gas	**Carbon neutral fuel**				• **Applicable to existing ships with minor modifications**	• Supply instability
Bio diesel		Room Temp.	1	1		
CH_3OH		**Room Temp.**	**2.3**	**1.5**		• High cost for carbon capture
NH_3		-34°C or 10bar	4.1	1.2	• **Low technical barrier** • **Low price among carbon-neutral fuels**	• Toxicity • Absence of law or regulation
H_2		-253°C or 700bar	7.6	Too High	• Easy production by renewable energy electrolysis	• High price • High technical barrier
Battery		Room Temp.	Too big		• Applicable for small ship	• High price • Low energy density • Shore power supply system

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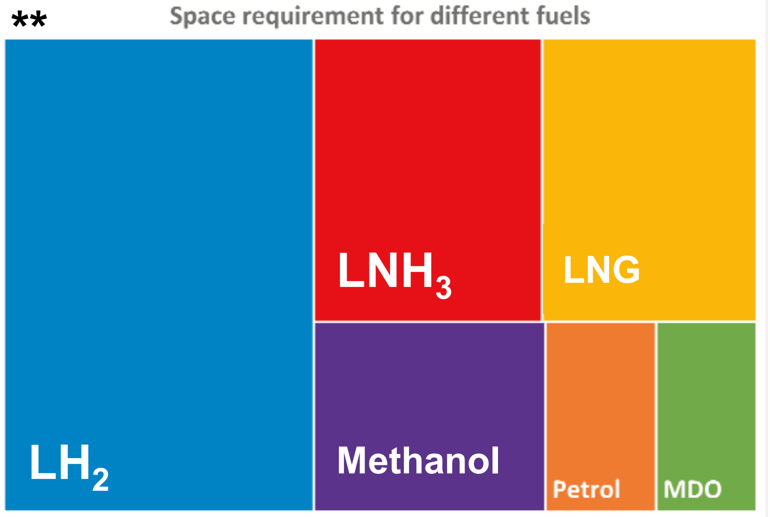

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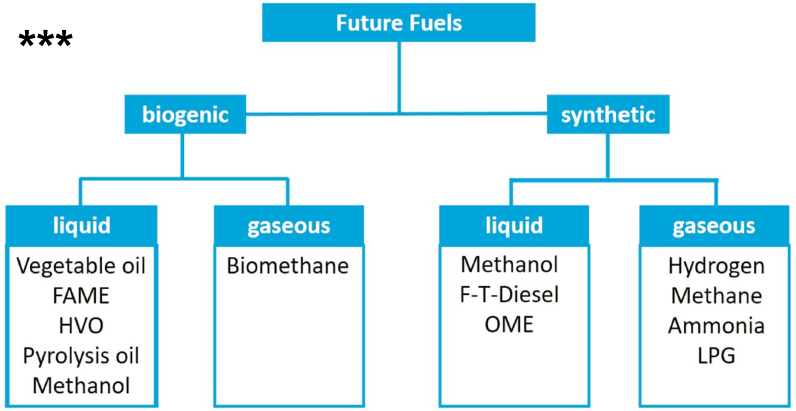


* MARITIME ASSESSMENT OF SELECTED ALTERNATIVE FUELS AND TECHNOLOGIES, DNV GL, 2019

** 7th Large Engine Symposium, ABC's DZ Dual Fuel Methanol engine, Anglo Belgian Corporation NV, 2022

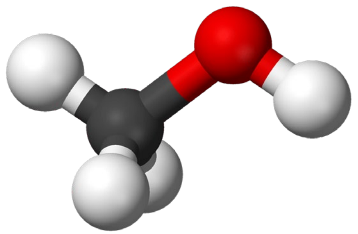
*** 7th Large Engine Symposium, Research approaches and methods for future fuels and lubricants in marine applications, FVTR GmbH, 2022

➔ **Considering the high energy density requirements of ships, ammonia and methanol are being considered as alternative fuels**

Methanol as alternative fuel for marine engine

KAIST

- Molecules & state



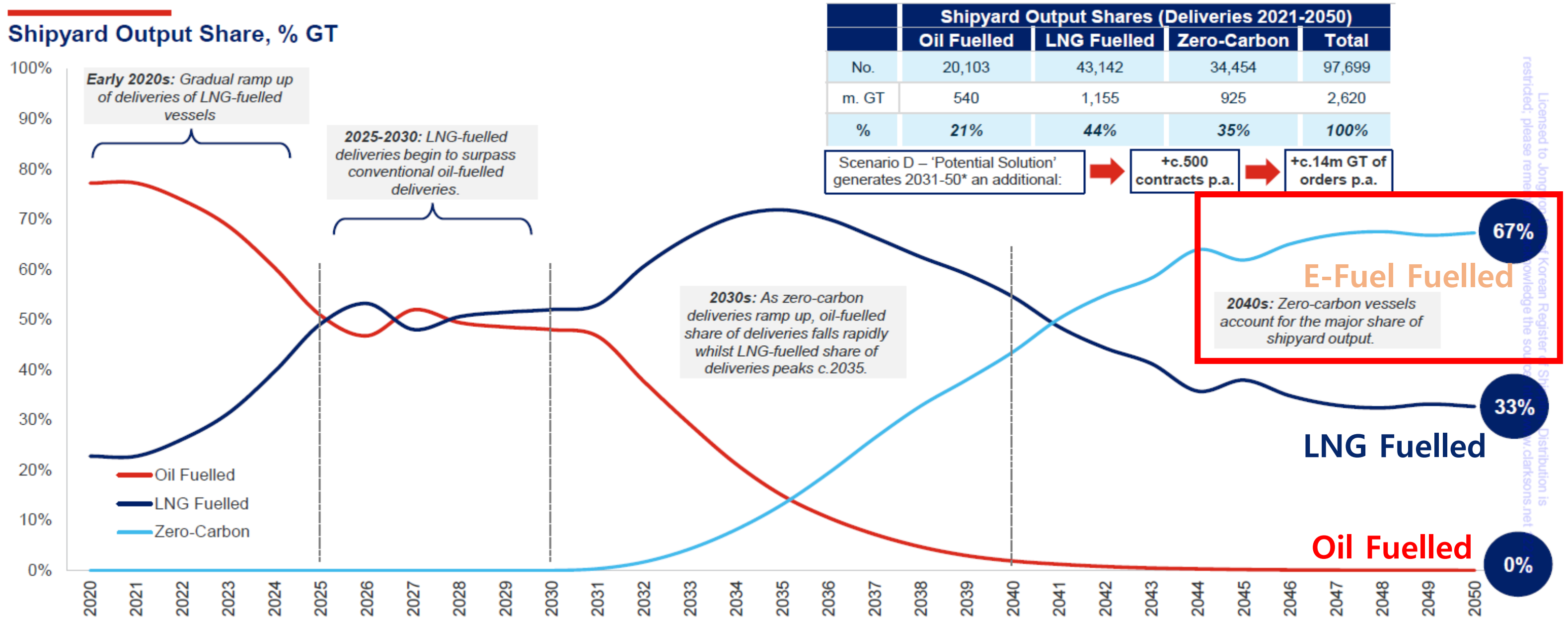
[CH_3OH]

(Liquid state at room temp.)

- Methanol supply chain outlook

Source: DNV
– Alternative Fuels Insight

- Alternative fuels shares outlook of shipyard output



	Shipyard Output Shares (Deliveries 2021-2050)			
	Oil Fuelled	LNG Fuelled	Zero-Carbon	Total
No.	20,103	43,142	34,454	97,699
m. GT	540	1,155	925	2,620
%	21%	44%	35%	100%

Source : Clarkson research

- Easy to handle(Liquid) → **technical constraints ↓↓↓**
- Liquid fuel → **High energy density** (among alt. fuel)
- Single carbon → No C-C bond → low PM, NOx
- In the long run, E-fuel are main fuel for marine engine
  → Methanol: representative fuel for e-Fuel
- Plans to build **green methanol production** bases are underway in the whole world: **guaranteed at least 730,000 tonnes/year by 2025**

Methanol as a fuel for CI engine

- **Properties of Methanol as a fuel for CI engine (Heavy-duty marine engine → needs high torque → CI better)**
  - **Different properties from conventional fuel:** density, **evaporation**, **viscosity**, **penetration, diffusion of vapors** etc…
  - **Low CN(Cetane number) – Main issue**
    - **High auto-ignition temperature**: low cetane number → strategy to improve ignition
    - High latent heat of vaporization → High octane number → Lower CN
  - Required more injection volume due to low LHV
    - oxygen-containing fuel (partially oxidized) → low LHV → required **more injection volume** → **need to change injection system**

	Euro-diesel	Methanol
Chemical formula	$C_{14}H_{28}$	CH_3OH
Auto ignition temperature(℃)	254	464
Lower heating value (MJ/kg)	42.74	20.27
Cetane number	56.5	4
Stoichiometric air/fuel ratio	14.7	6.66
Octane number	Not applicable	109
Heat of vaporization (MJ/kg)	0.27	1.11

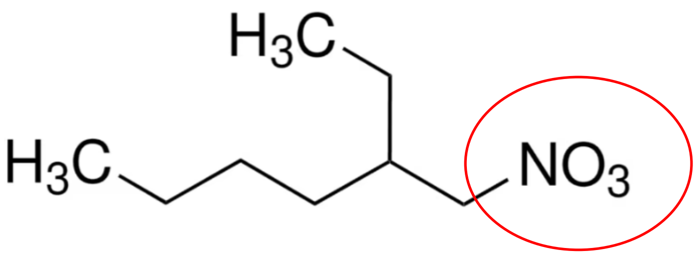
[Comparison of Diesel and Methanol properties]

- **Understanding how the characteristics different from the conventional fuel will differ in the process of combustion in IC engine**
- **Various strategies to compensate for the low cetane number**

Source: Ciniviz, M., et al. / Scientific Research and Essays, 6(15), (2011) 3189-3199.

Strategy for applying methanol to CI engine

- Method of methanol fuel supply and combustion in the CI engine
  – how to improve auto-ignition properties(Low CN – main issue of CI methanol engine)
  - Case 1. Dual fuel strategy: Methanol + pilot fuel(High CN igniter: Diesel, bio-diesel, DME…)
  - Case 2. Methanol – ignition enhancer(=cetane booster:**2-EHN**, Beraid 3555M etc…) blending
    - In this case, because only single fuel is supplied, the facilities can become simpler.



❖ **2-Ethylhexyl nitrate(2-EHN)**

- 2-EHN Formula: $C_8H_{17}NO_3$
- Combustion reaction: $C_8H_{17}NO_3 + 12.5\ O_2 \rightarrow 8\ CO_2 + 8.5\ H_2O + NO_2$
- The nitrate ester group (NO_3) which contains **oxygens** is easily decomposed during the combustion and releases oxygen, which helps the combustion of the fuel, which greatly improves the **auto-ignition performance**.

- **In this study, by experimental methods the effect of the cetane booster(2-EHN) on methanol fuel's auto ignition performance is evaluated.**

Contents

Objectives of the research

- The necessity for the research
  - Methanol is promising e-fuel for the HD field, especially marine engine
  - In the HD marine engine, higher torque is needed. So, even methanol is attempted to be burned by compression ignition strategy.
  - Especially, a substance called Cetane booster or Ignition Enhancer can be mixed with methanol to improve the auto-ignition performance.

- Objective of this research
  - Studying the basic mechanisms of combustion of methanol blened with 2-EHN, one of the ignition enhancer (Cetane booster) for actual engine application

- Methodology of this research
  - For the fundamental combustion research, (1) combustion visualization analysis and (2) combustion pressure analysis are appropriate
  - By using CVCC(Constant volume combustion chamber), accurate images and pressures data are obtained.
  - For comparing the spray characteristics, spray visualization experiment is conducted in CVCC firstly.
  - And then, methanol combustion experiment is conducted in CVCC.

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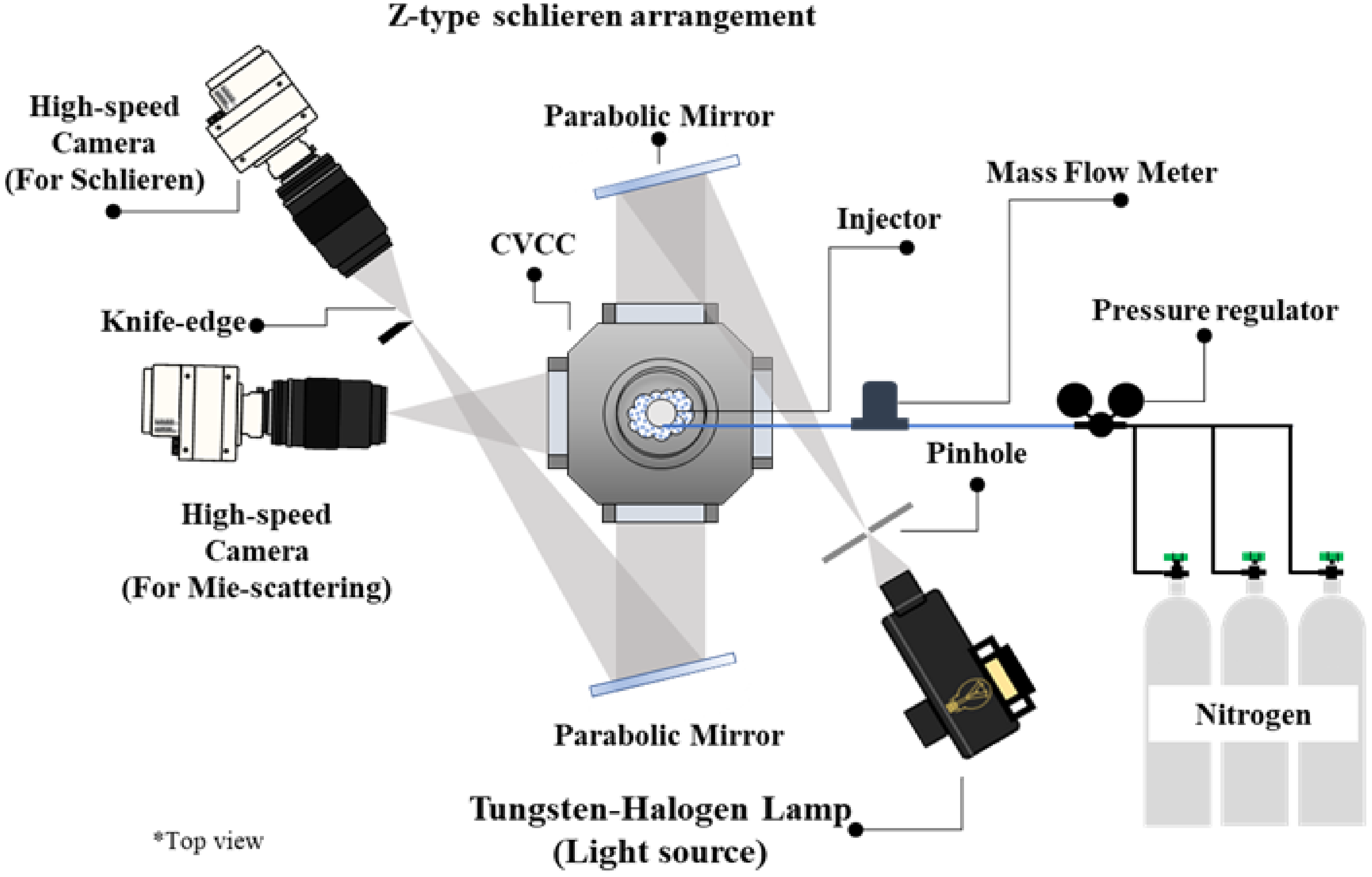
Methodology – Apparatus

- Spray visualization experiment setup



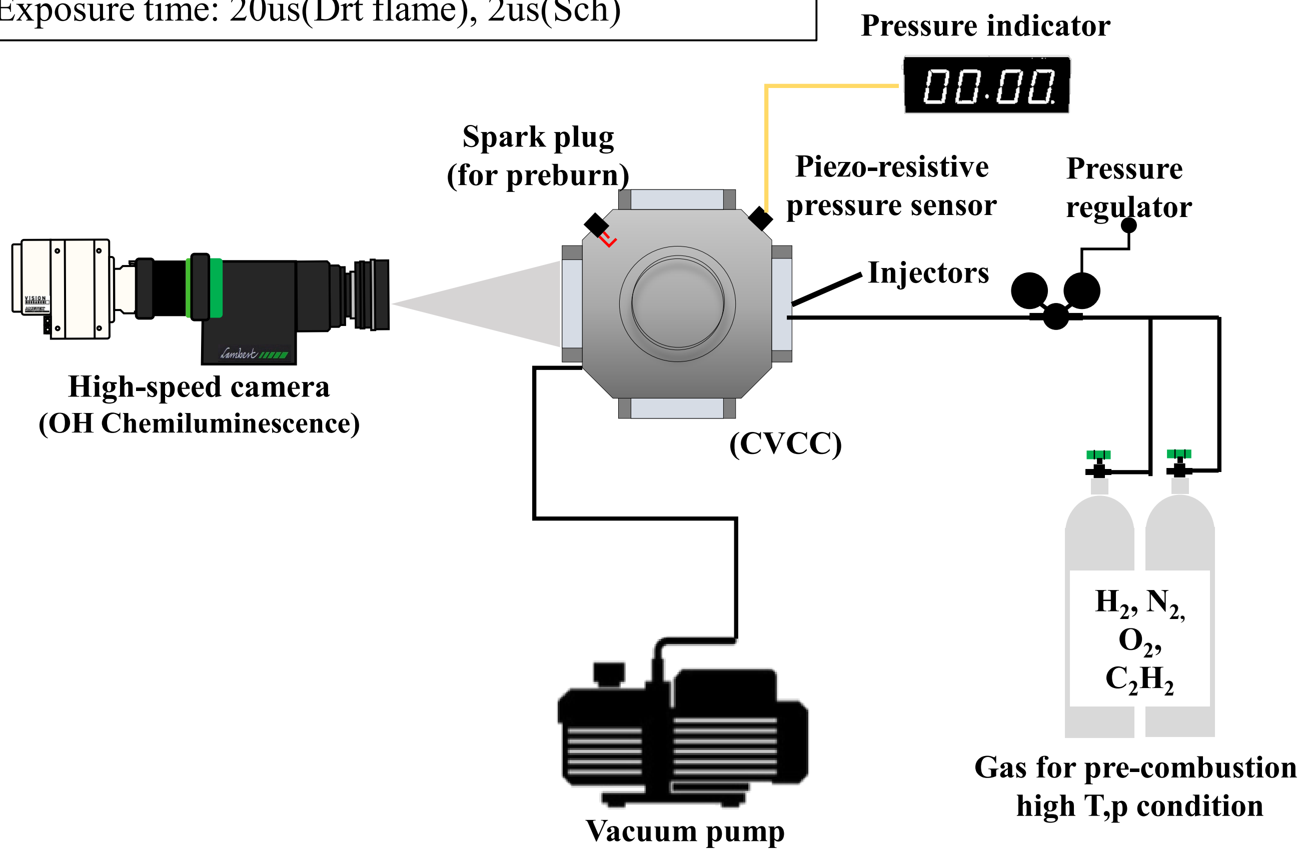
Parameter	Value
Inj. pressure	500bar
Inj. duration	700 μs
Injector type	Diesel injector (single hole modification)
Ambient gas	N_2 N_2+H_2O+CO_2 (pre-burn)
Ambient condition	Case1: 500K, 10bar Case2: 1000K, 50bar (pre-burn)
Fuel type	Diesel, **Methanol**
Mie-scattering	Liquid phase
Schlieren	Gas+Liquid phase

Methodology – Apparatus

- Apparatus for flame visualization

Camera setting
Frame rate: 52,000fps(OH-Chemiluminescence)
Exposure time: 20us(Drt flame), 2us(Sch)

*Top view



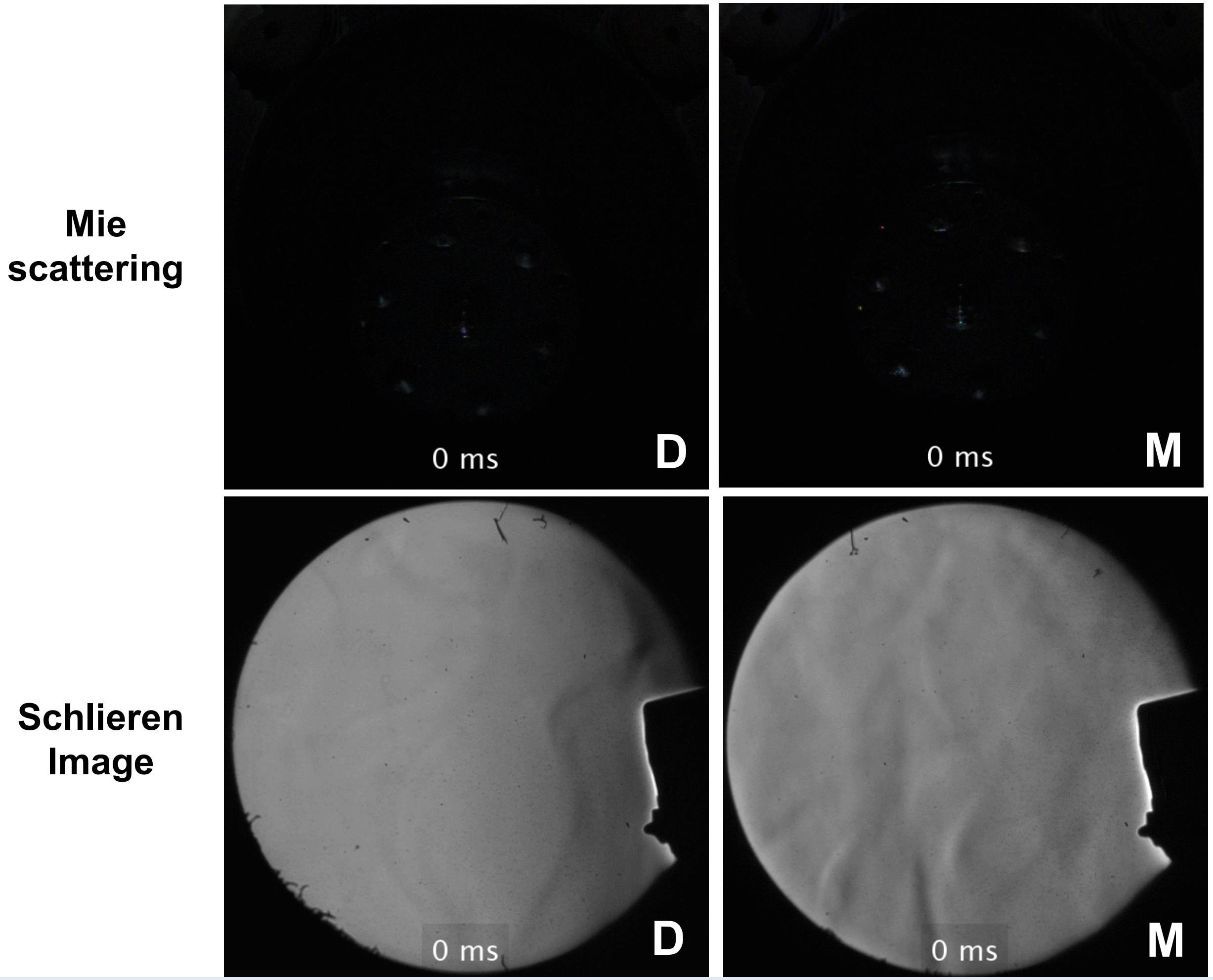
CVCC Specification		
Item	**Unit**	**Value**
Volume	cc	1400
Fuel supply	-	Common-rail DI
Methanol injection pressure	bar	500
Methanol injection duration	us	2500

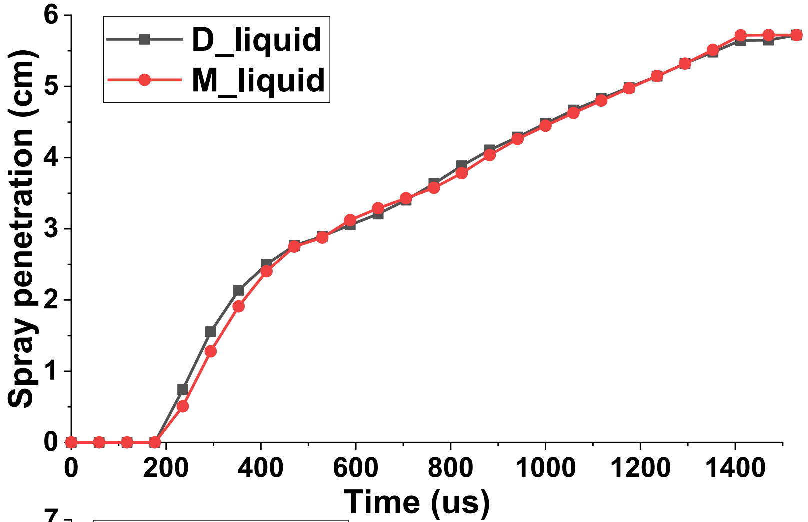
Experiment condition		
Parameters	**Unit**	**Range**
Ambient composition	Air (after preburn)	
Ambient temperature	**K**	**1000 ~ 1200**
Cetane booster (CB; 2-EHN) volume fraction	**%**	**3,5,7,10**

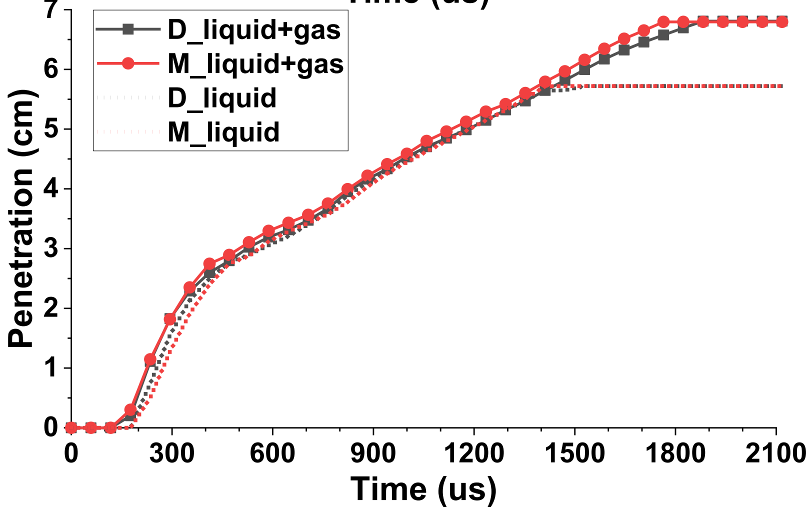
Contents

Spray experiment: Diesel vs Methanol

- Spray comparison under low ambient Temp. & pressure (500K, 10bar)



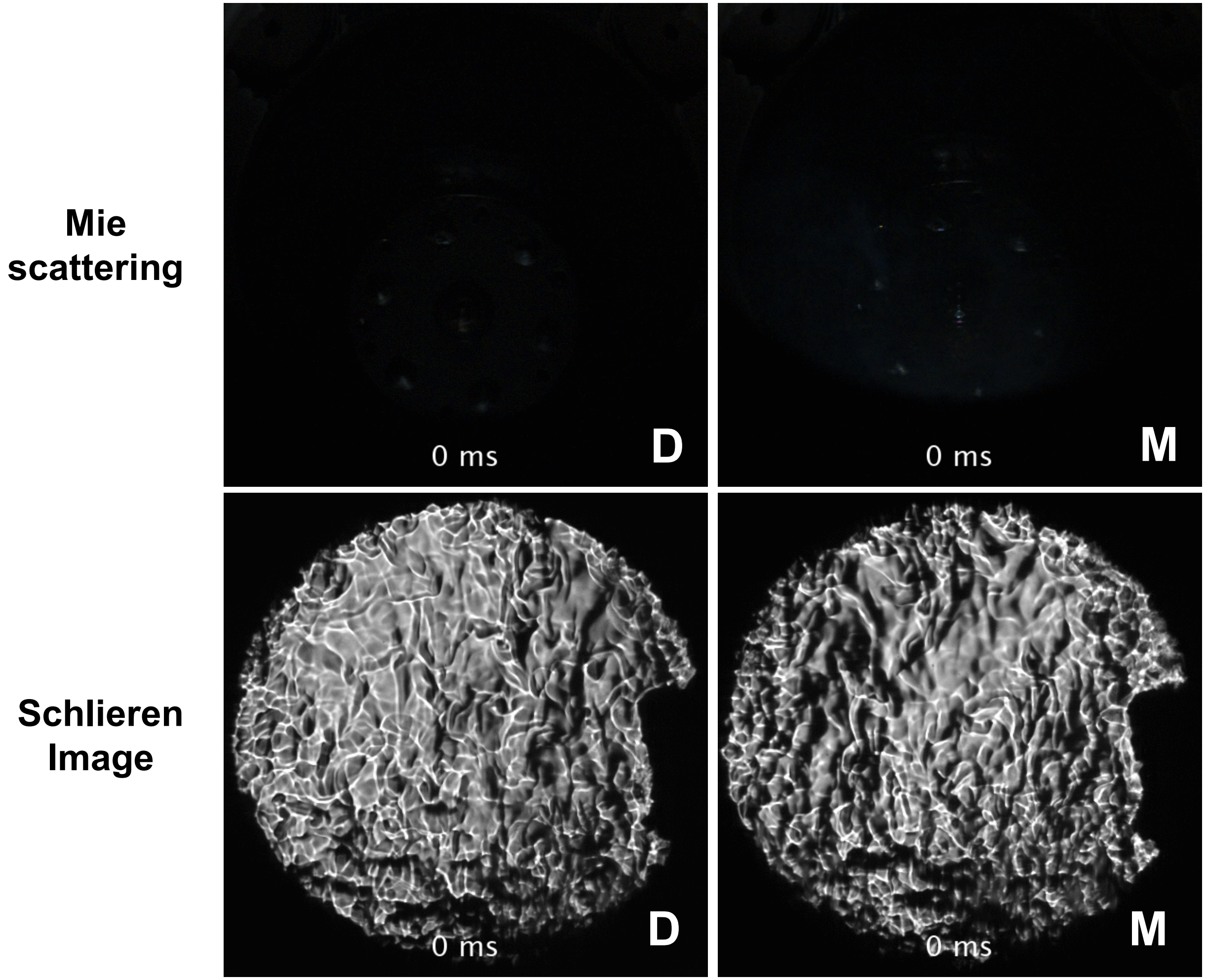


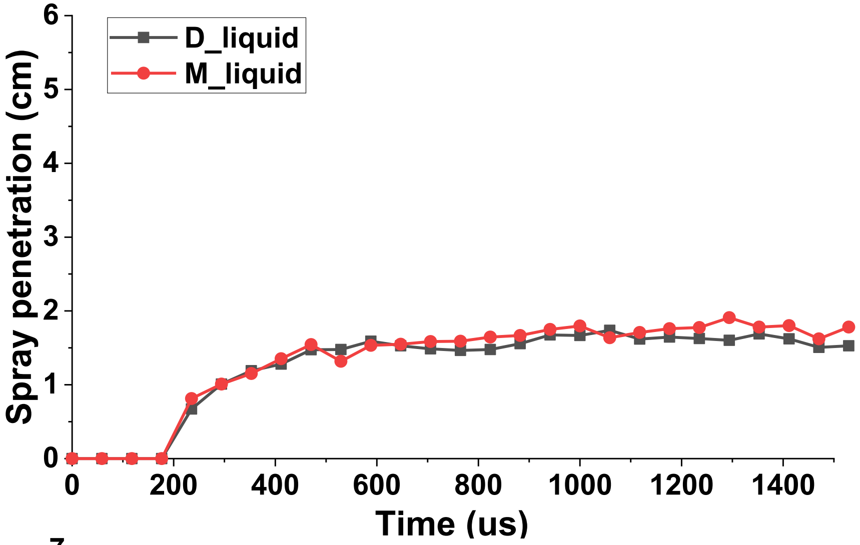


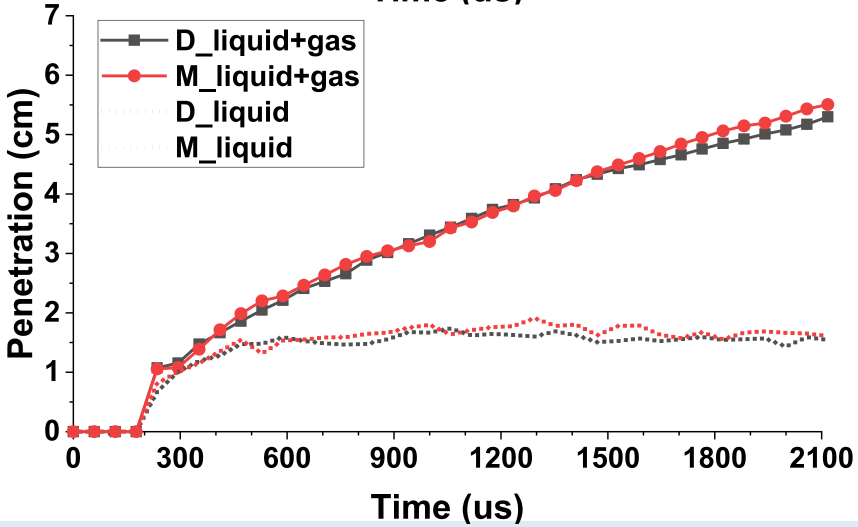
- **Methanol has almost same spray pattern with diesel**
- Under this low ambient Temp. & pressure condition, both diesel and methanol is hardly vaporized.

Spray experiment: Diesel vs Methanol

- Spray comparison under high ambient Temp. & pressure (1000K, 50bar)





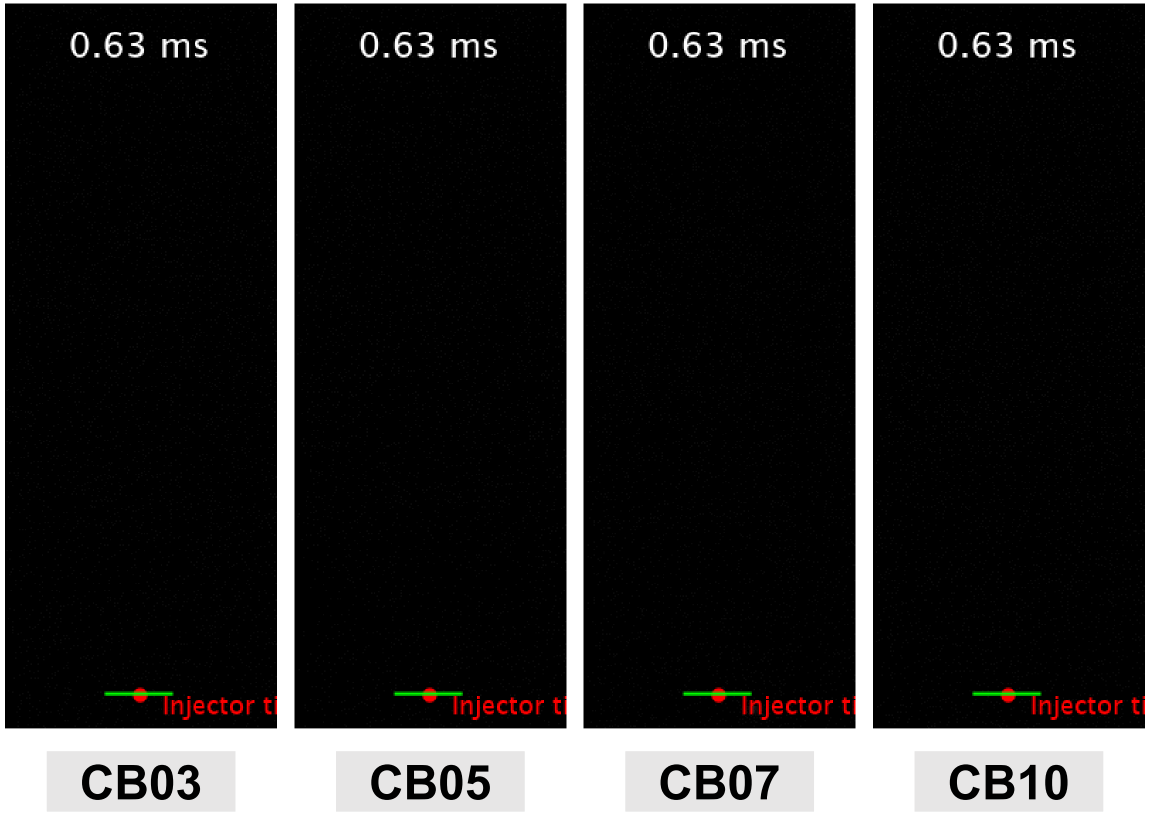


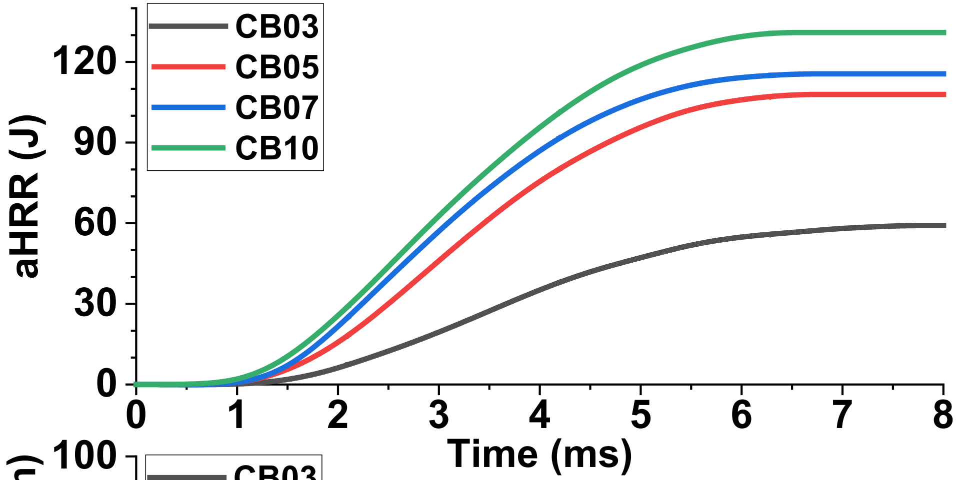
- **Methanol has almost same spray pattern with diesel in high ambient Temp. & pressure condition also.**
- Under high ambient Temp. & pressure condition, both diesel and methanol is vaporized similarly.

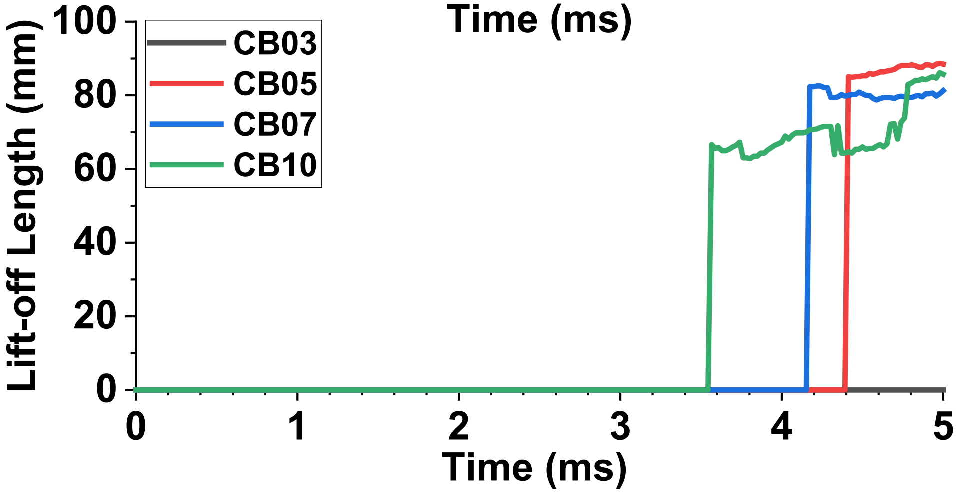
Contents

Combustion experiment: The auto-ignition of methanol blended with cetane booster

- Low Temp. Condition: 1000K, 25bar



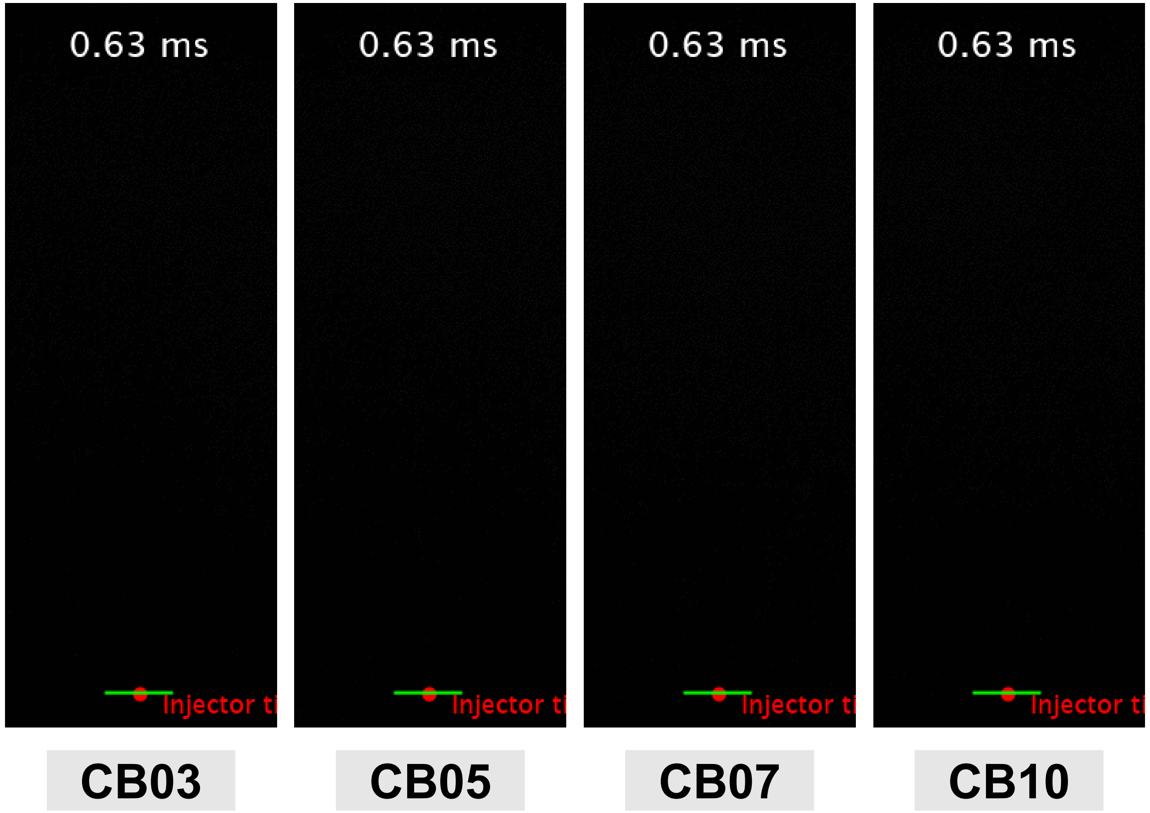


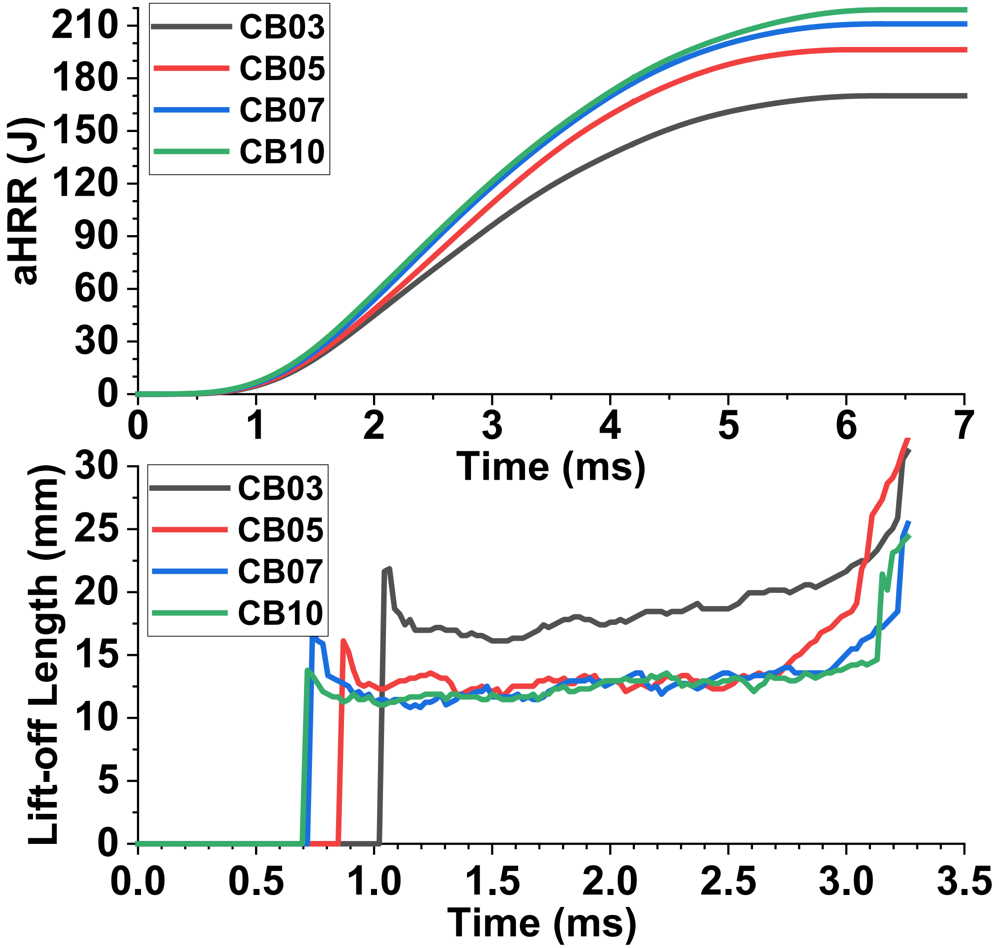


- **As fraction of CB(cetane booster) increases, aHRR(accumulated heat release rate) is increased**
- **Especially, in case of CB 03%, the methanol fuel was hardly burned. (OH chemiluminescence not detected)**
- **As CB increases, lift-off length(injector tip to flame distance) is decreased.**
- **As CB increases, ignition delay(measured by images and aHRR data both) is shortened.**

Combustion experiment: The auto-ignition of methanol blended with cetane booster

- High Temp. Condition: 1200K, 45bar

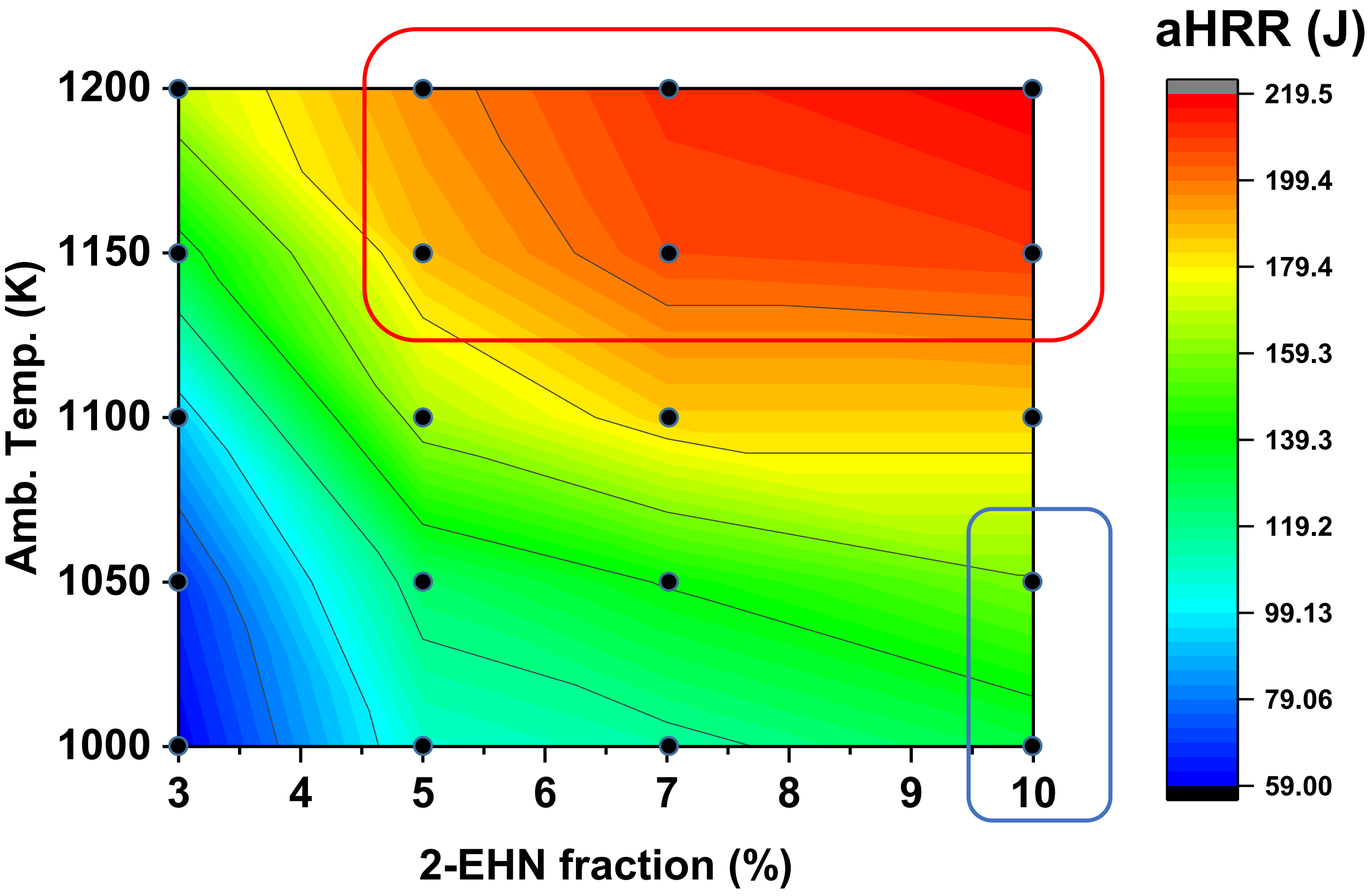




- **As fraction of CB(cetane booster) increases, aHRR(accumulated heat release rate) is increased.**
- **In 1200K ambient condition, all CB case except 3% is burned similarly and the lift off length is also similar. (saturated)**
- **As CB increases, ignition delay(measured by images and aHRR data both) is shortened.**

Combustion experiment: The auto-ignition of methanol blended with cetane booster

- Accumulated heat release rate(aHRR) contour map depending on ambient condition & 2-EHN fraction(cetane booster, CB)



- Accumulated heat release rate(aHRR) can be an **indicator of how much fuel is burned**.
- The effect of **ambient temperature** is more **dominant** than the cetane booster(CB) fraction
- Under conditions of **ambient temperature less than 1100K**, even if the fraction of CB is 10%, the fuel still **does not burn well**.
- At **ambient temperature** above 1150K and the CB fraction more than 5%, the aHRR is **similarly saturated.** (maximum combustion eff. estimated) cf) Amb. T.=1200K, CB=10%: aHRR/LHV_{fuel} = 85%

Contents

Conclusion

- **Objective**
  - Studying the basic mechanisms of combustion of methanol blened with 2-EHN, one of the ignition enhancer (Cetane booster) for actual engine application
- **Conclusion**
  - **The following results are derived by measuring the combustion image and pressure**
    - As fraction of **CB(cetane booster) increases**, **aHRR(accumulated heat release rate) is increased**
    - As CB increases, ignition delay is shortened and lift-off length(injector tip to flame distance) is decreased.
    - The effect of **ambient temperature** is more **dominant** than the cetane booster(CB) fraction
    - At **ambient temperature** above 1150K and the CB fraction more than 5%, the aHRR is similarly saturated.
- **Applying the results to combustion in engine**
  - Based on CVCC experiment result, because more than 1150K ambient temperature is needed for stable combustion of methanol even in case of 10% of CB fraction, higher compression ratio CI engine is worth considering.
- Future works
  - **Multi-stage injection** to burn more fuel: Some reported that combustion efficiency can be increased.
    : If **pilot fuel is injected before main fuel** injection, 2-EHN is spread over a wider and then initial combustion can become intensified.
  - Engine experiment: In CI engine, real performance and emission could be measured with fuel for methanol with 2-EHN

Thank you for your kind attention.

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