Xue-Song Bai
University of Lund
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World Maritime University
Ossi Kaario
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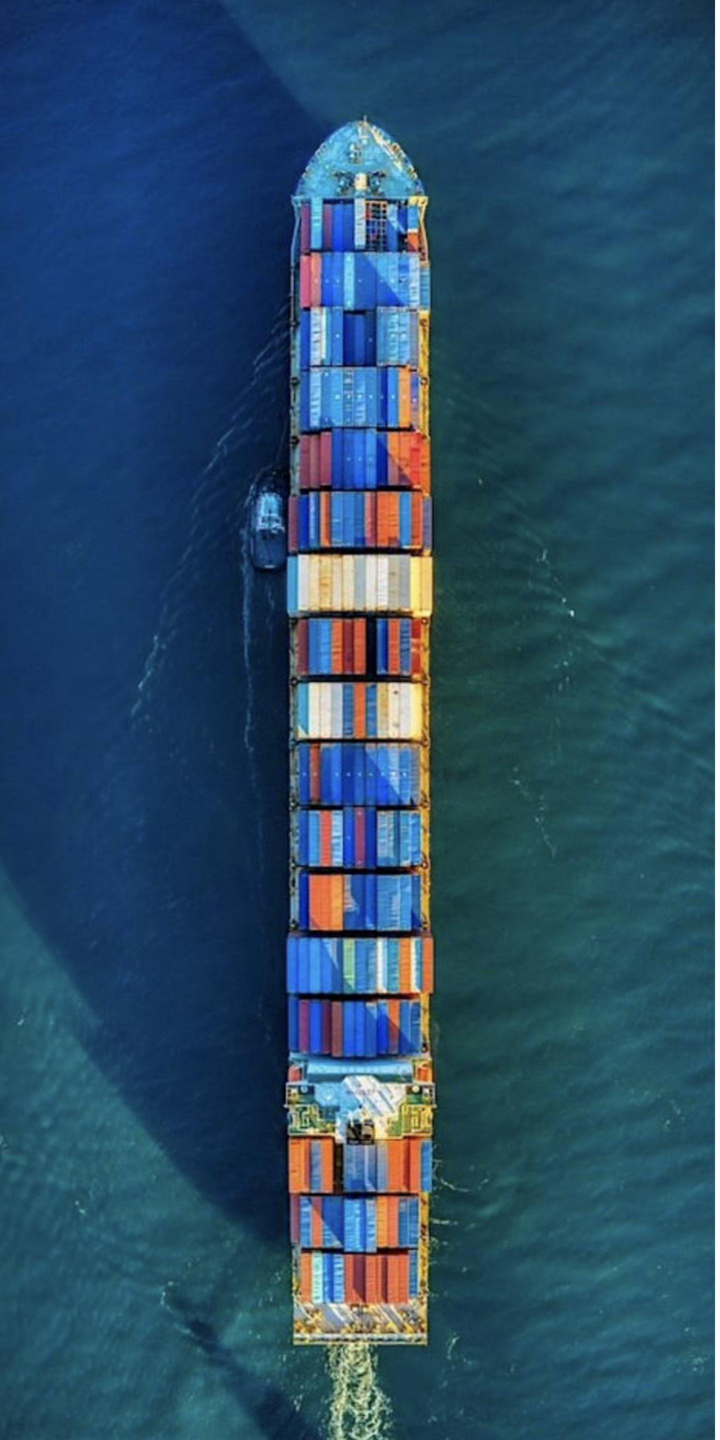
Terese Løvås
Norwegian University of Science and Technology

Nordic Energy Research

From the CAHEMA Project



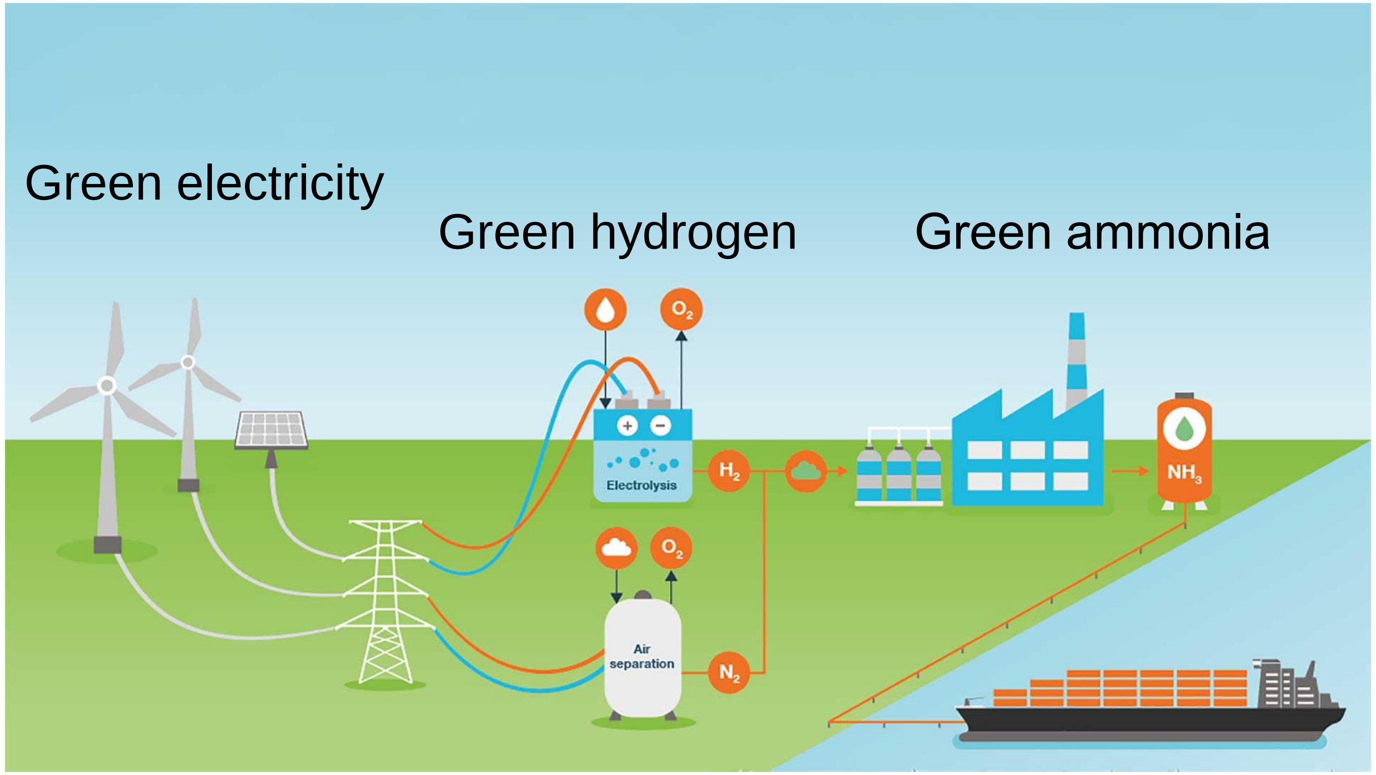
Towards the use of ammonia in marine engines

Xue-Song Bai, Ossi Kaario, Alessandro Schönborn, Tuan Dong, Michal Lewandowski, Terese Lovas

CAHEMA Project Consortium

The Nordic Maritime Transport and Energy Research Programme Conference
May 3-4, 2023, WMU, Malmö

Concepts of Ammonia/Hydrogen Engines for Marine Application



Green marine transport

Can we use green ammonia and hydrogen in current marine engines?

- Answer: No!

New marine engine technologies need to be developed

- Fundamental understanding
- New engine concepts

CAHEMA addresses

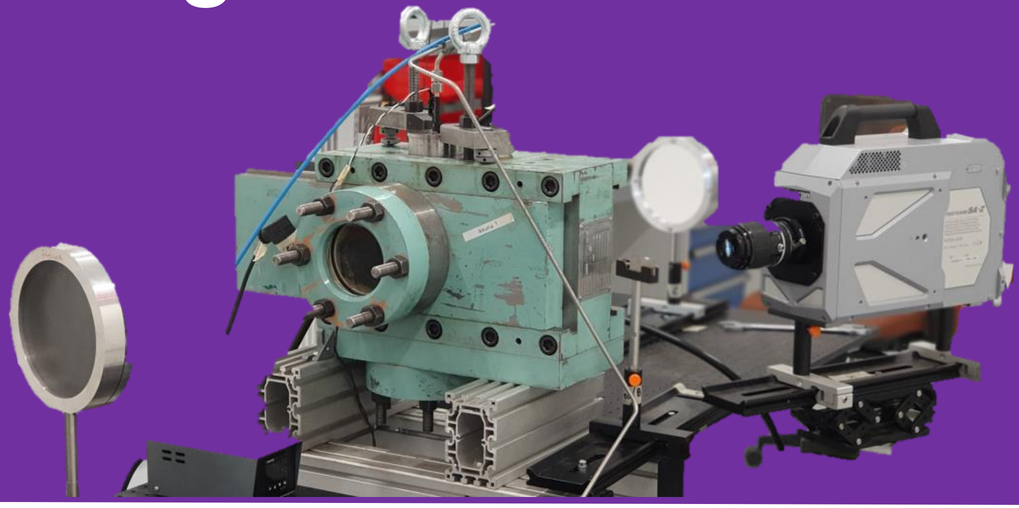
- Chemical kinetics of ammonia ignition and emission
- Physics of ammonia spray/air mixing and combustion
- New engine concepts
- Social and economical aspects

Aalto University
School of Engineering

Energy Conversion Research Group

Aalto University
School of Engineering

Experimental Studies on Ammonia and Hydrogen Injection and Mixing



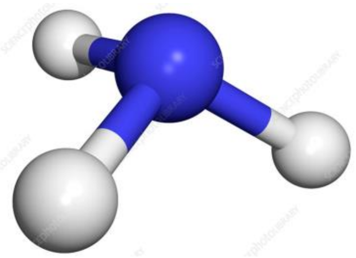
CAHEMA 2023

Ossi Kaario, Saad Akram, Cheng Qiang, Martti Larmi
Aalto University, Finland

04.05.2023

Cheng, Kaario et al., Dynamics of the Ammonia Spray Using High-Speed Schlieren Imaging, SAE paper 2022-01-0053, 2022.
Akram, Kaario et al., Experimental Study on Flash Boiling of Ammonia Fuel Sprays – A Potential Alternative Fuel, SAE paper 2023-01-0304, 2023.

NH3 Properties



- No carbon
- Gas in ambient conditions
- Liquid in 10 bar
- Corrosive
- Toxic

Ammonia toxicity

Ammonia concentration [ppm]	Effects on humans
5-10	Detectable by smell
50	Feeling of discomfort
100	Irritation
200 - 300	Irritation to eyes and throat
300 - 500	Not fatal, but bearable for short time
2500 - 5000	Life threating in 30 minutes
5000 - 10000	Fatal in short time

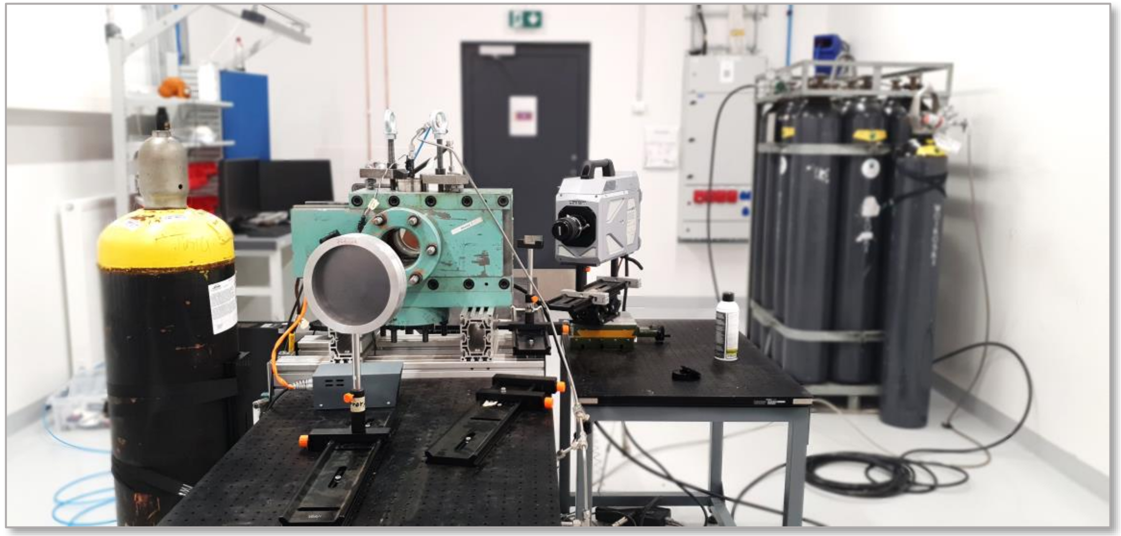
		Ammonia		Diesel
Low flame speed (ambient conditions, $\phi = 1$)		7	cm/s	(50 cm/s)
Stoichiometric air-fuel ratio		6.1	kg Air/ kg Fuel	(14.5)
Requires high ignition energy		8	mJ	(1.15 mJ)
High latent heat	(293 K)	1185	kJ/kg	(292 kJ/kg)
High vapor pressure	(323 K)	20	bar	(0.004 bar)
Low viscosity	(323K)	1.5e-3	kg/ms	(1e-4 kg/ms)
Heating value		18.6	kJ/kg	(44 kJ/kg)

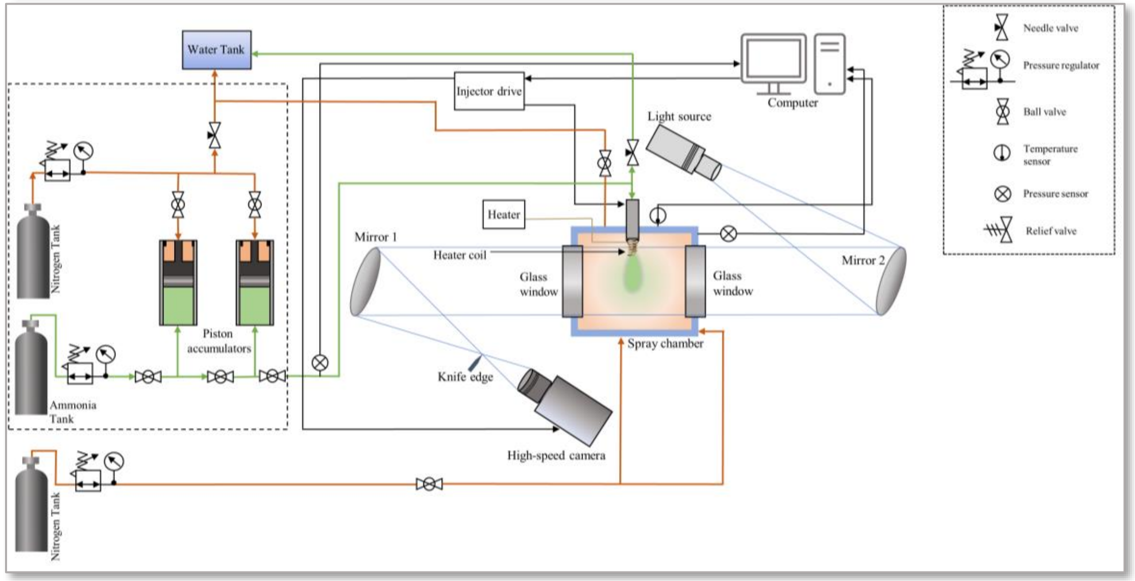
Safety for NH3 experiments

- Personal Protective Equipment (PPE)
    - Safety shoes
    - Safety googles
    - Respiratory mask
    - Handheld ammonia detector
- Ventilation
    - Independent fume hood or separate ventilation for the room
- Emergency equipment
    - Eye wash station
    - Stand alone leak detector
- Dedicated safe storage
    - Should be kept in cool, dry and ventilated area
    - Should be kept away from heat, flames and other ignition sources
- Safe handling and transport
- Training
- Testing in controlled environment

Note: Official approval is also required for ammonia use

Experimental setup





Safety gear for ammonia handling

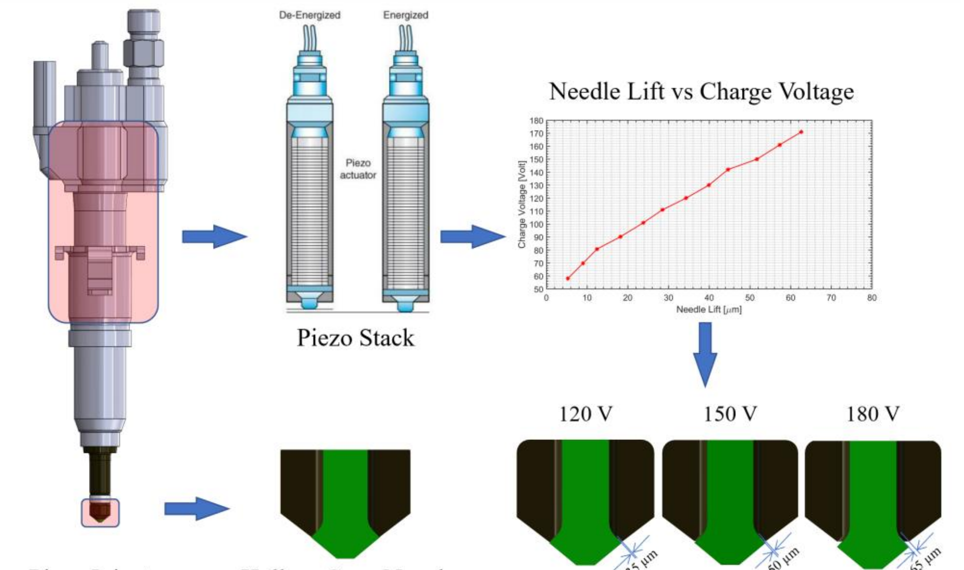
Experimental test setup

- Constant volume spray chamber
  - Glass windows for optical access
  - Ports for fuel injection, chamber pressurizing, heating and temperature & pressure monitoring
- Nitrogen and ammonia bottles
- Fuel injection system
  - Piston accumulators
- Fuel heating system
  - Heater coil attached with temperature controller
- LabVIEW for P and T monitoring
- Z-type schlieren imaging system

Fuel injectors

Gasoline injector - Bosch
- 6 holes / 1 hole
- Orifice dia. = 0.2mm
- Solenoid driven

Hollow-cone piezo injector
- Max Orifice opening. = 0.065mm
- Piezo driven



Experimental conditions

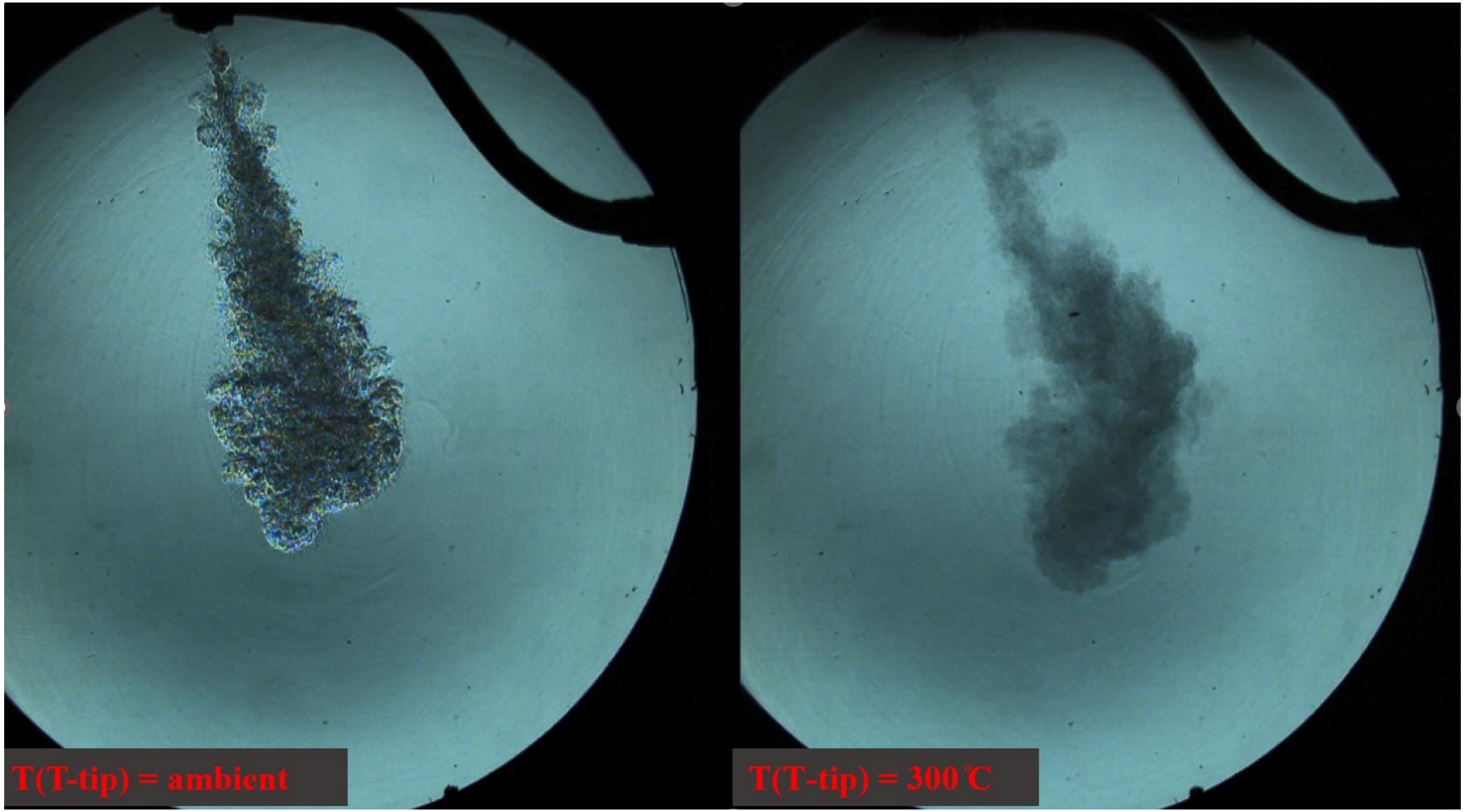
Aim: Investigating flash boiling fuel sprays	
Fuels	Ammonia, Gasoline
Nozzle configuration	Two nozzle types / Multi-hole and single-hole
Injection pressure (bar)	150
Chamber pressure (bar)	5, 10, 20, 30
Injector tip Temperature (Deg. C)	Ambient, 100, 200, 250, & 300
Injection duration	3ms
Imaging mode	High-speed (45000fps)
Imaging method	High speed schlieren imaging
Spray parameters to be analyzed	Spray tip penetration and spray area

Cheng, Kaario et al., Dynamics of the Ammonia Spray Using High-Speed Schlieren Imaging, SAE paper 2022-01-0053, 2022.

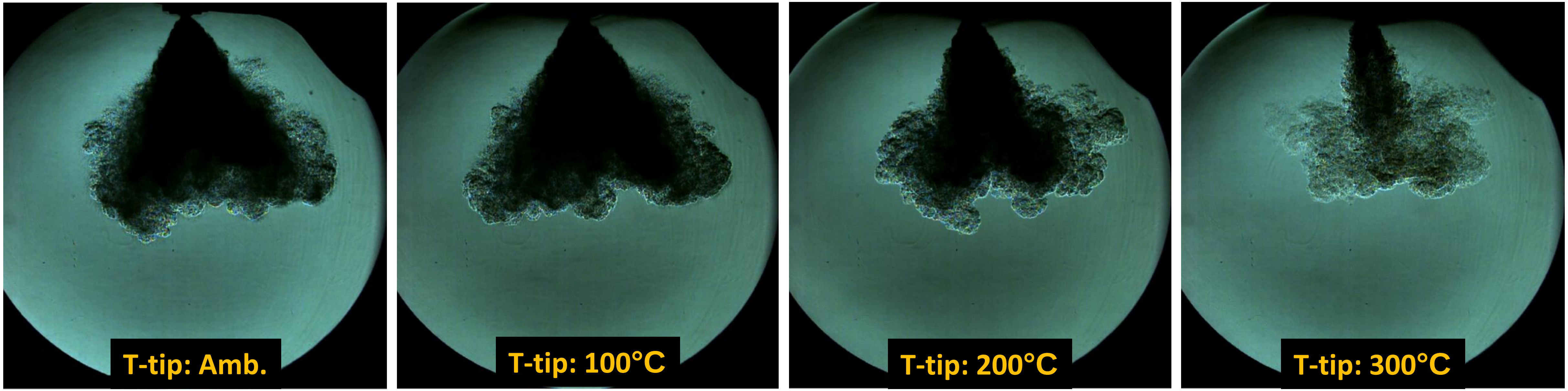
Akram, Kaario et al., Experimental Study on Flash Boiling of Ammonia Fuel Sprays – A Potential Alternative Fuel, SAE paper 2023-01-0304, 2023.

Results (single-hole nozzle)

- Ammonia
- Inj. Press.: 150bar
- Ch. Press.: 30bar
- Inj. Dur.: 3ms
- T(T-tip): ambient Vs 300℃



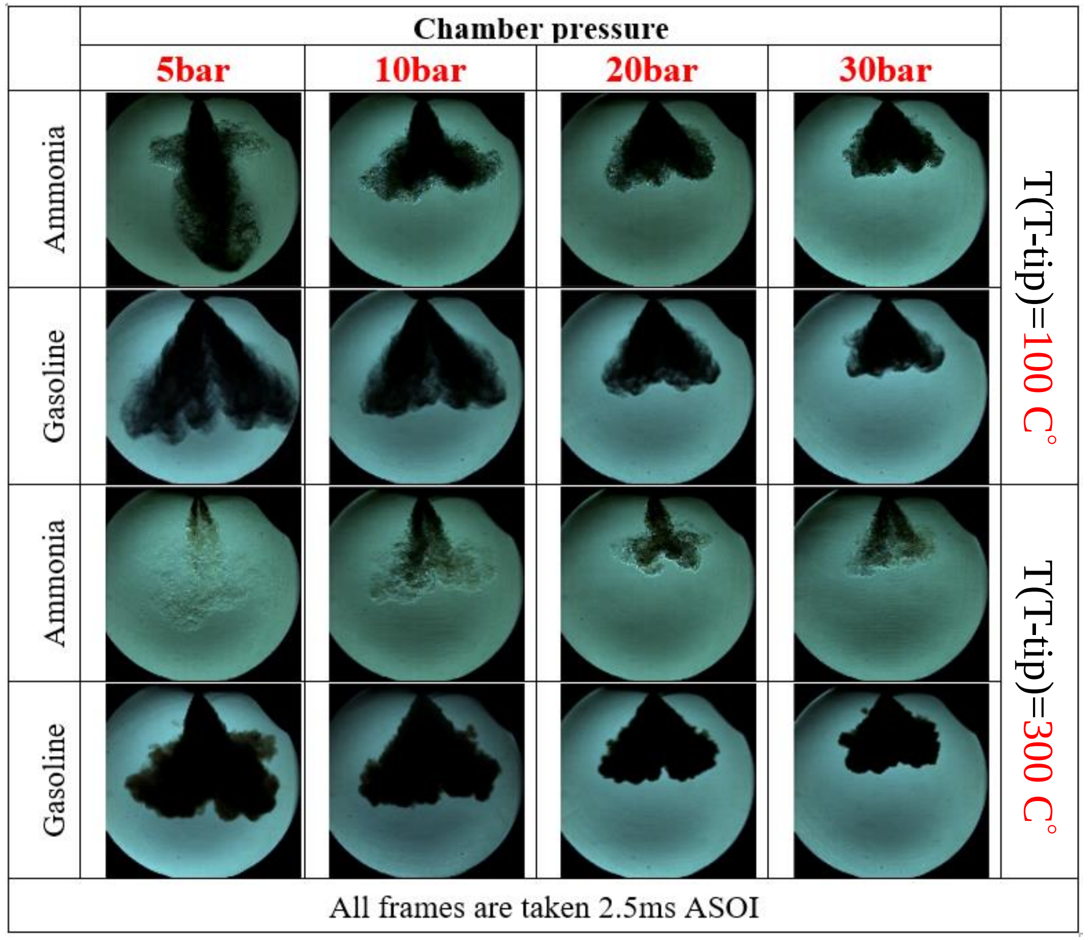
Visual observations (Hollow-cone injector)



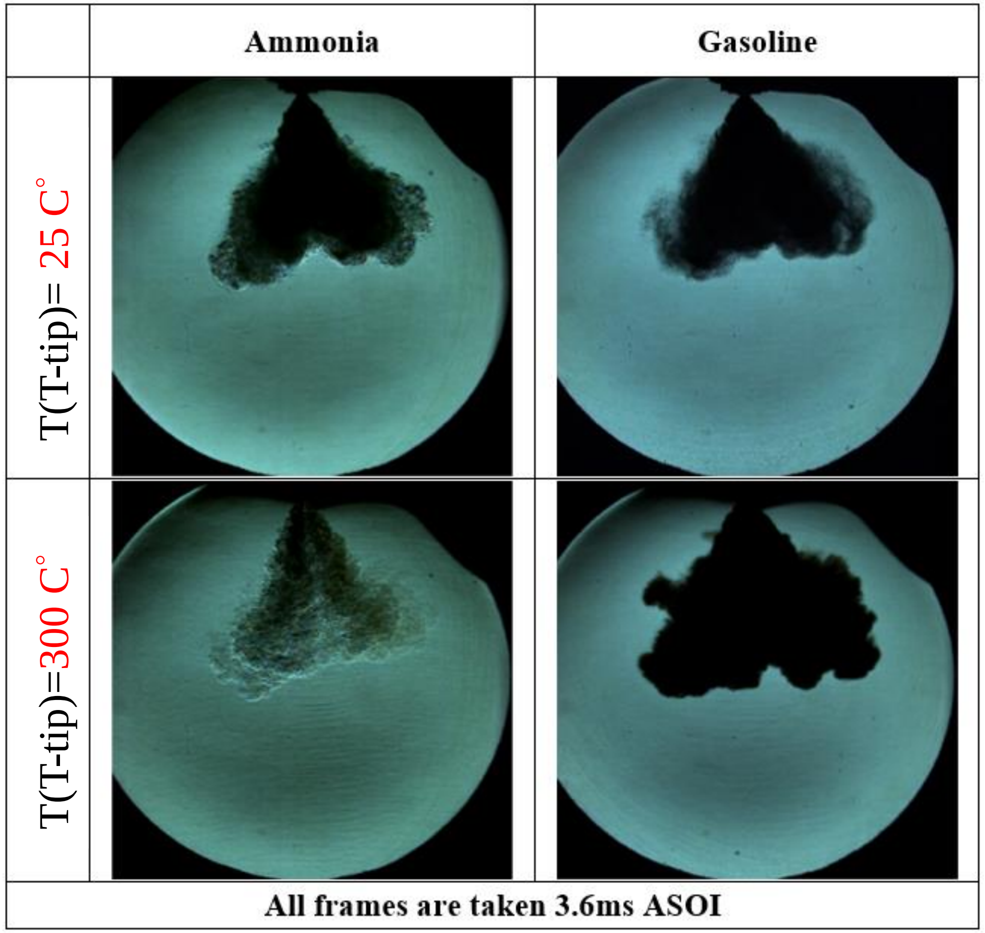
Ammonia, Ch.Press.20bar, Inj.Press.150bar

Comparing ammonia sprays by varying injector tip temperature

Visual observations (Hollow-cone injector)



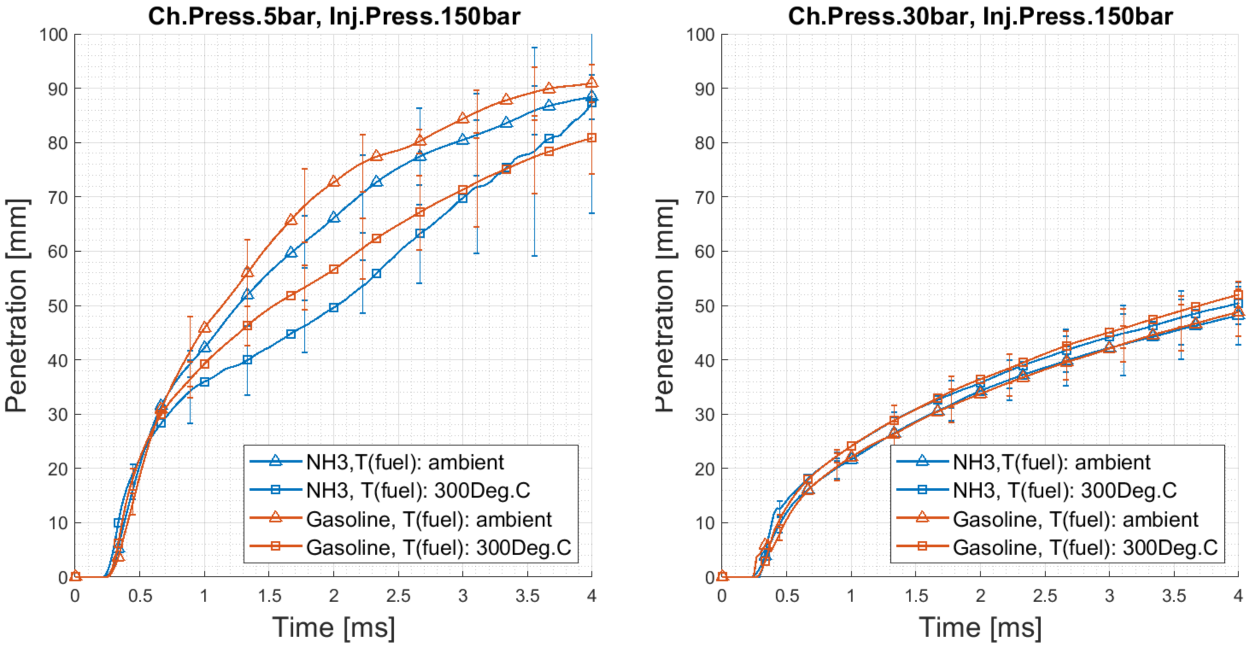
Comparison of ammonia and gasoline sprays in terms of fuel temperature and chamber pressure effect at 150 bar Inj. Press. Time: 2.5ms ASOI



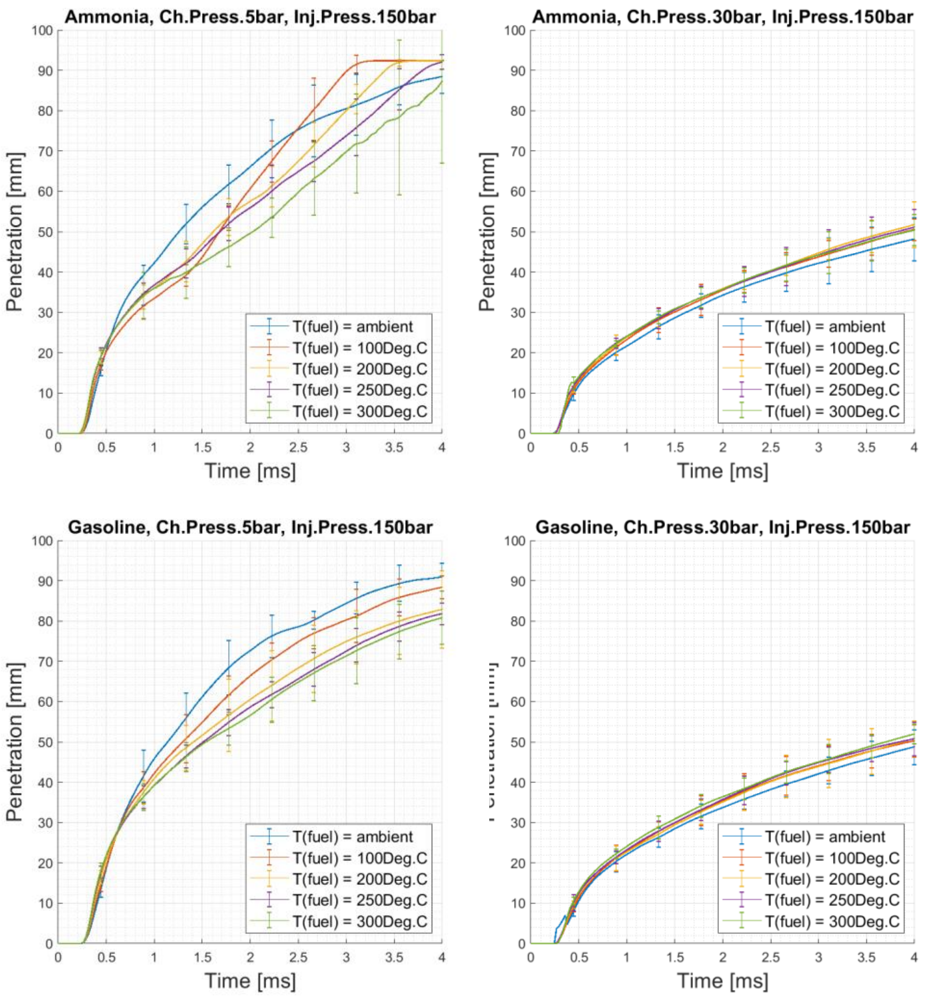
Comparison of ambient fuel temperature and super heating condition for ammonia and gasoline at 150bar Inj. Press. and 30bar Ch. Press. Time: 3.6ms ASOI

Results (multi-hole nozzle)

Spray tip penetration

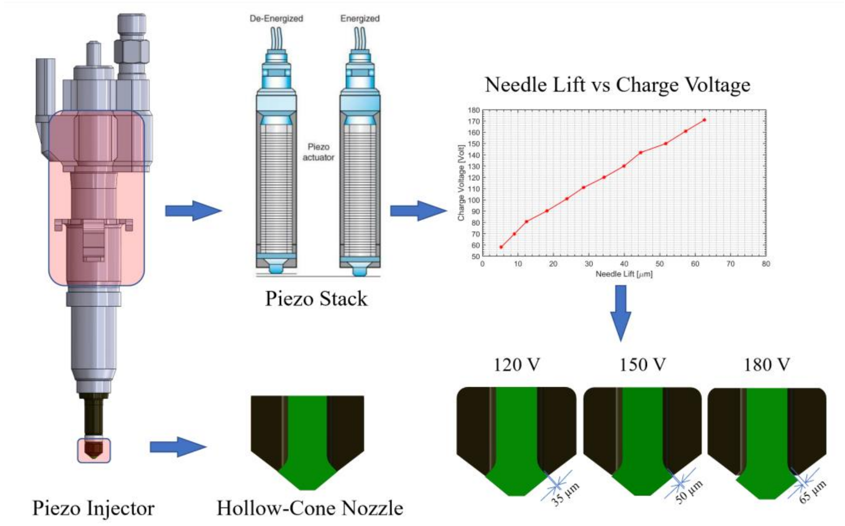


Spray tip penetration comparison of ammonia and gasoline at 150bar Inj. Press. for ambient and 300℃ fuel temperatures and at a) Ch. Press. 5bar, b) Ch. Press. 30bar

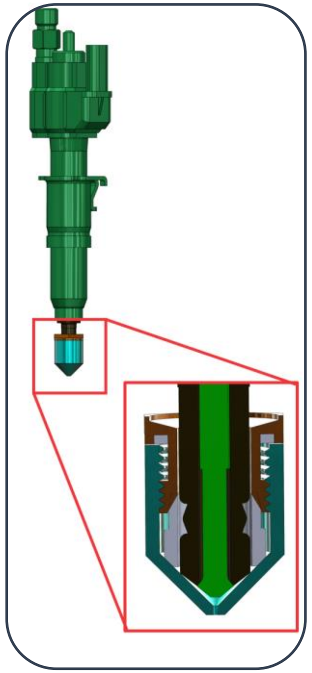


Spray tip penetration in terms of chamber pressure and fuel temperature at 150bar injection pressure for ammonia and gasoline. a) Ammonia, Ch. Press. 5bar b) Ammonia, Ch. Press. 30bar c) Gasoline, Ch. Press. 5bar d) Gasoline, Ch. Press. 30bar

Hydrogen Jets Using High-speed Schlieren Imaging

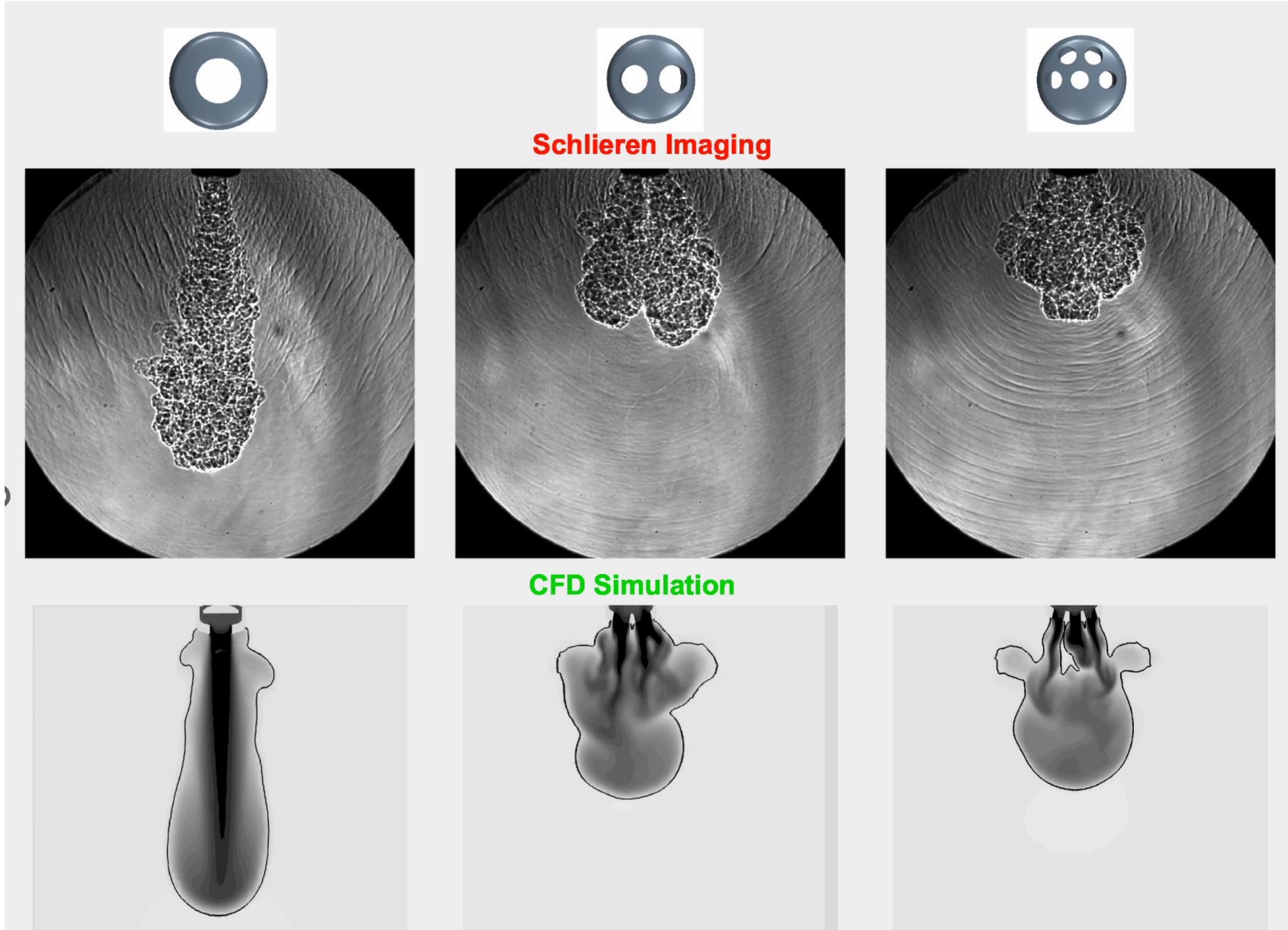


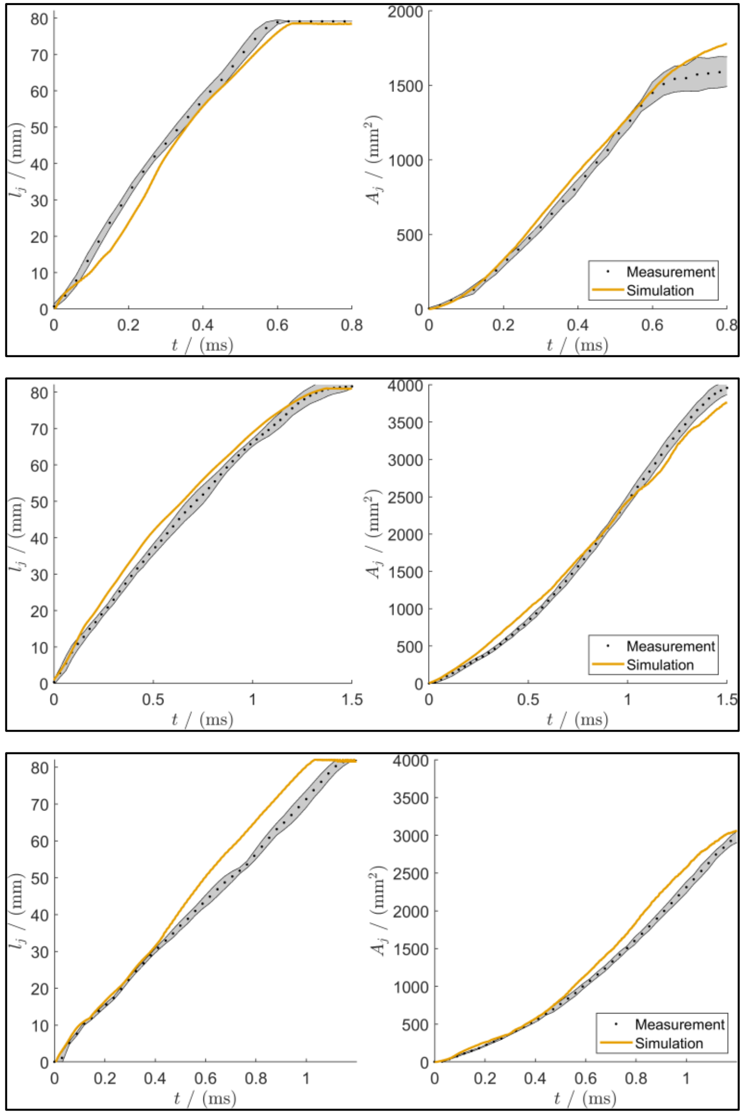
Hollow-cone piezo injector + nozzle cap
→ Single hole nozzle



Modified Single-Hole Injector

H_2 Jets with Different Injector Caps





Conclusions

- **Ammonia and H_2 are a very different type of fuels compared to many other fuels !**
- **No carbon but …**
- **NH_3: Toxic and corrosive**
- **NH_3: Evaporates very easily, very low flame speed, high ignition energy**
- **H_2: Low ignition energy, high flame speed, high diffusion rate**

- **The use of ammonia and H_2 in engines has open questions while our present work contributed to the fundamental understanding of their use**

Norwegian University of Science and Technology

Chemical kinetic modeling of ignition and emissions

Michał T. Lewandowski, C. Netzer, K.A. Pedersen, K.O. Bjørgen, T. Løvås
Department of Energy and Process Engineering

State-of-the-art of the ammonia/Hydrogen/n-heptane combustion mechanism

Ammonia mechanisms

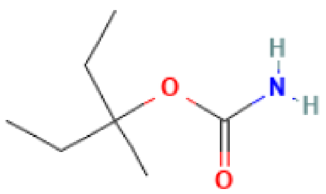
Reference	N_s	N_R	IDT	Available
Lindstedt et al. (1994)	21	95	N/A	NO
Nakamura et al. (2017)	33	232	N/A	NO
Shrestha et al. (2018)	125	1090	Good	YES
Stagni et al. (2019)	31	203	Slightly shorter	YES
Bertolino et al. (2020)	24	210	Short	YES
Glarborg et al. (2018)	151	1397	Short	YES
Mathieu et al (2014)	35	159	Good	NO
Klippenstein et al. (2010)	21	64	Short	NO
Mevel et al. (2009)	32	203	Long	Yes

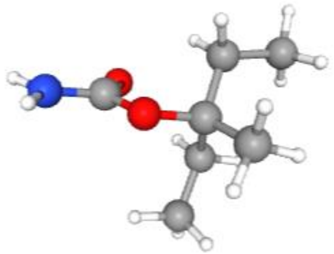
Ammonia/heptane blend mechanisms

Reference	N_s	N_R	Available
CRECK GROUP (1994) C1-C16 HT+Soot mechanism	452	24041	YES
Yu et al. (2020)	1376	6499	YES

Development of reduced chemical kinetic mechanisms

- Lumping – example of a single step
- Lumping – all steps combined
- Performance assessment in homogeneous reactor
  - Constant Volume Reactor CVR (ignition delay times)
  - Perfectly Stirred Reactor (species profiles)
- Performance assessment in engine like conditions
  - Stochastic Reactor Model (SRM)





Lumping:

Example of a single step

Emylcamate $C_7H_{15}NO_2$-1, $C_7H_{15}NO_2$-2, $C_7H_{15}NO_2$-3, $C_7H_{15}NO_2$-4

1. Check criteria for isomer lumping

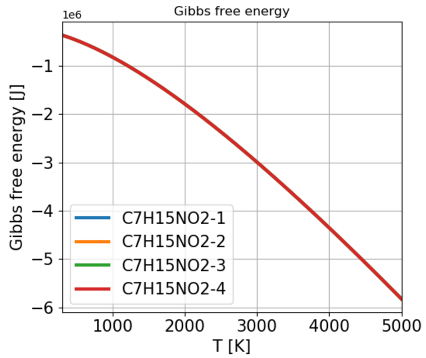
   Free Gibbs energies difference < 1 kJ

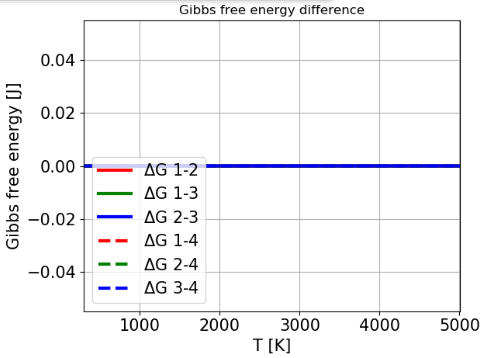
$$G_k^0 = \left[\frac{H_k^0}{RT} - \frac{S_k^0}{R}\right] RT$$

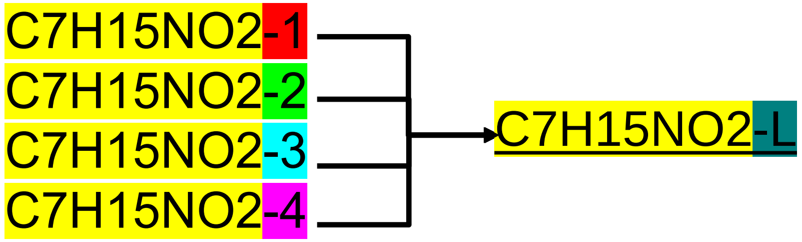
2. Calculate new rate coefficient

$$k_k^* = k_k \prod_{j=1}^{N_L} \left(\frac{1}{N_L}\right)^{\upsilon'_{j,k}}$$

C7H15NO2-X







Lumping:

All steps combined

- 128 lumping steps performed
- 269 species reduced

Mechanism version	No. species	No. reactions
Full	1 369	6 314 (11 542)
Lumped	1 100	6 313 (11 540)

- Performance assesseed for pure n-heptane, ammonia and 4 blends

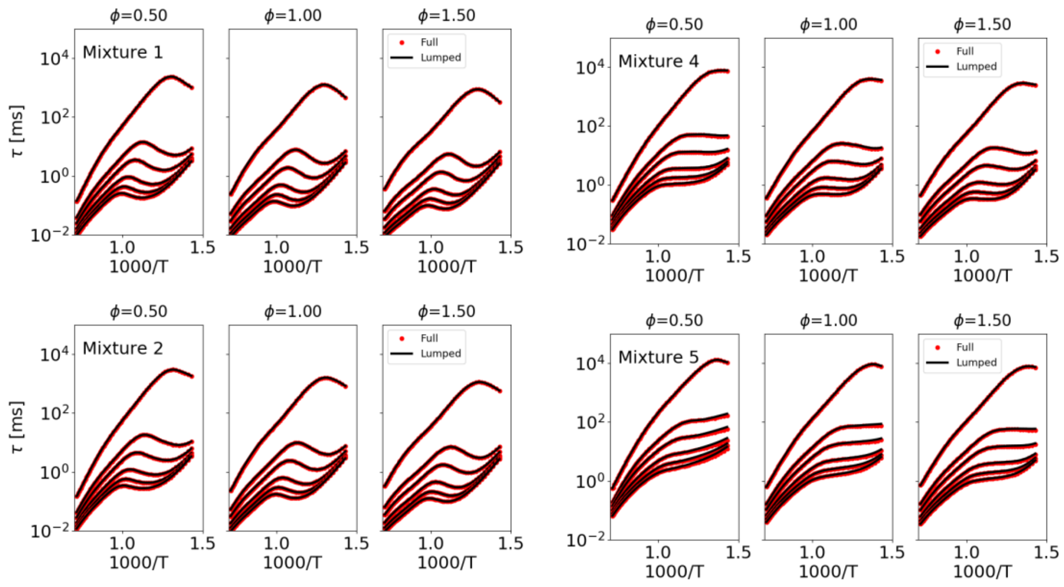
Mixture no	1	2	3	4	5	6
N-C7H16 [% mass]	100	80	60	40	20	0
NH3 [% mass]	0	20	40	60	80	100
AES [%]	0	9	22	39	63	100

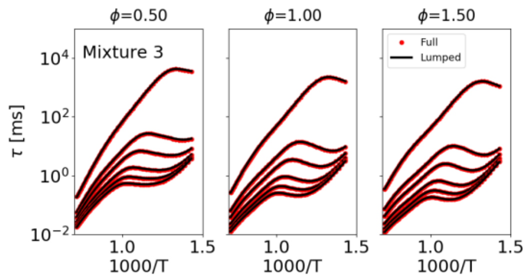
Performance assessment

CVR (ignition delay times)

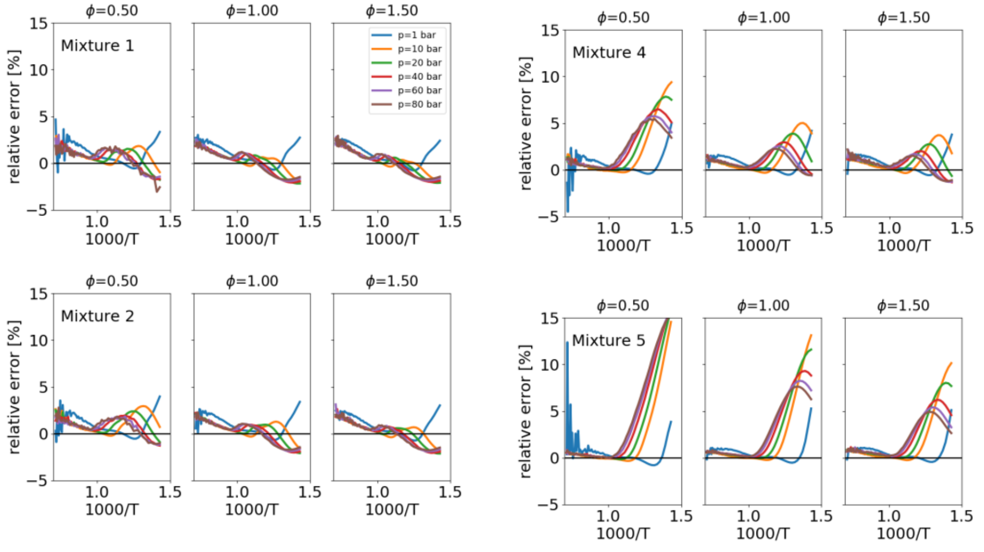
Parameter	values
Pressure [bar]	1, 10, 20, 40, 60, 80
Equivalence ratio [-]	0.5, 1.0, 1.5
Temperature [K]	700 - 1400 ($\Delta T = 10$)

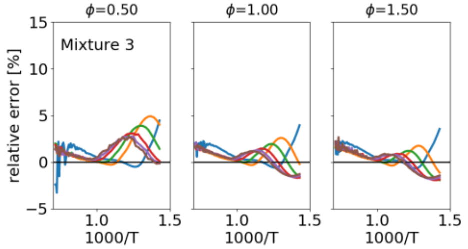
We compare the performance of the lump mechanism with the original one (full)





Nearly identical IDTs for wide range of mixtures, pressures and temperatures





Very small relative errors
Larger deviations at high ammonia content and low temperatures where IDTs are high

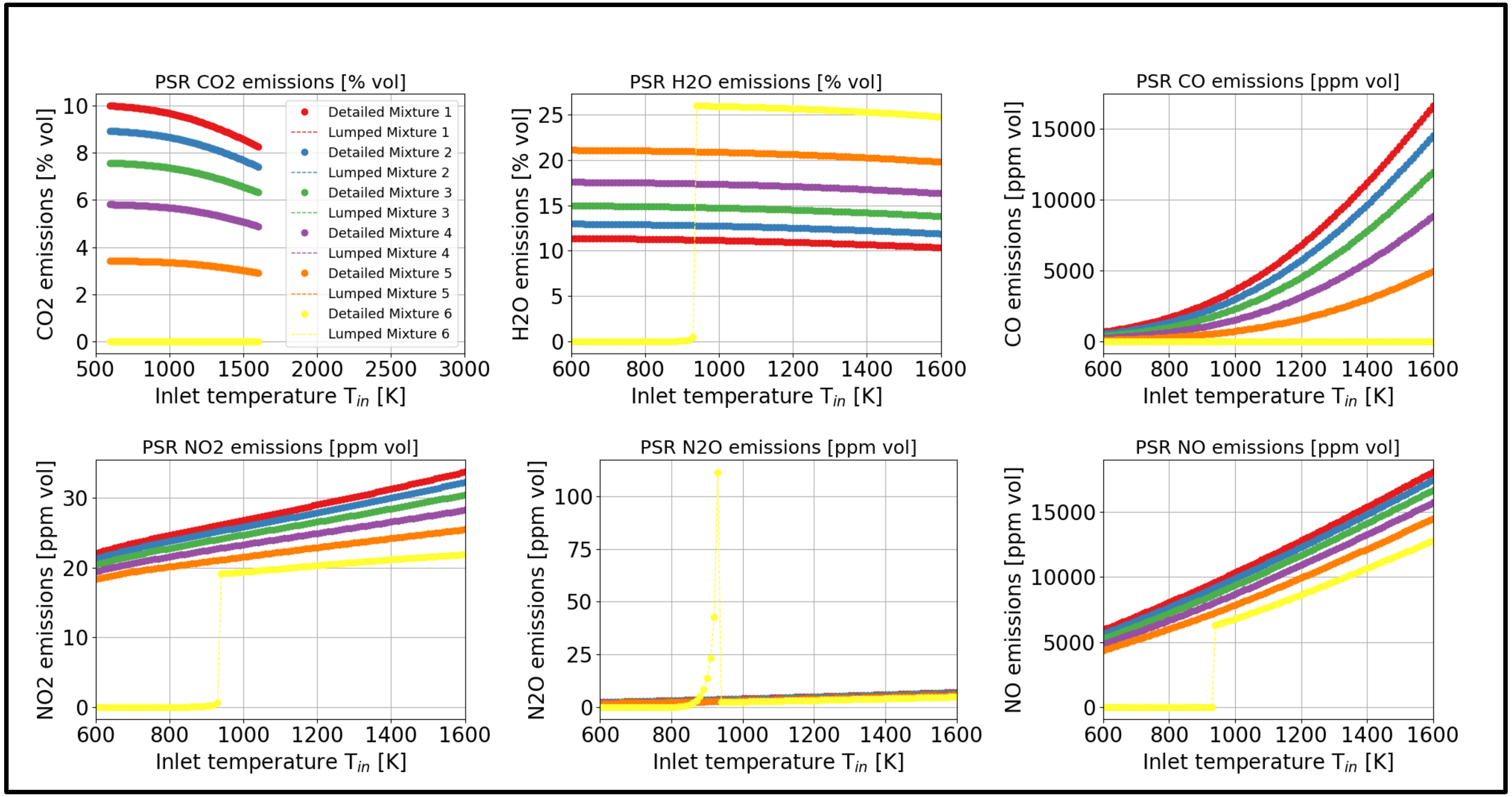
NTNU

Performance assessment

PSR (species profiles)

Parameter	values
Residence time [s]	1
Pressure [bar]	60
Equivalence ratio [-]	0.8
Temperature [K]	600 - 1600 ($\Delta T = 10$)

We compare the performance of the lump mechanism with the original one (full)



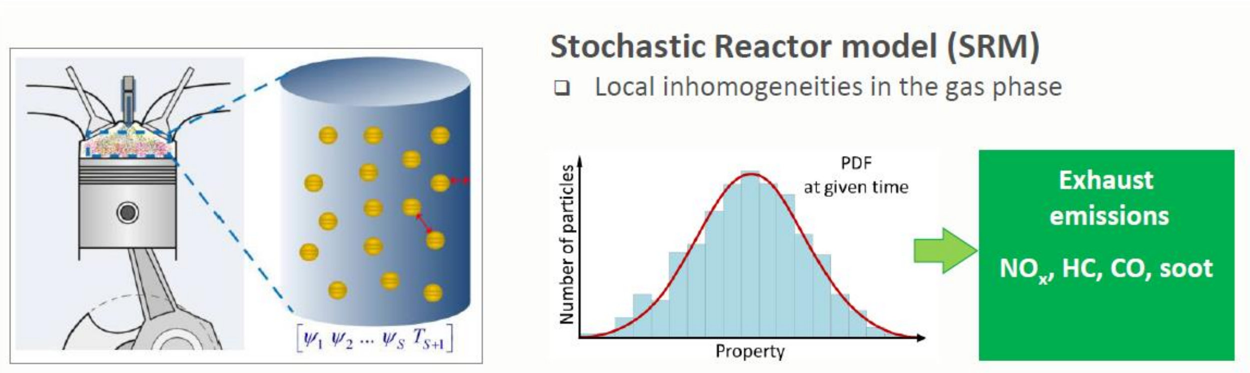
No visible differences in the species profiles of: CO_2, H_2O, CO, NO_2, N_2O and NO

NTNU

Performance assessment

Stochastic Reactor Model (SRM)

- Stochastic Reactor Model represents real engine performance,
- It includes variable pressure, volume (piston movement), mixing process, heat transfer, fuel injection, combustion,
- Gas mixture in an engine cylinder is considered as an ensemble of notional particles which represent a one-point and one-time PDF for a set of scalar variables (species mass fractions and enthalpy).



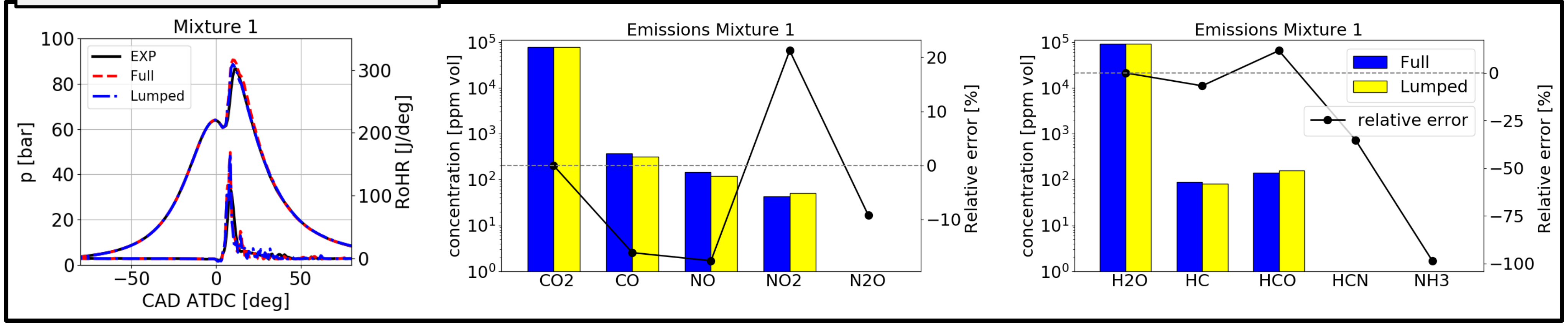
- Mixture is not homogeneous
- Distribution of mixture properties is available
- Crucial for emissions prediction

Performance assessment

Stochastic Reactor Model (SRM)

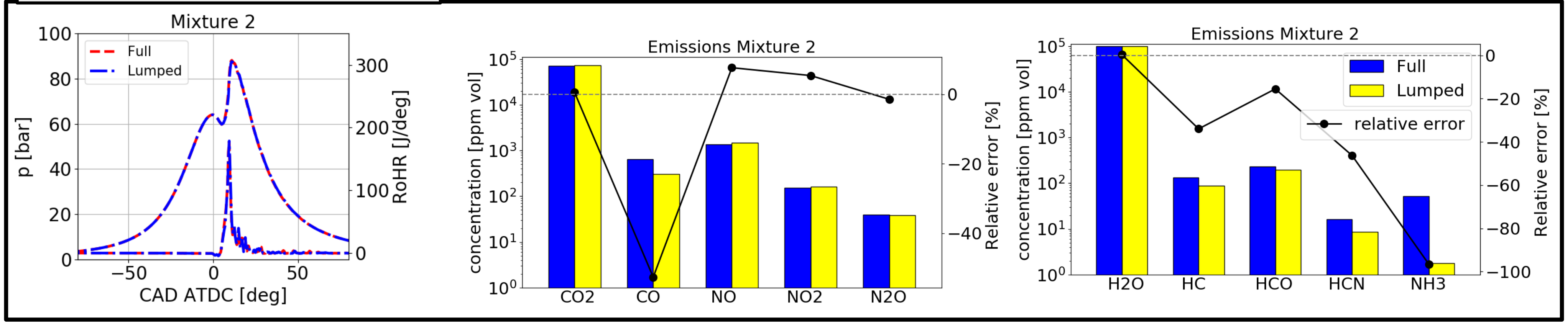
Parameter	values
Speed [rpm]	2000
Bore [m]	0.08
Stroke [m]	0.096
Connecting rod [m]	0.14
Compression ratio [-]	0.096
Injected fuel mass [mg]	19.2
Equivalence ratio [-]	0.625
EGR amount [%]	33

Mixture 1: 100% N-heptane



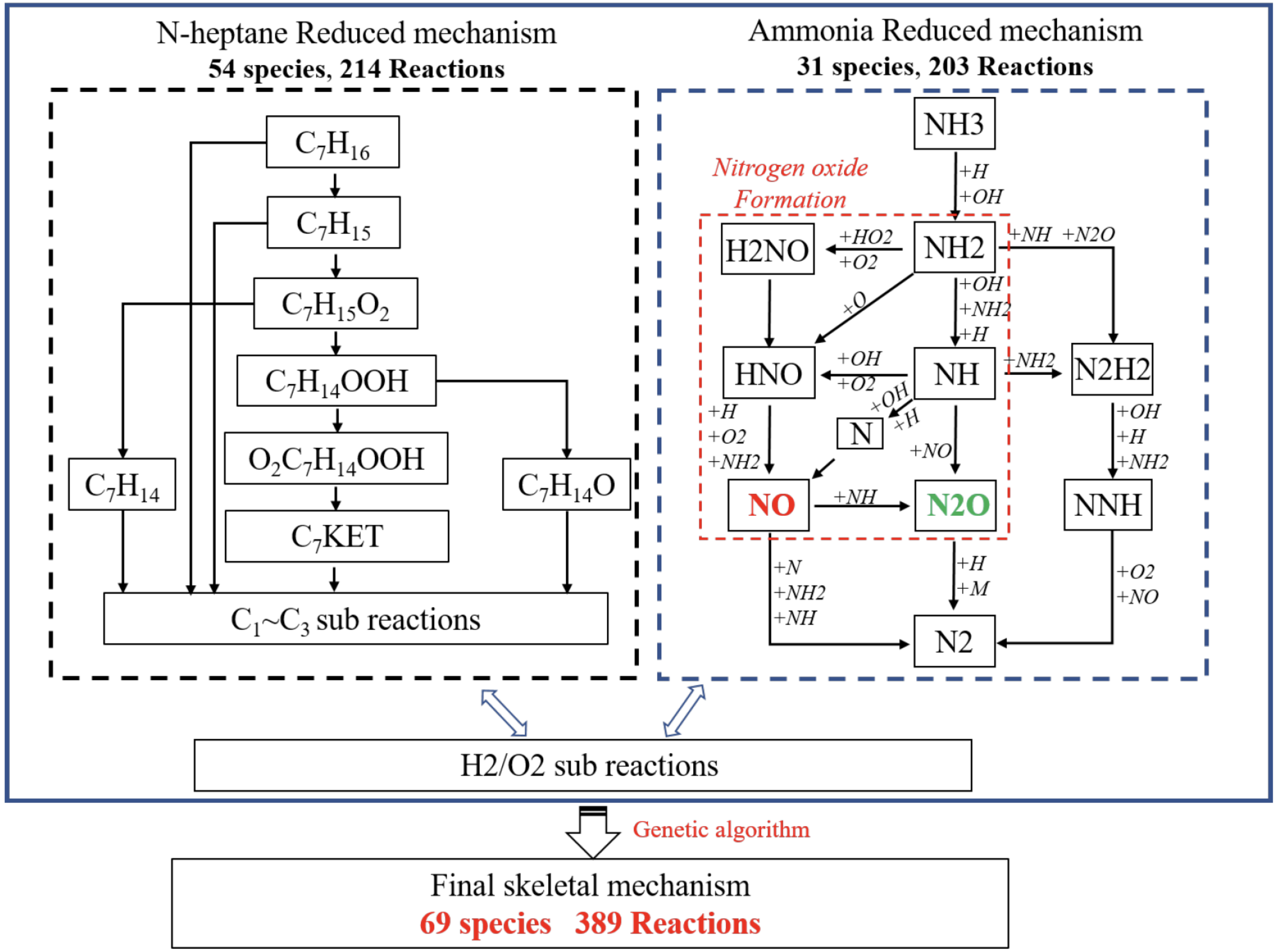
Very similar performance of full and lumped mechanism for pure diesel conditions

Mixture 2: 20% ammonia



Satisfactory performance at 20% ammonia however NH_3 underestimated

CFD model development and validation
- chemical kinetic mechanism



1. Chang, et al. *Combustion and Flame* 236 (2022): 111785.
2. Bertolino, et al. *Combustion and Flame* 229 (2021): 111366.

Sensitivity study to identify the most important reactions

Validation with experimental data

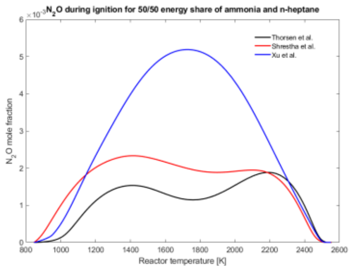
Xu et al., A skeletal chemical kinetic mechanism for ammonia/n-heptane Combustion, Fuel 331, 125830, 2023

Performance assessment

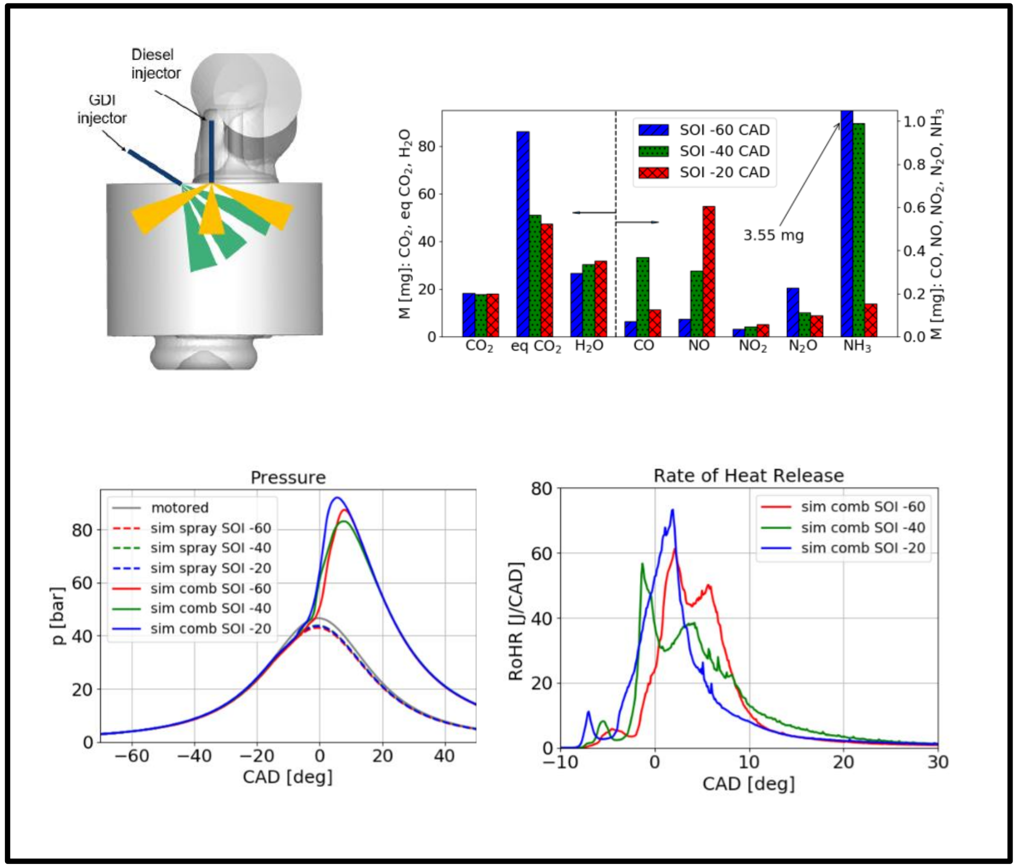
Computational Fluid Dynamic (CFD)

- CFD model based on the single cylinder Hatz engine from NTNU motorlab has been built and tested using skeletal mechanism of Xu et al. Fuel 2023: 69 species, 389 reactions

- Next step includes performance assessment of the final reduced chemical kinetic mechanism with a focus on N_2O formation pathways



Detailed kinetic analysis showed differences beetween skeletal and detailed mechanisms where hydrocarbon – ammonia interactions are important



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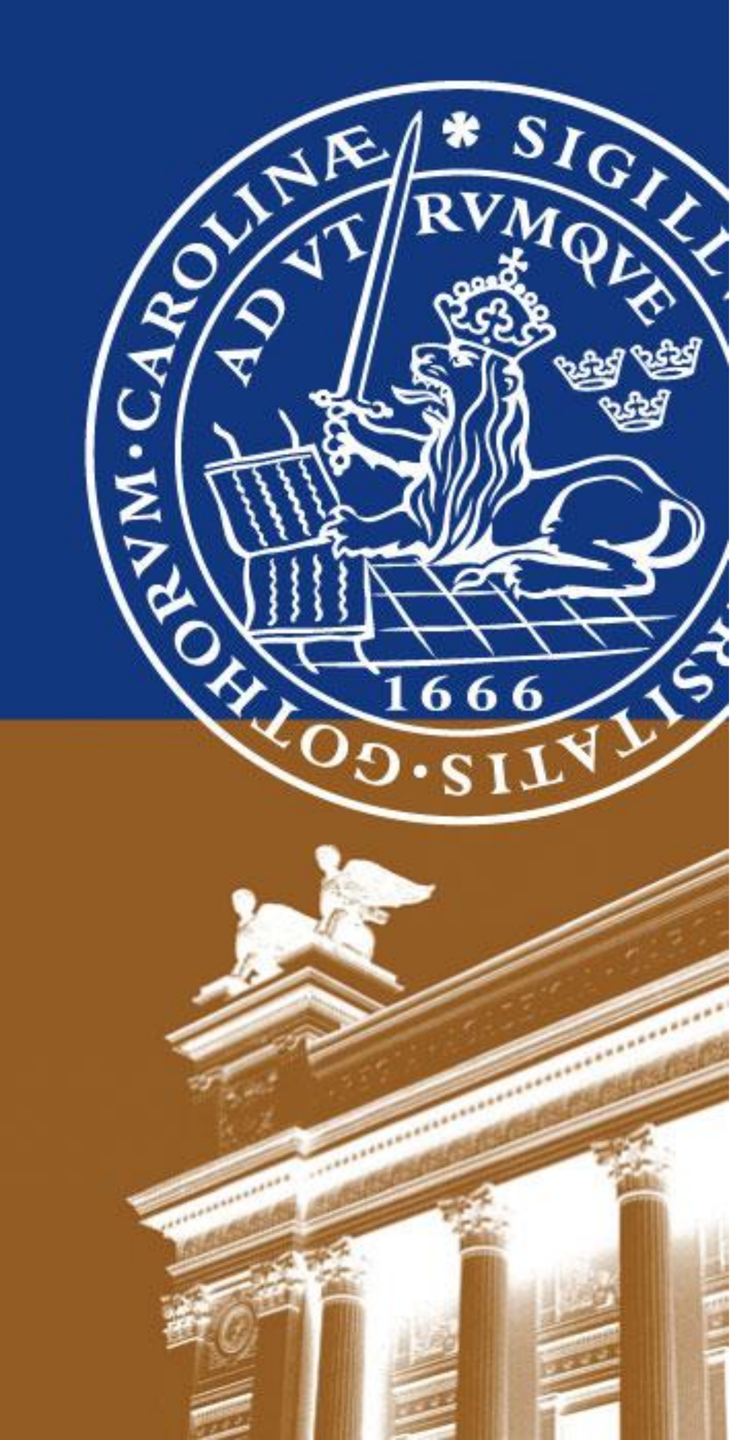
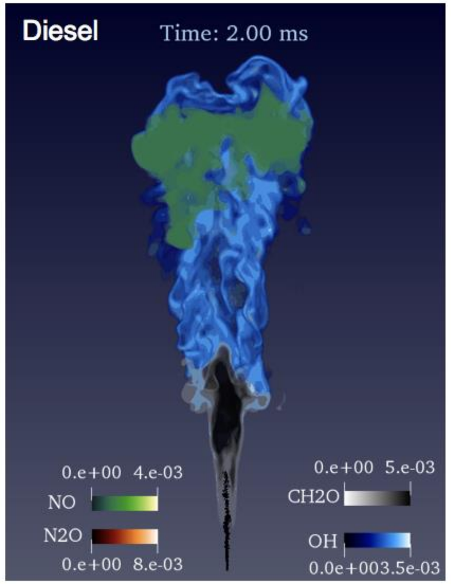
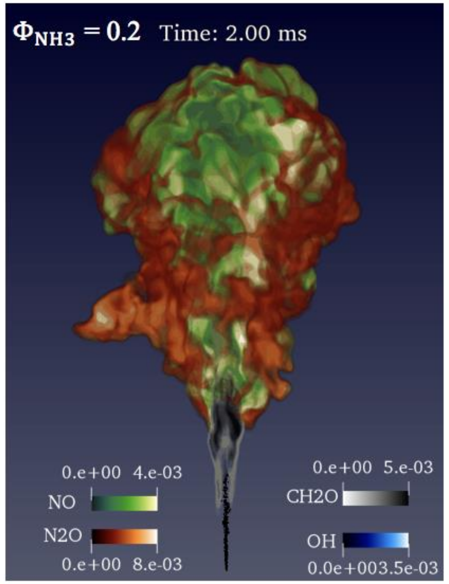
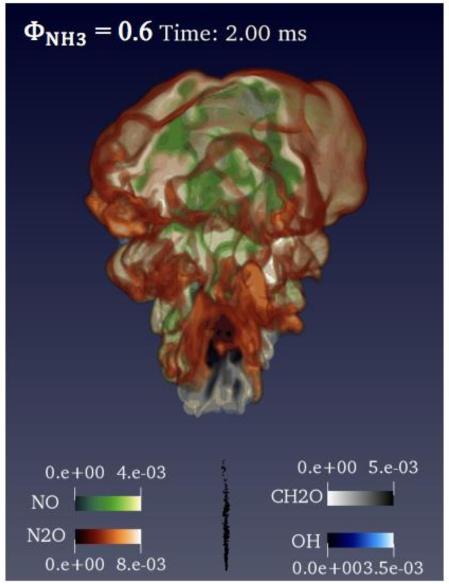


Concepts of Ammonia/Hydrogen Engines for Marine Application – CFD modeling

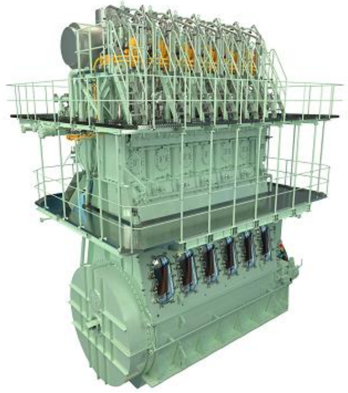
Leilei Xu, Xue-Song Bai





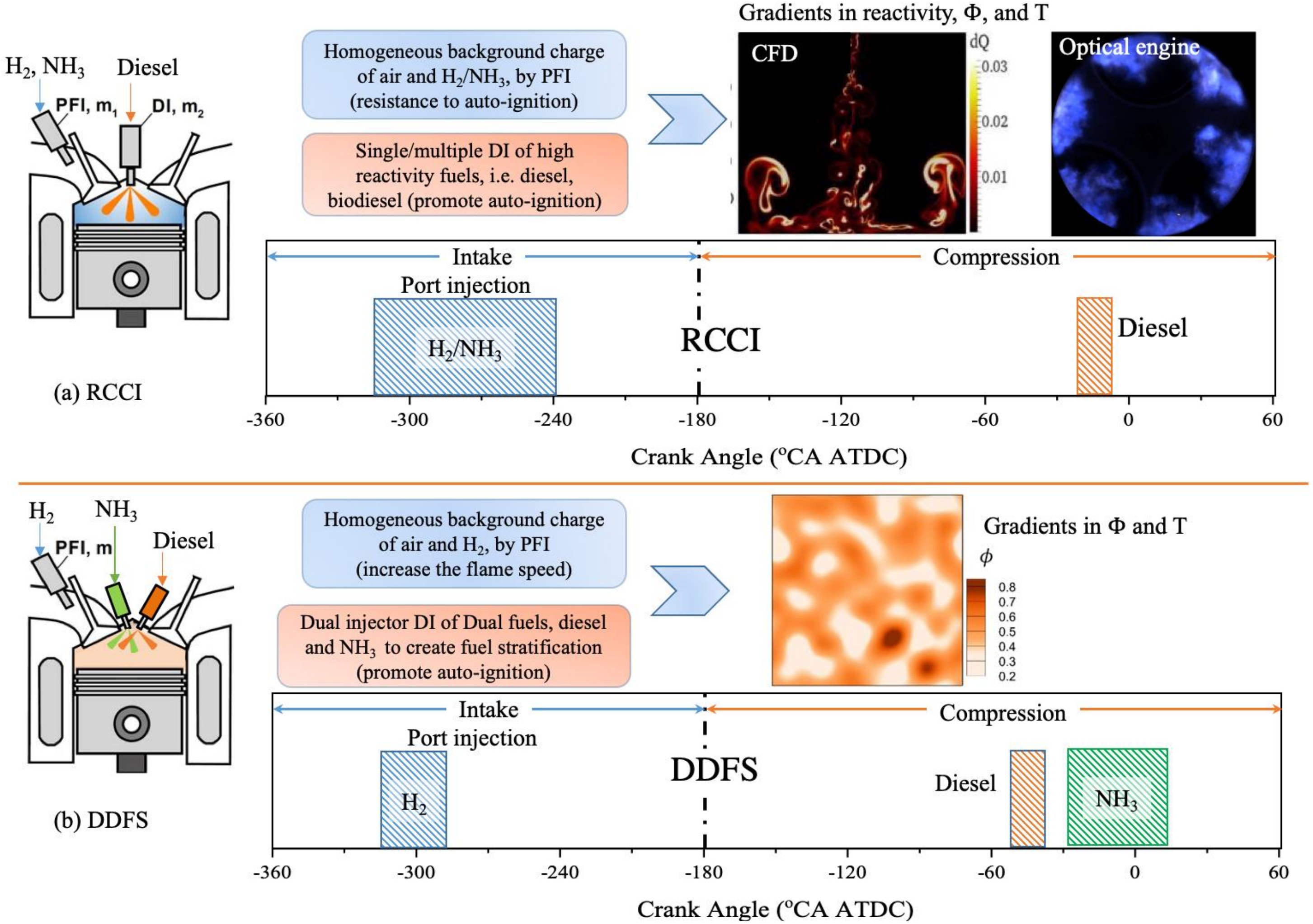


Concepts of Ammonia/Hydrogen Engines for Marine Application

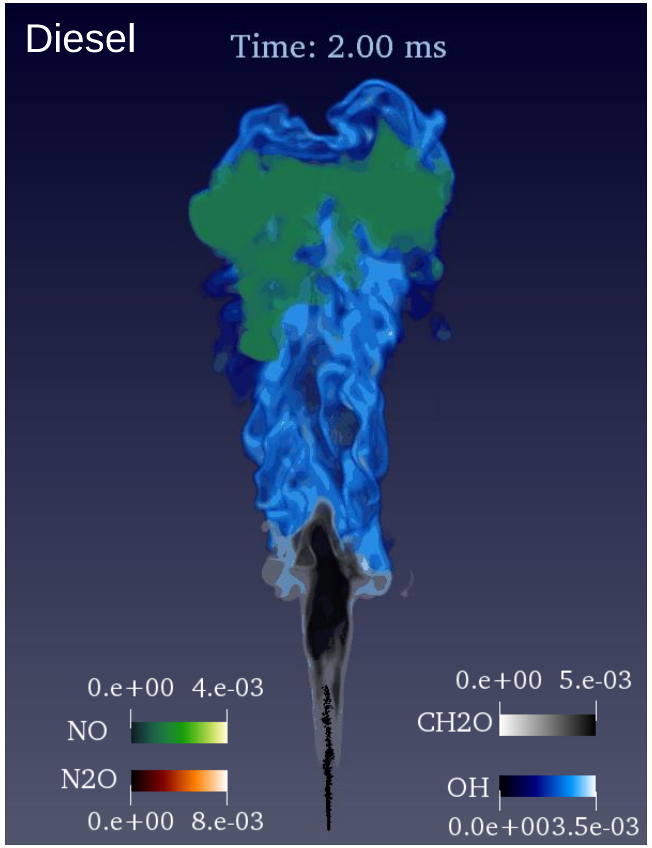


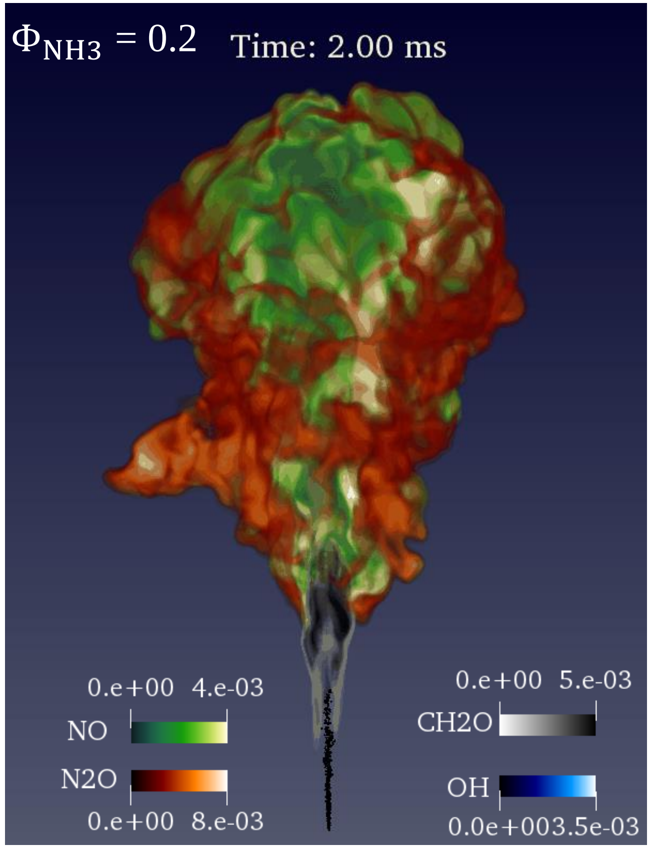
MAN ES AMMONIA ENGINE PROJECT - AENGINE

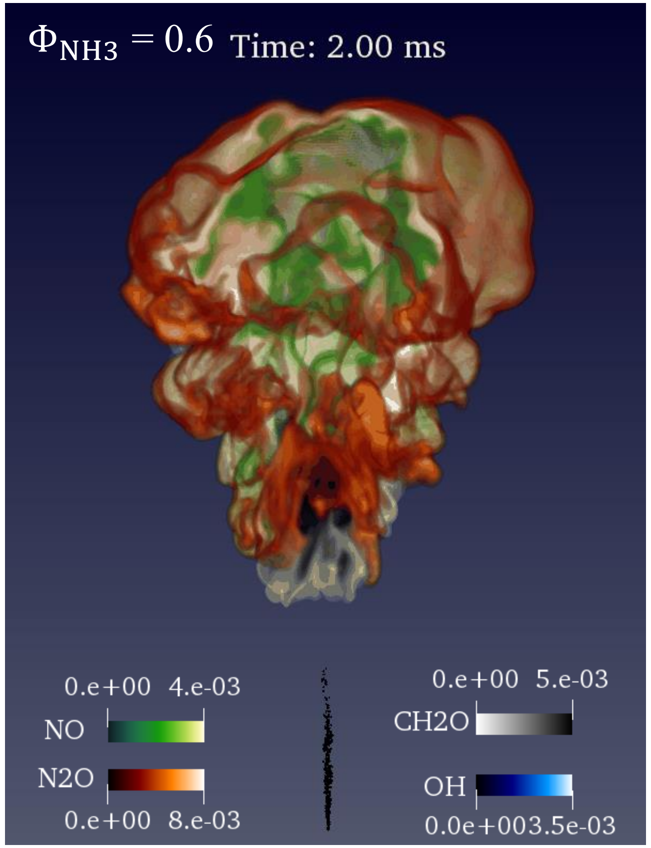
WÄRTSILÄ AMMONIA AND HYDROGEN RESEARCH



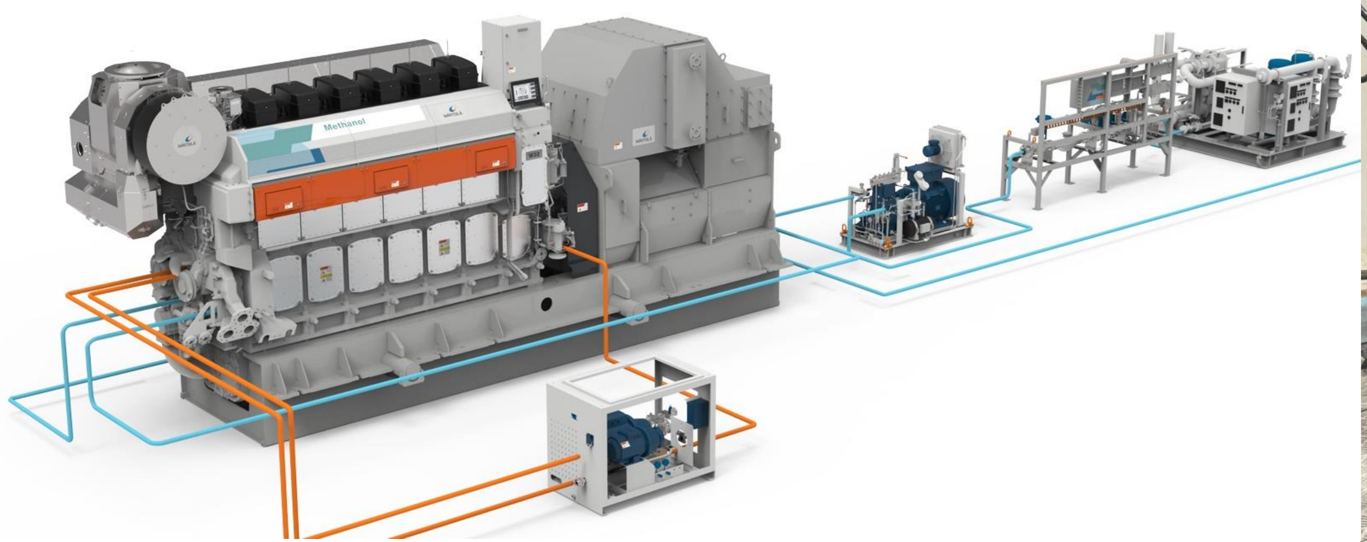
NH3/n-heptane combustion under RCCI conditions







Studies of RCCI concept engines

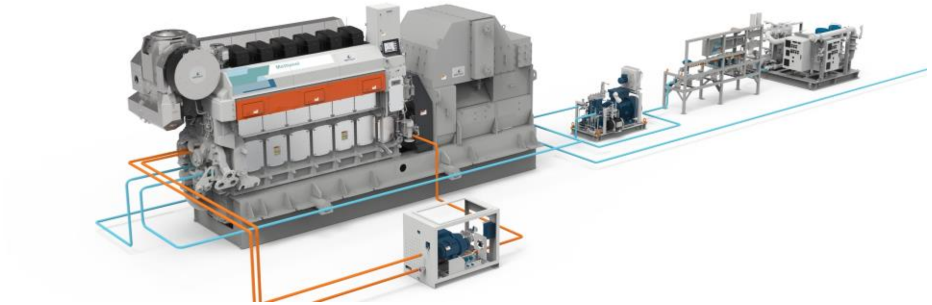


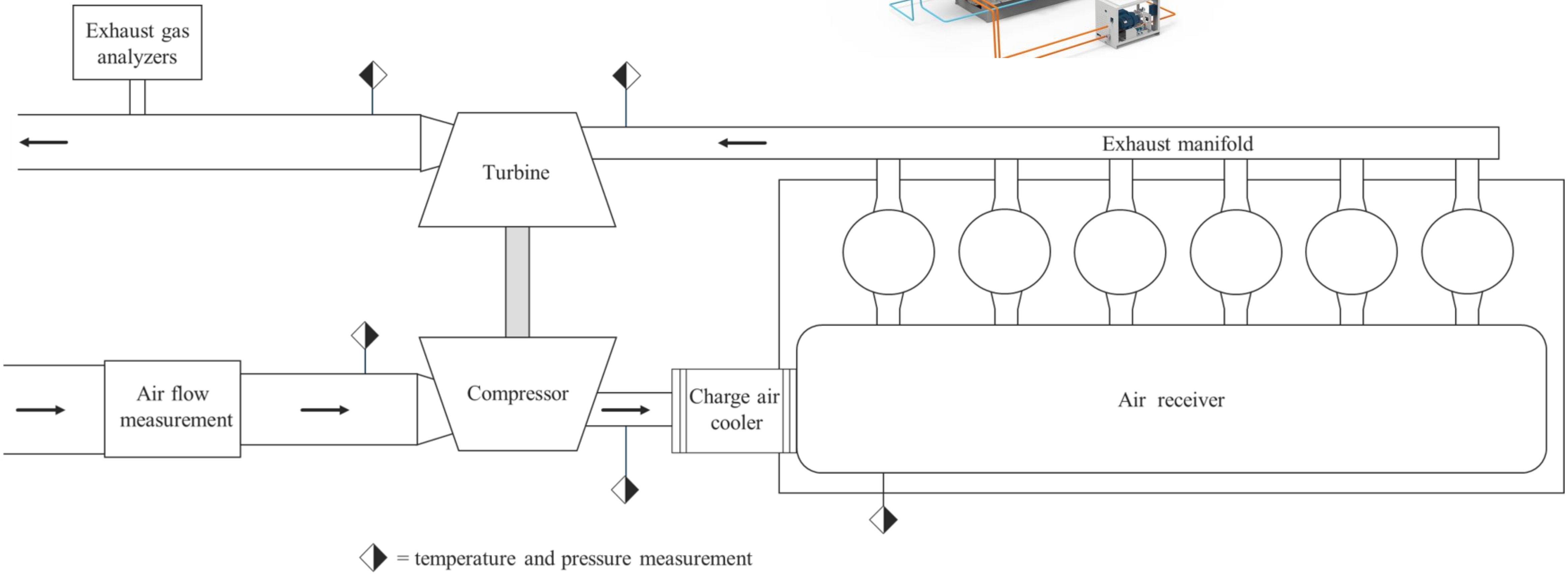
Wärtsilä W32 engine

SJTU dual-fuel lab engine

Scania D13 engine

Wärtsilä dual-fuel engine





Numerical simulation and engine experiment of RCCI engine concepts

Table 3: Experimental cases setup. EP is the premixed fuels energy share ratio. Φ_{pre} is the equivalence ratio of the premixed fuels/air mixtures.

Case	Load	EP	Φ_{pre}	Fuel mass (g/cycle)			SOI_D	Injection P	Duration	Initial pressure	Engine type
				CH_4	NH_3	Diesel	°CA	MPa	°CA	bar	
1	7.4	91.5%	0.57	1.216	0	0.125	-20	90	16	1.112	LNG engine
2	6.97	76.35%	0.682	0	2.82	0.351	-25	150	33.44	0.820	NH_3 engine
3	10.17	72.16%	0.687	0	3.82	0.610	-24	190	49.44	1.112	NH_3 engine

Engine experiments @Wärtsilä

Table 4: Additional simulation cases setup. EP is the premixed fuels energy share ratio. Φ_{pre} is the equivalence ratio of the premixed fuels/air mixtures.

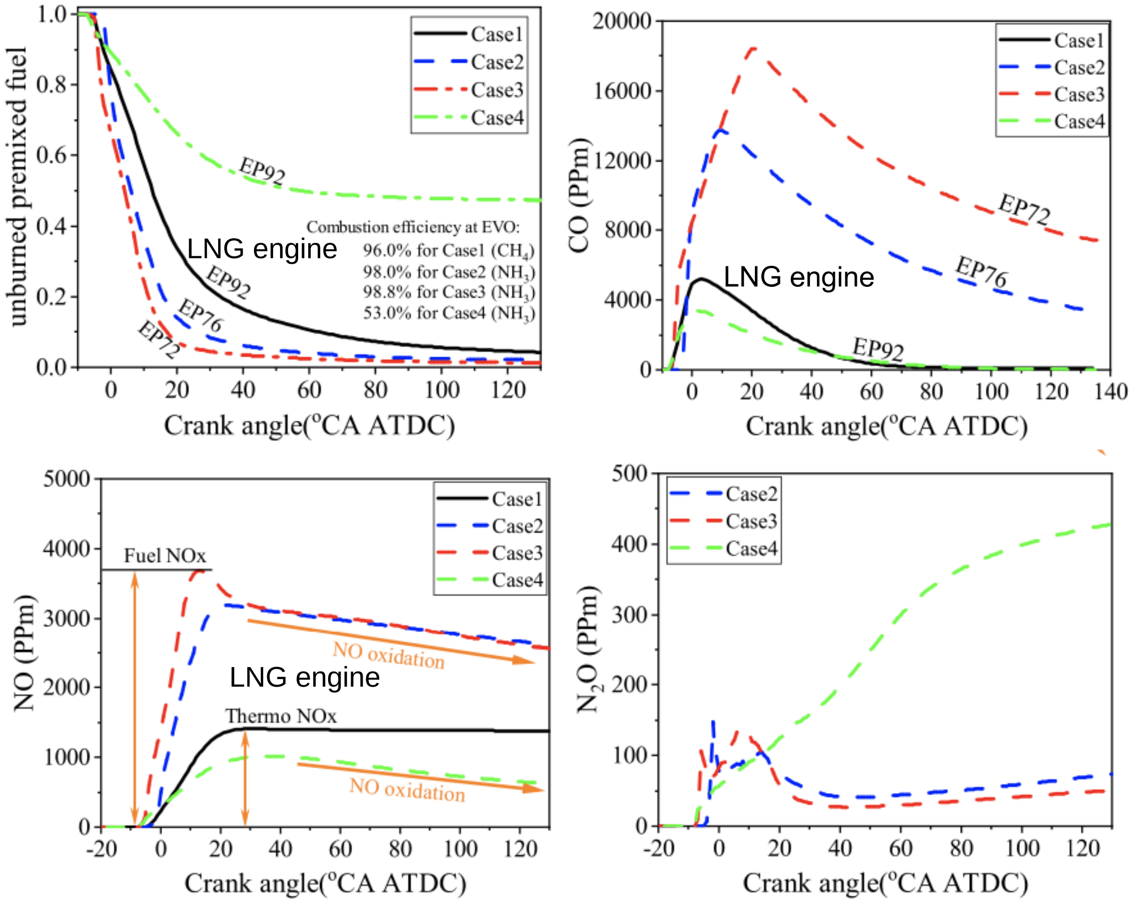
Case	Expected load	No. holes	EP	Φ_{pre}	Fuel mass (g/cycle)			SOI_D	Duration	Initial pressure
					CH_4	NH_3	Diesel	°CA	°CA	*bar*
4	7.4	4	91.5%	0.58	0	3.276	0.125	-20	16	1.112
5	7.4	8	91.5%	0.57	1.216	0	0.125	-20	8.64	1.112
6	7.4	8	91.5%	0.58	0	3.276	0.125	-20	8.64	1.112
7	7.4	8	91.5%	0.58	0	3.276	0.125	-15	8.64	1.112
8	7.4	8	91.5%	0.58	0	3.276	0.125	-10	8.64	1.112
9	7.4	8	92%	0.7	0	3.19	0.125	-20	8.64	0.83

Engine optimization studies

Numerical simulation and experimental studies of RCCI engine – Wärtsilä W32 engine

LNG/diesel W32 DF engine directly running ammonia:

- too low combustion efficiency
- Low NO emission
- High CO and N2O emission



High amount of diesel injection

- High CO emissions

High amount of diesel injection

- High NO emissions

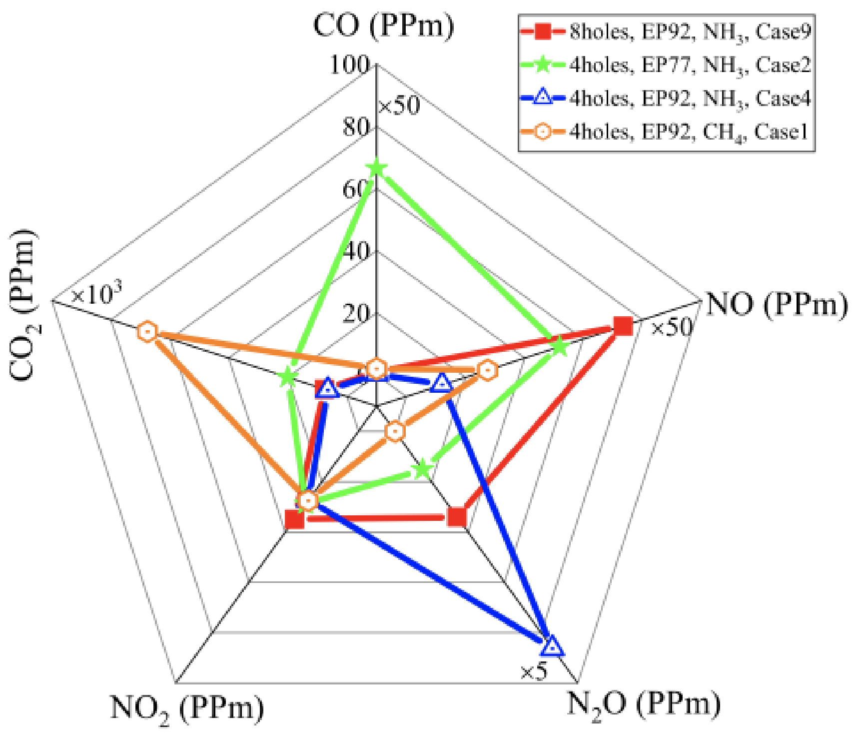
High amount of diesel injection

- low N2O emissions

Numerical simulation – optimization studies

Optimize W32 DF engine for ammonia operation:

- Increase of the number of injector holes
- Increase ammonia/air equivalence ratio
- Ammonia/diesel emulsion injection
- Earlier injection timing of diesel pilots



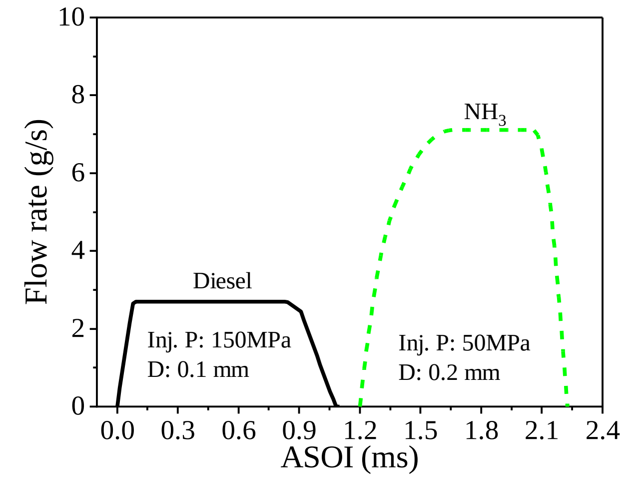
Hydrogen enriched ammonia RCCI engine – Scania D13 engine studies

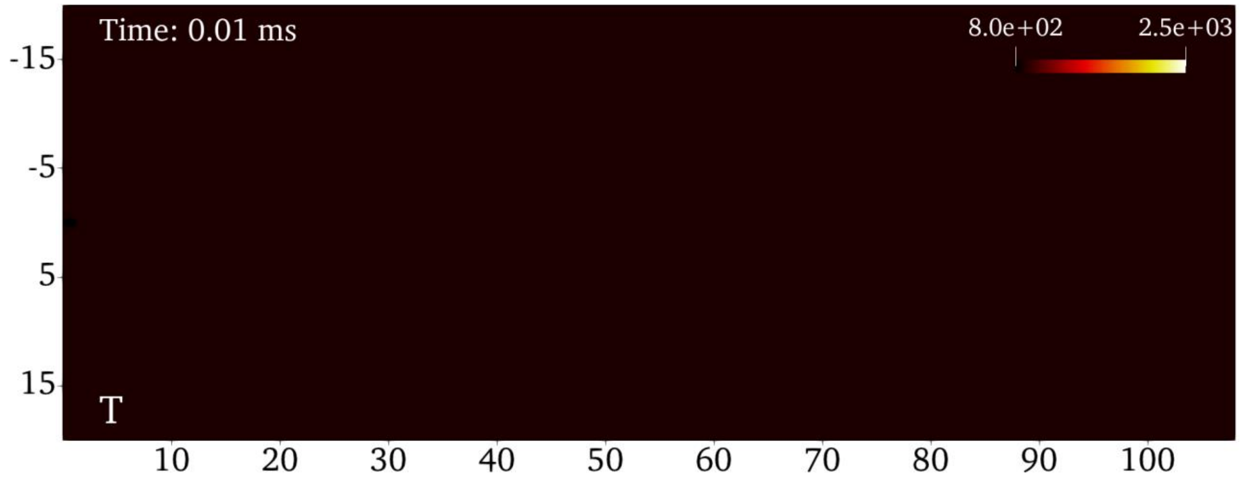
- The engine can operate effectively with up to 50% of the total energy replaced by premixed ammonia, with a penalty of slightly higher NO emissions compared to the diesel CDC engine and significant N2O emissions.
- Unburned ammonia is another issue, as nearly 20% of ammonia cannot completely burn even for the EP of 0.3 case.
- Blending hydrogen into the premixed ammonia significantly improves ammonia combustion efficiency, but with a trade-off of increased NO emissions.
- Ammonia leakage primarily originates from areas near the cold wall, the center of the cylinder, and the crevice.
- N2O mainly forms at the ammonia flame front.

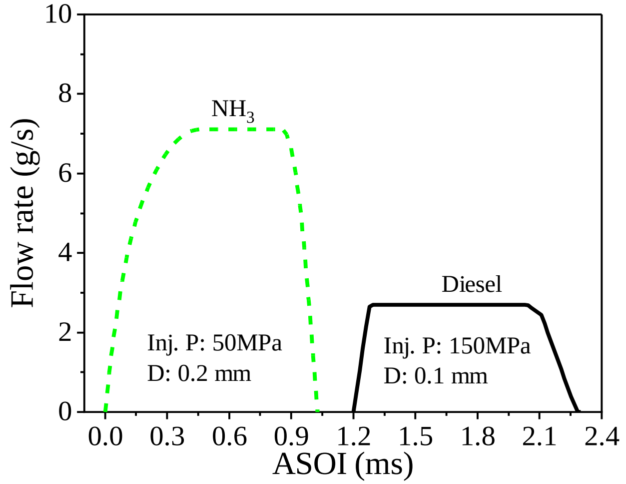
Scania D13 engine

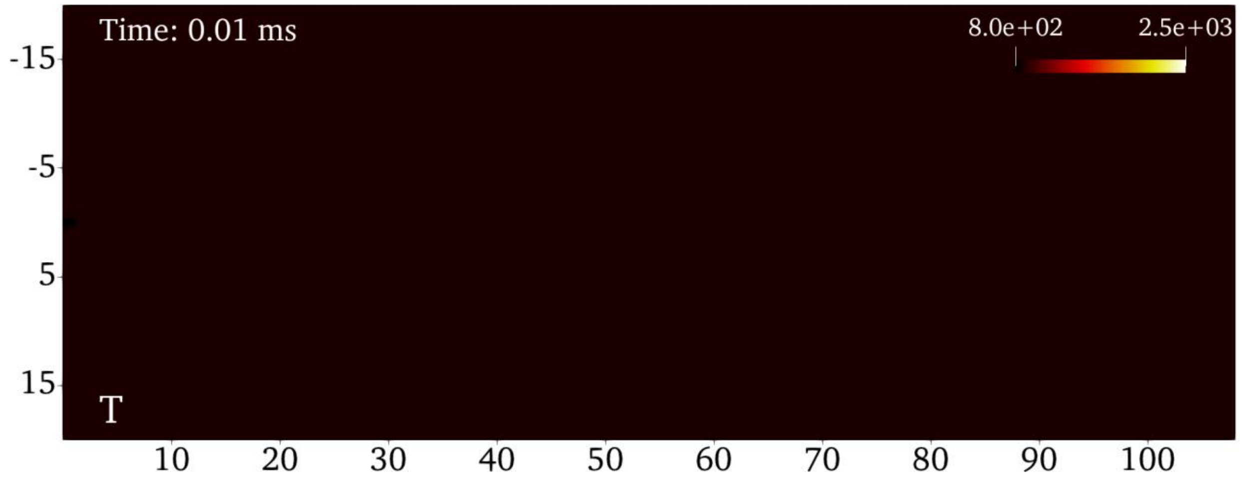
DDFS – Double direct injection dual-fuel stratification

- ECN spray H flame



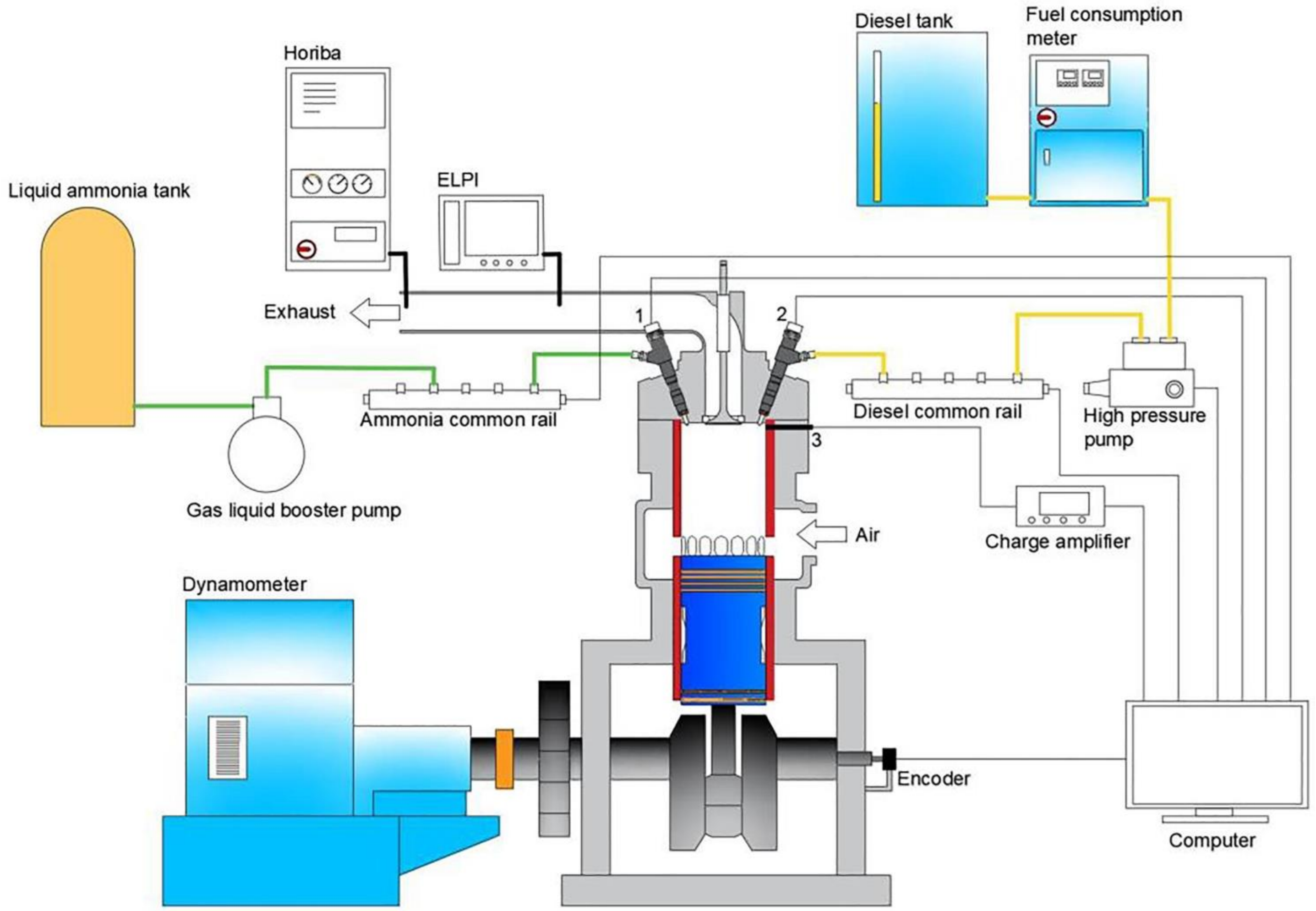






DDFS engine test - a two-stroke academic lab engine

- Two-stroke marine engine, flat piston
- Exhaust gas emissions, NOx, CO, THC were measured by Horiba MEXA 7100D/EGR analyzer.



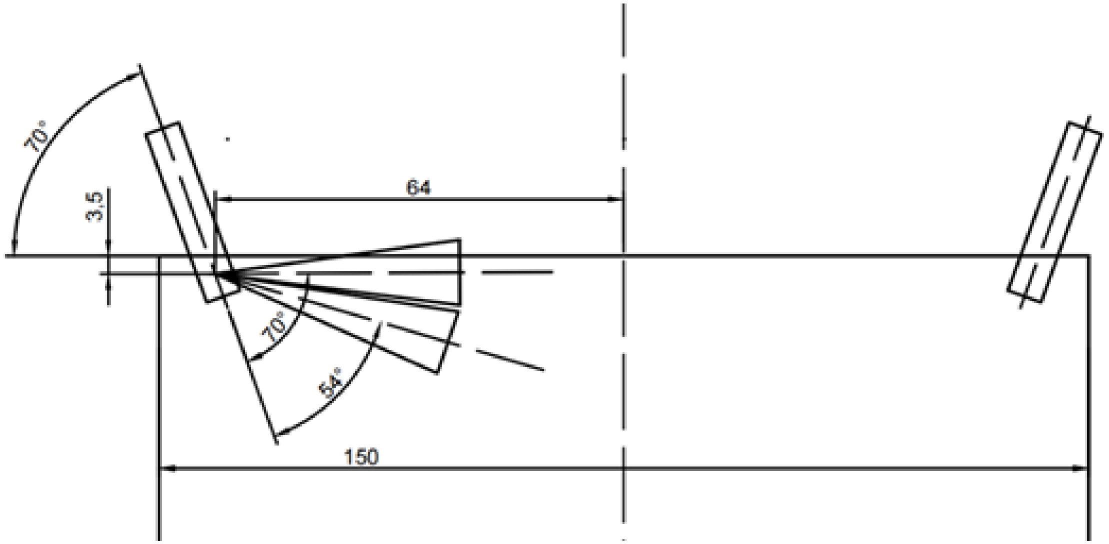
Zhang et al., Fuel 332, 126086, 2023

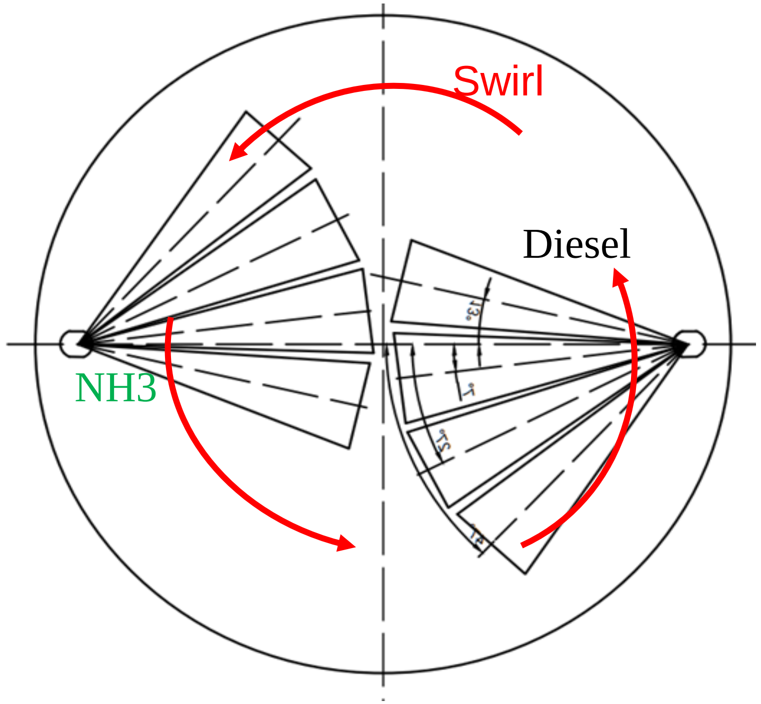
Injector specification

Zhang et al., Fuel 332, 126086, 2023

- Injectors are specially designed for the DDFS concept, four holes are activated
- injectors are symmetrically installed on both sides of the cylinder.
- Injector holes: 0.17 mm for both ammonia and diesel
- Injection pressure: 65MPa for ammonia, 100MPa for diesel

IMEP: 5.7 bar (full load)





Experimental and simulation cases

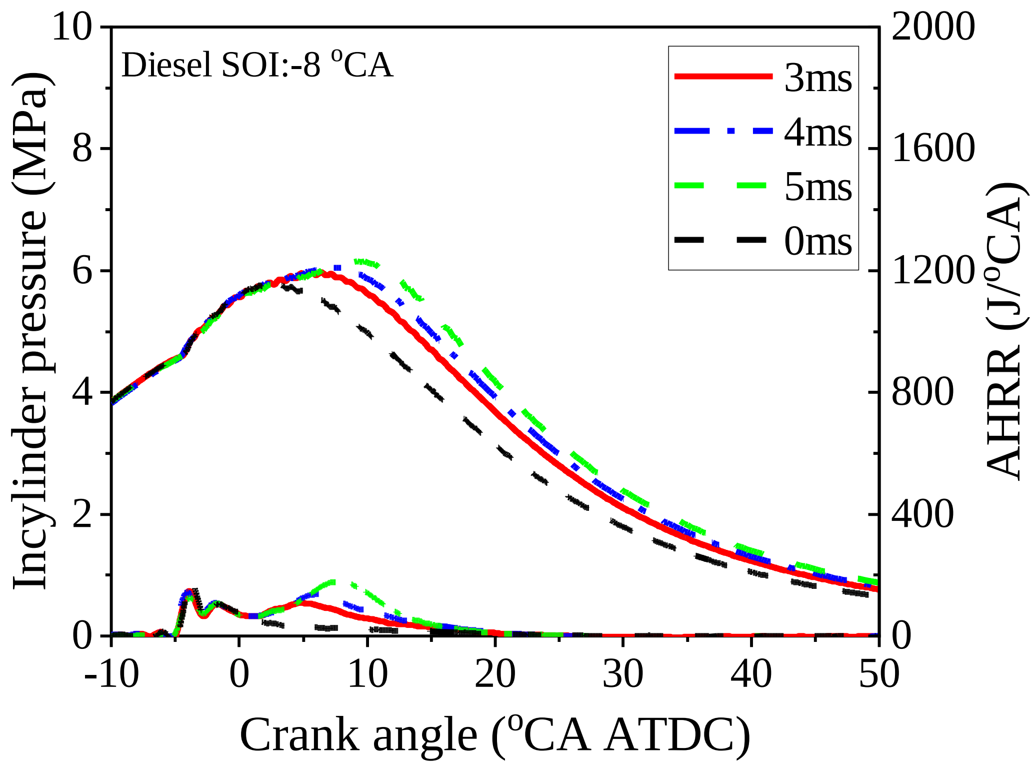
Case	Diesel			Ammonia			AE	Total Energy (J)	Engine load (bar)	Description
	SOI (CA ATDC)	EI (ms)	Mass (mg/cyc)	SOI (CA ATDC)	EI (ms)	Mass (mg/cyc)				
1a	-8	0.8	43.1	-8	0	0	0	1936	0.95	Pure Diesel
1b	-8	0.8	43.1	-8	3	62.3	37.5%	3096	2.05	
1c	-8	0.8	43.1	-8	4	81.4	43.9%	3452	2.56	DDFS
1d	-8	0.8	43.1	-8	5	103.7	49.4%	3867	3.08	

Ammonia Energy share ratio (AE)

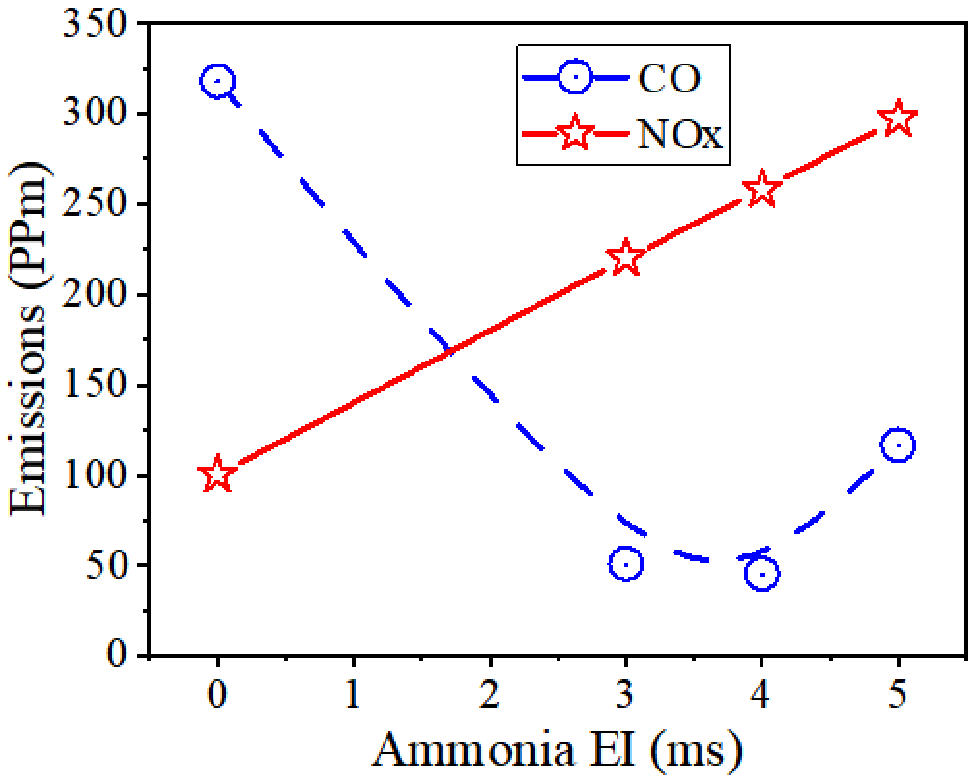
$$AE=\frac{m_{NH3}\times LHV_{NH3}}{m_{diesel}\times LHV_{diesel}+m_{NH3}\times LHV_{NH3}}$$

Engine full load is 5.7bar

Engine performance – metal engine experiments

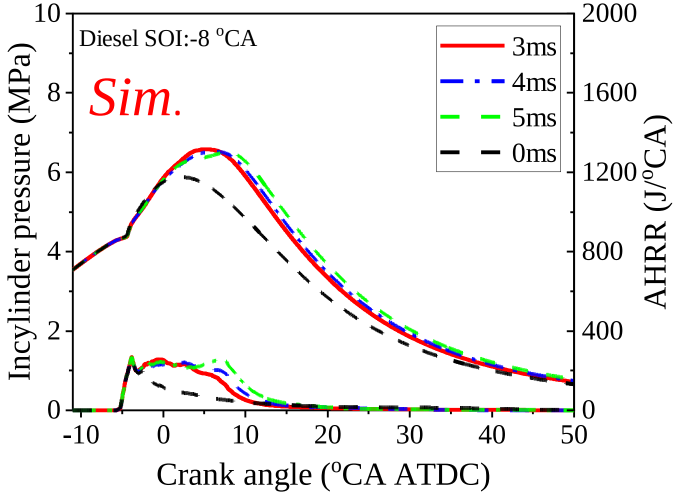


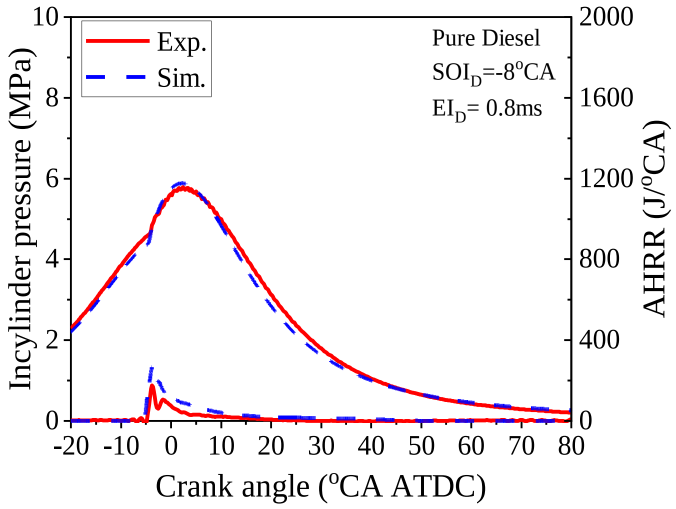
In-cylinder pressure and apparent heat release rate

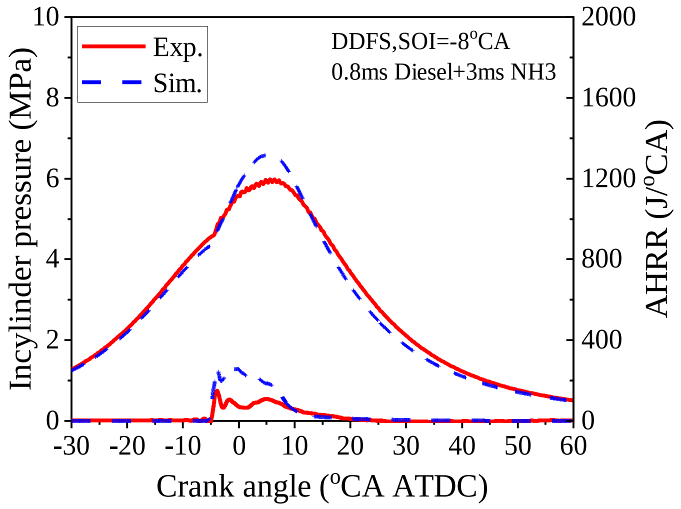


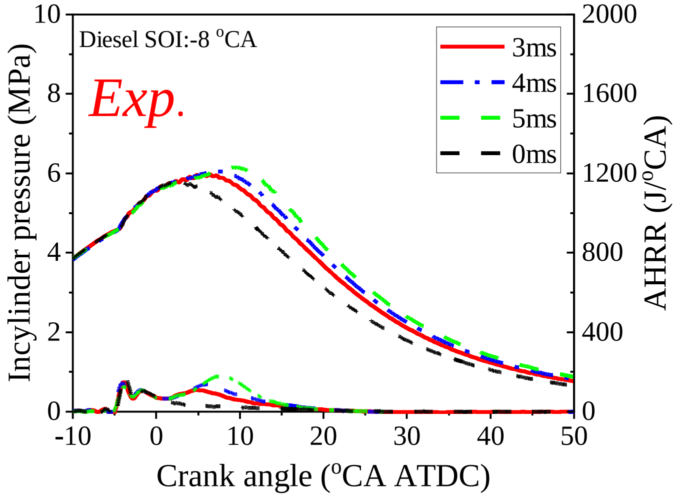
NOx emission vs ammonia/diesel energy ratio

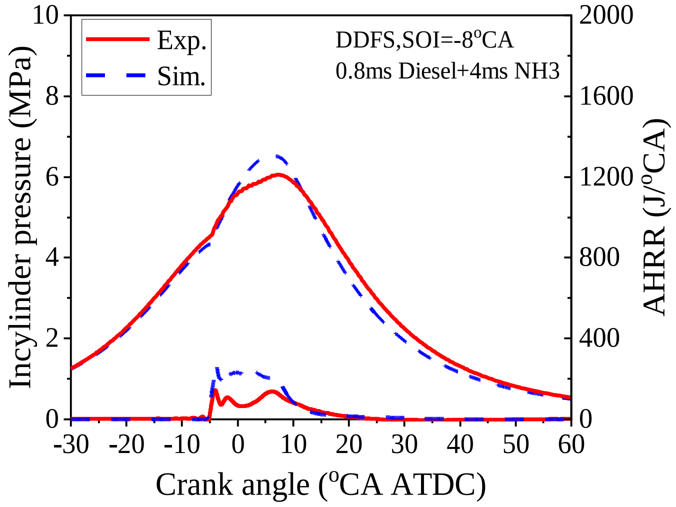
In-cylinder pressure and heat release rate

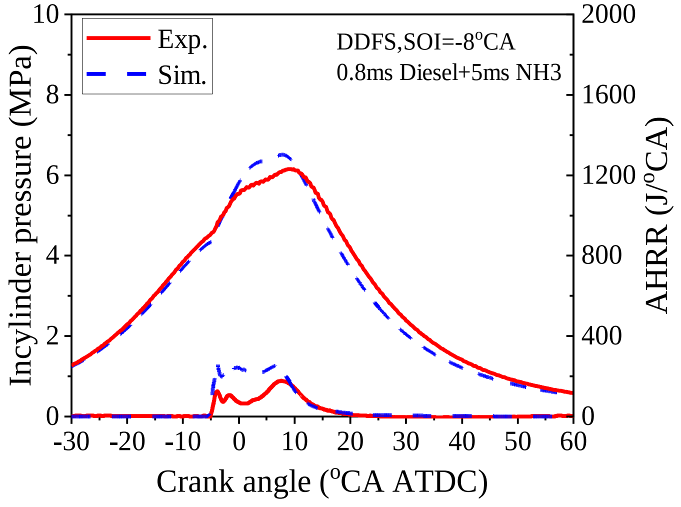




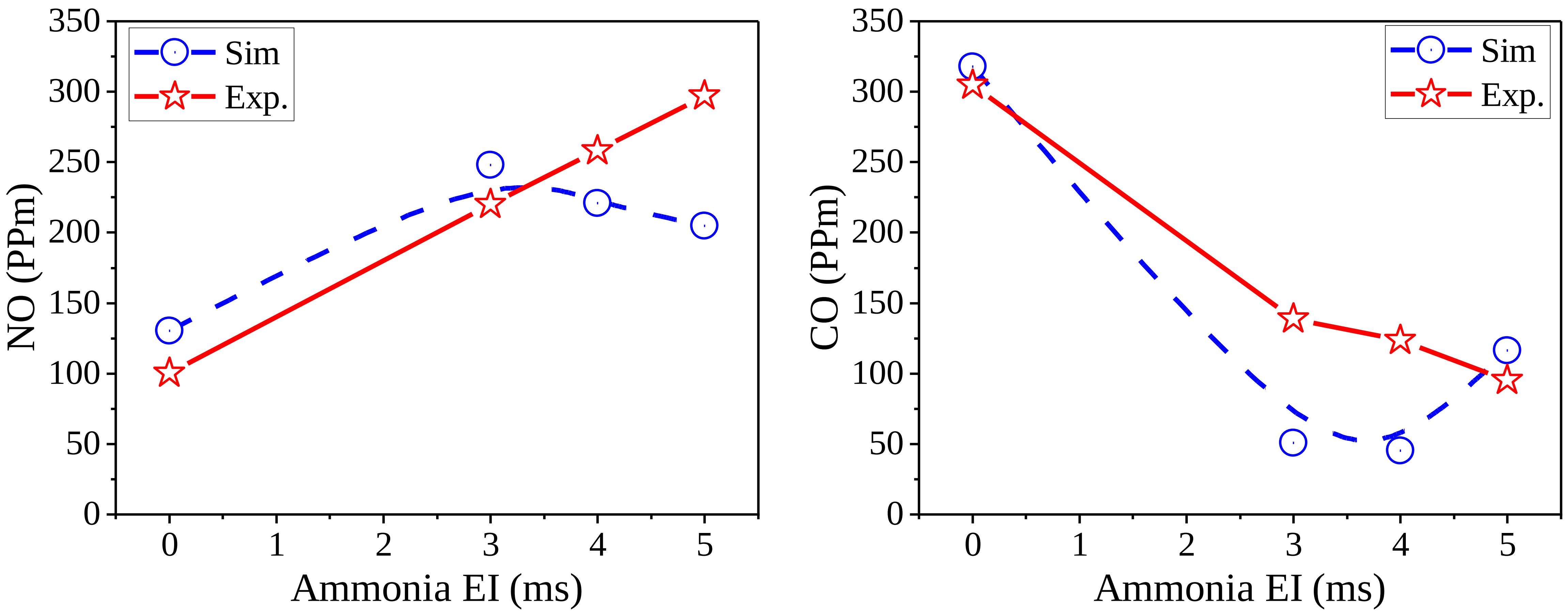








NO and CO emissions



Experimental and simulation cases

- Effect of the **ammonia** injection timing (AE=50%)

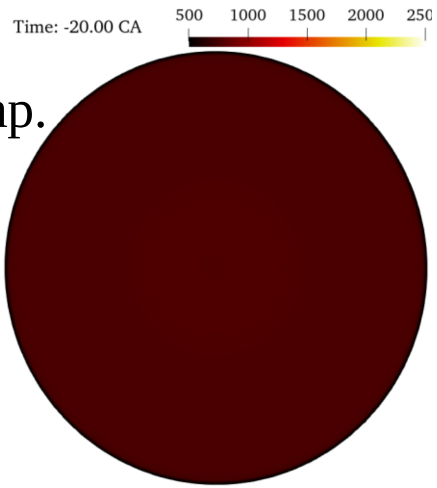
Case	Diesel			Ammonia			AE	Total Energy (J)	Description
	SOI (CA ATDC)	EI (ms)	Mass (mg/cyc)	SOI (CA ATDC)	EI (ms)	Mass (mg/cyc)			
2b	-8	0.8	43.1	-8	5	103.7	49.4%	3867	DDFS
2c	-8	0.8	43.1	-16	5	103.7	49.4%	3867	DDFS
2d	-8	0.8	43.1	0	5	103.7	49.4%	3867	DDFS
2a	-8	1.6	87.2	-	-	-	-	3916	Pure diesel (same energy)

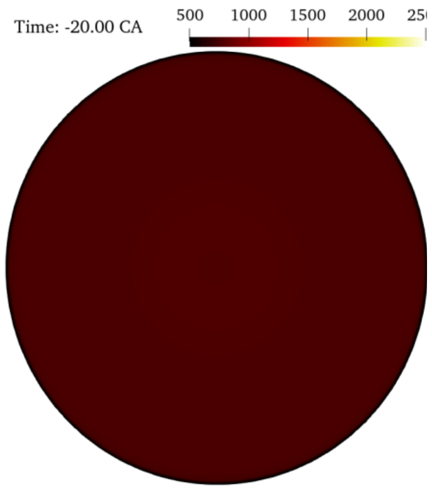
Impact of the ammonia injection timing (AE=50%)

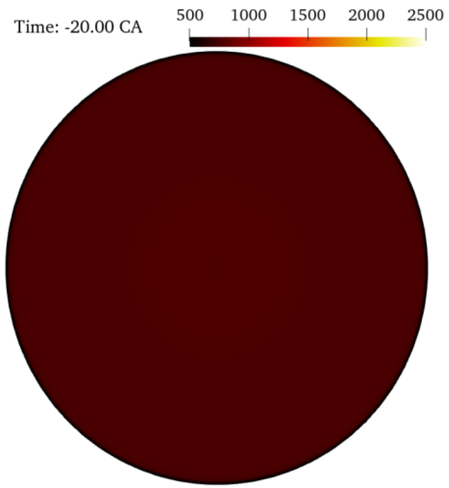
Diesel SOI: -8 ºCA

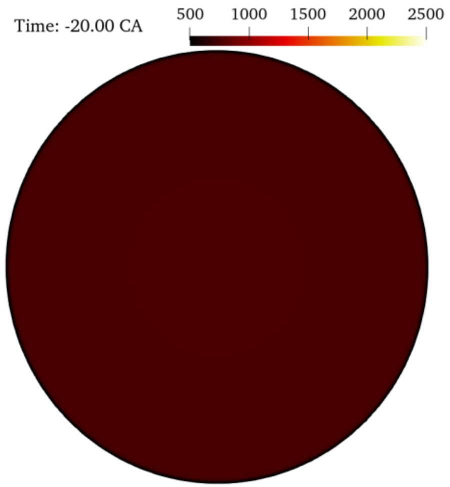
NH_3 SOI: -16 ºCA | -8 ºCA | 0 ºCA

Temp.

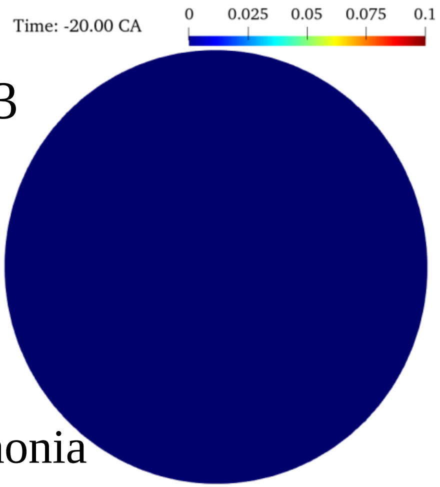


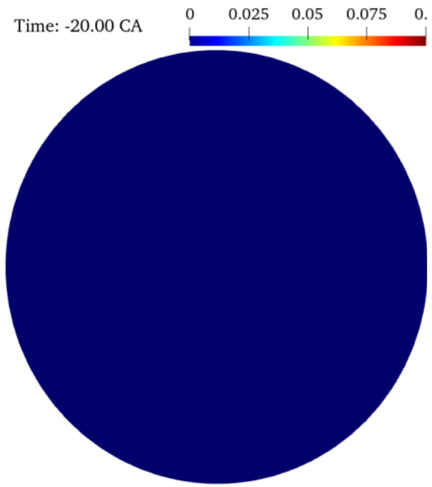


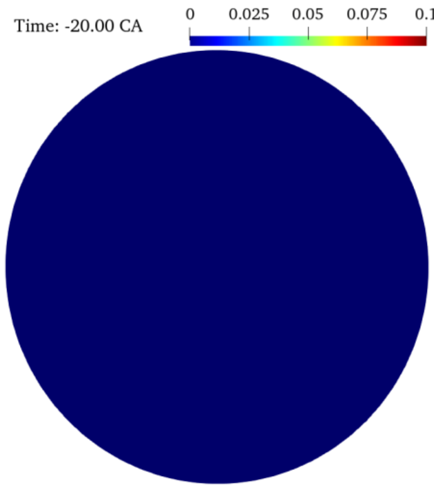




NH3





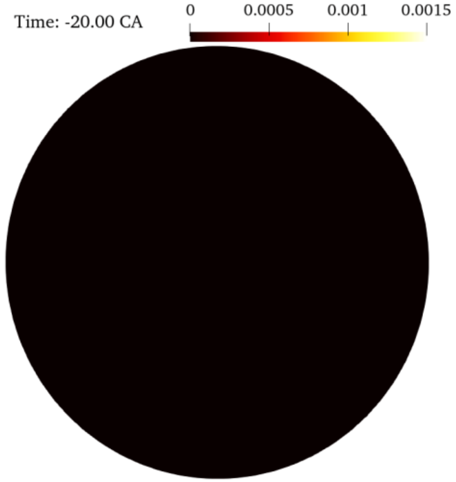


Pure diesel case
Same load

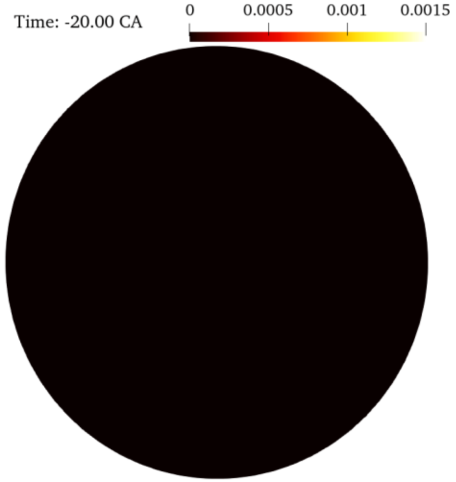
Ammonia Combustion efficiency: 75.66% | 95.39% | 20.61%

NO Emissions

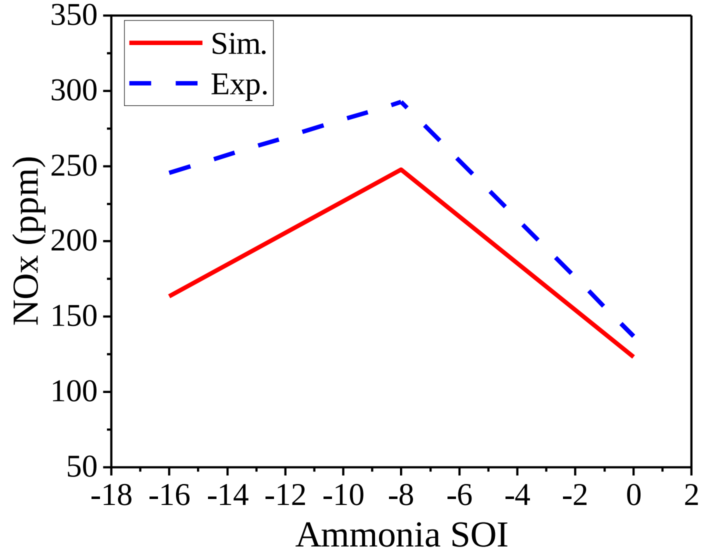
NOx emissions is related to the ammonia combustion efficiency

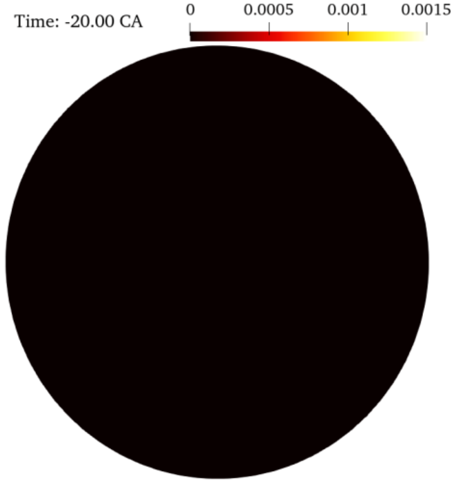


NH3 SOI:-16^{o}CA

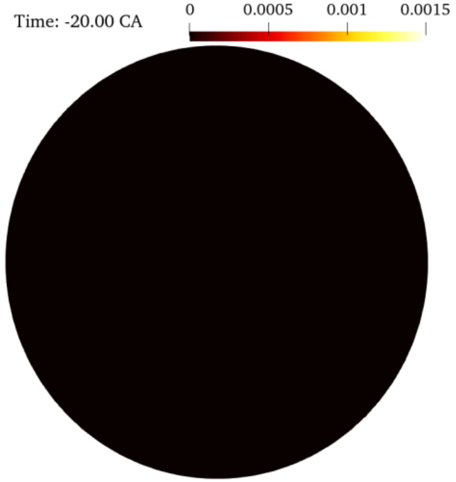


NH3 SOI:-8^{o}CA

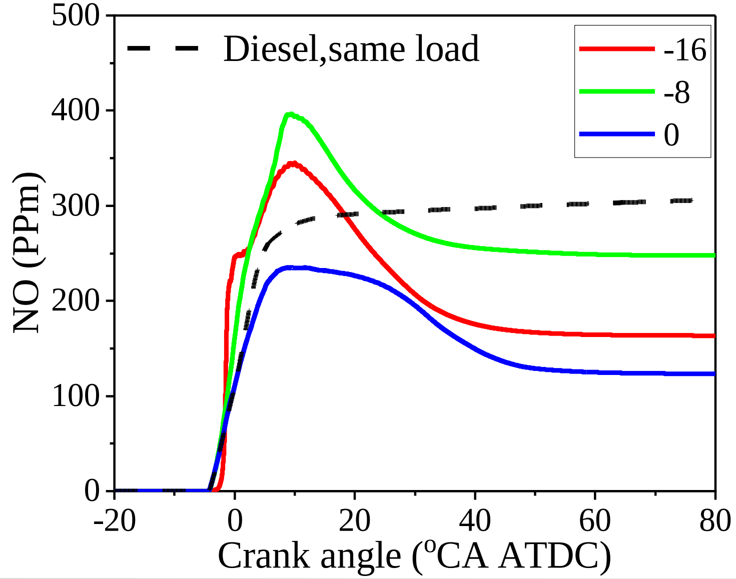




NH3 SOI: 0^{o}CA

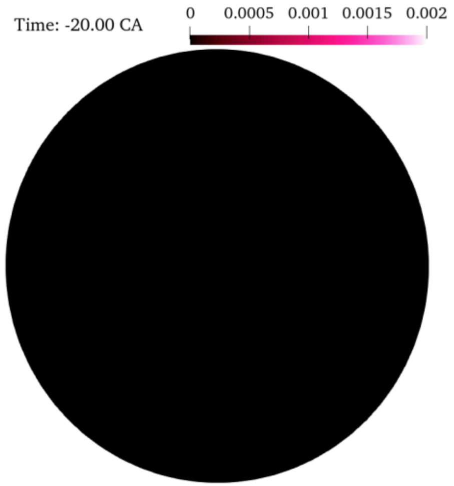


Pure diesel (same load)

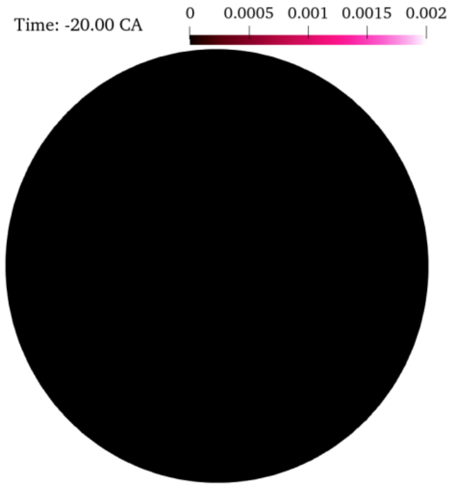


N2O Emissions

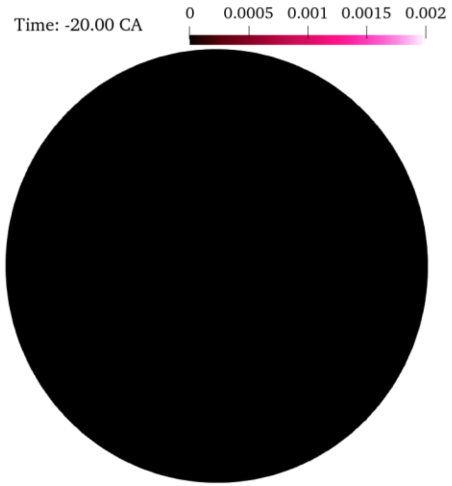
NH3 SOI:-16^{o}CA

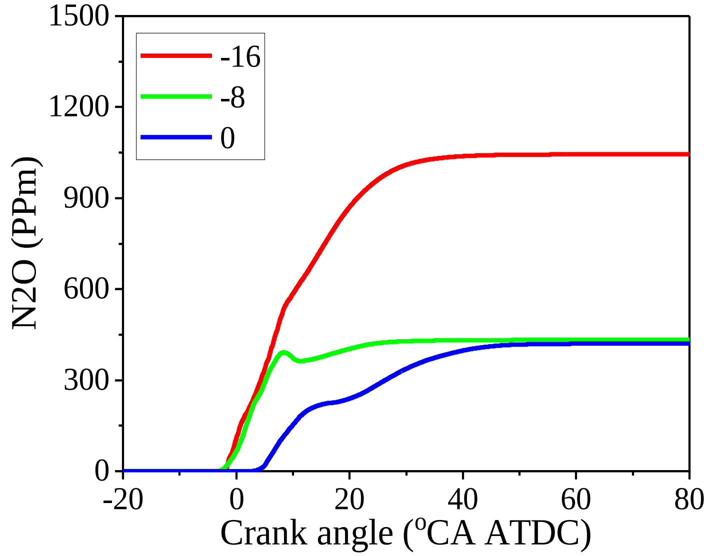


NH3 SOI:-8^{o}CA



NH3 SOI: 0^{o}CA





Major findings – DDFS engine concepts

- Diesel/ammonia interaction
  - Ammonia combustion needs complete engulfment by diesel flame
- NOx emission
  - Thermal NO contributes sustainably to the total NO emission
  - Unburned ammonia can reduce NO
- N2O emission
  - Formed at the flame front
  - N2O is mainly from incomplete combustion in the lean ammonia mixture
- CO emissions
  - CO emission is in general lower in DDFS than in pure diesel case
- DDFS is sensitive to ammonia injection timing

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People. Development. Impact.

Life cycle assessment and cost-benefit analysis of ammonia/hydrogen-driven marine propulsion

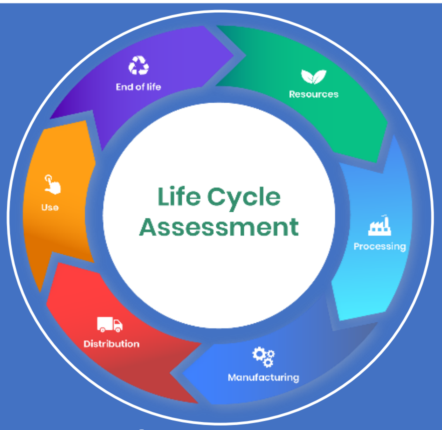
CAHEMA

Concepts of ammonia/hydrogen engines
for marine application

Tuan Dong and Alessandro Schönborn
Maritime Energy Management
World Maritime University

WP4 framework

Environment



Life-cycle assessment

- Air pollutants
- Greenhouse gas emissions

Economic

Economic cost of engines and fuels

Benefit of ammonia/hydrogen engines

Society

Public health benefits of cleaner fuels

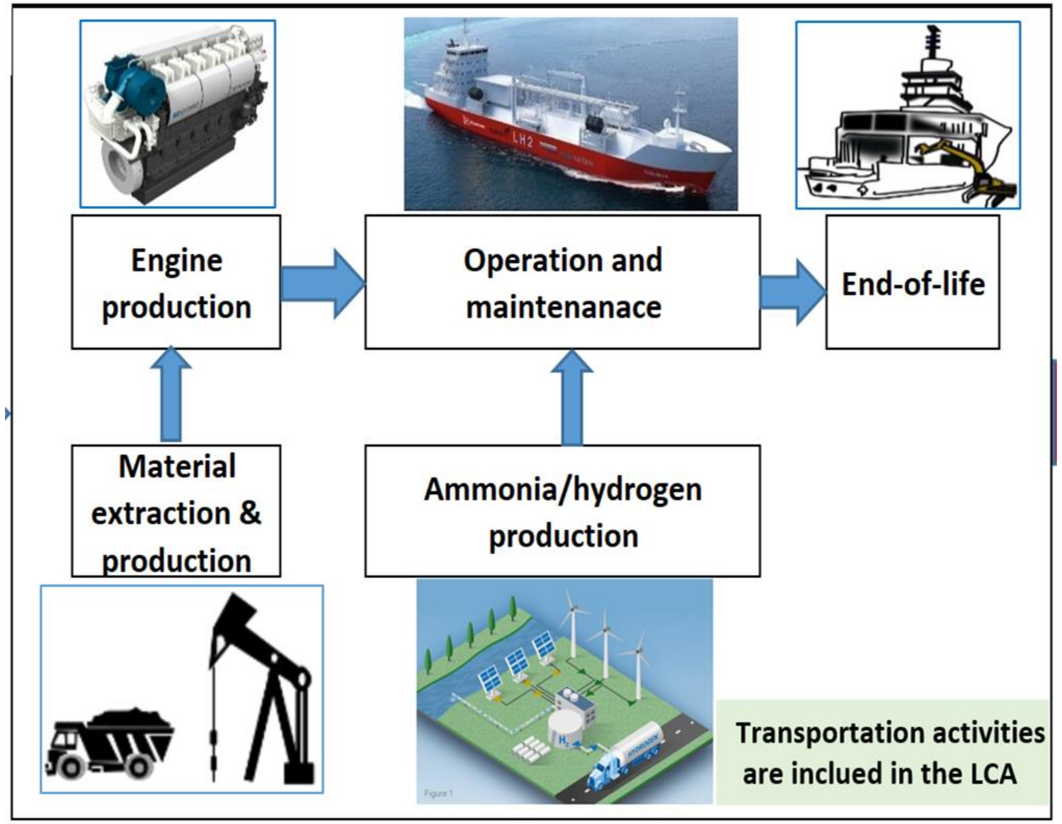
Effects of using ammonia/hydrogen engine on public health

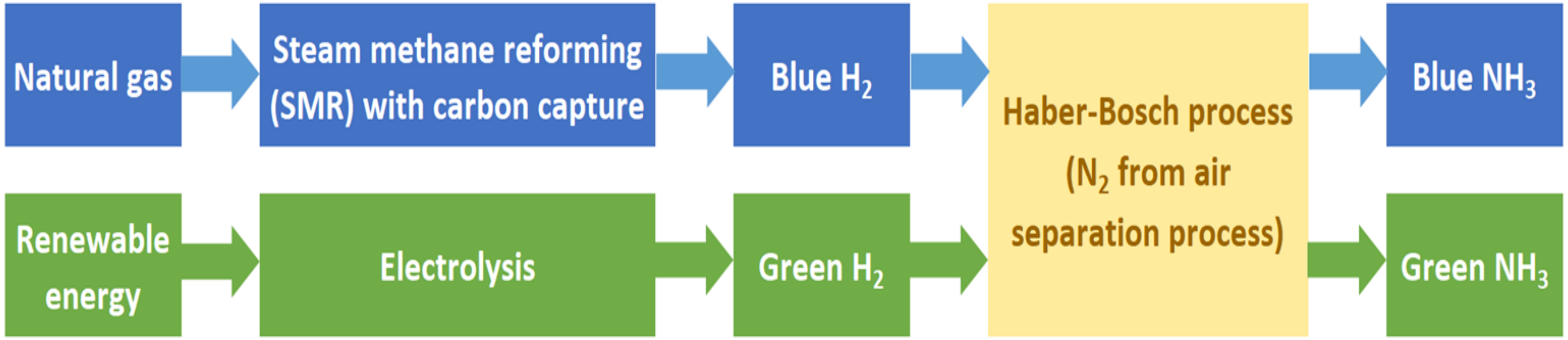
COST BENEFIT ANALYSIS

Environmental - Life cycle assessment (LCA)

- The life cycle phases consist material extraction & production (for marine engines), ammonia/hydrogen production, transportation activities, operation and end-of-life.

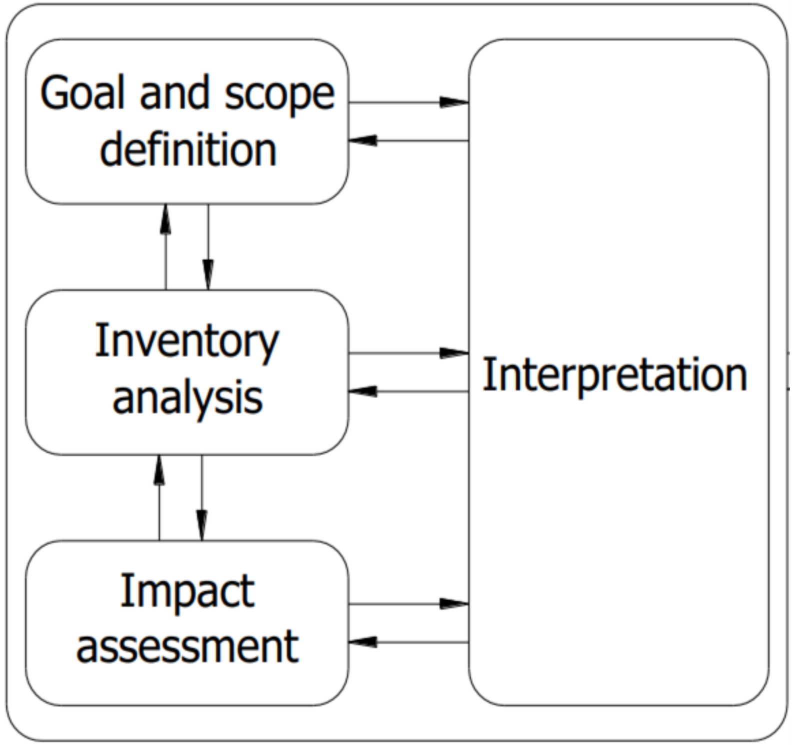
- Ship operation phase dominates the environmental impacts and emissions in the ship's life cycle (more than 94% for global warming potential (GWP).



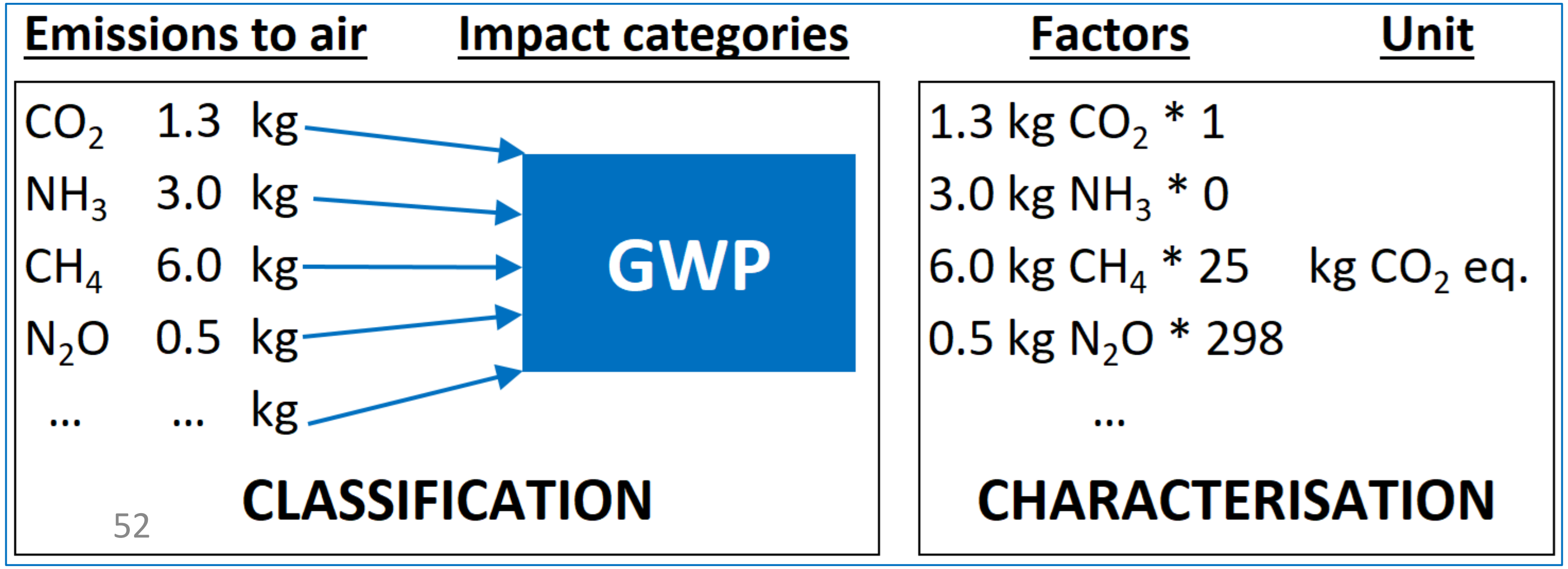


Environmental Life cycle assessment (LCA)

- To evaluate GWP and socio-economic benefits of ammonia/hydrogen engines (for both “green” and “blue” ammonia/hydrogen).
- To recommend for emissions and environmental impacts regulations on the basis of a cost-benefit analysis comparing the economic cost of engine and emissions abatement technologies



LCA framework (ISO 14040, 2006)



LCA - scenarios

Table. Eight scenarios in the study

Scenarios	Items	Unit	MDO	NH3	H2
MDO 2-stroke	Energy contribution	-	100.0%	0.0%	0.0%
	Energy	kWh	1.000	0.000	0.000
	Mass	g	**180.20**	0.00	0.00
NH3 2-stroke	Energy contribution	-	5.0%	95.0%	0.0%
	Energy	kWh	0.050	0.950	0.000
	Mass	g	9.01	392.08	0.00
MDO 4-stroke	Energy contribution	-	100.0%	0.0%	0.0%
	Energy	kWh	1.000	0.000	0.000
	Mass	g	**219.30**	0.00	0.00
NH3 4-stroke	Energy contribution	-	**12.0%**	**88.0%**	0.0%
	Energy	kWh	0.4	0.6	0
	Mass	g	87.72	301.36	0.00
H2 4-stroke	Energy contribution	-	1.5%	0.0%	98.5%
	Energy	kWh	0.015	0.000	0.985
	Mass	g	3.39	0.00	78.98

- *"Blue" and "green" H2 and NH3 are included.*

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LCA – Scope definition & Assumption

- Functional unit: ***grams emission/kWh delivered to the propeller shaft***
- Emissions: CO_2, CH_4, N_2O, NO_X, CO, NMVOC, SO_X, PM10, PM2.5, black carbon, unburned H_2 & NH_3. Environmental indicators: GWP100 & GWP20
- Production site: Yara (Norway) from renewable energy (wind energy)
- Fuel transportation distance: 800 km
- Energy used for liquefaction process: 0.836 kWh/kgNH_3; 10kWh/kgH_2
- Energy used for Haber-Bosch (H-B) process: 1.17 MJ/kgNH_3
- 90% of CO_2 is captured in CCS
- The amount of H_2, NH_3, CO_2 in SMR and H-B process are calculated based on SMR and H-B chemical reaction.
- Vessel's lifespan: 25 years

LCA Database

Tank-to-wake emission factors

- EFs of MDO are taken from IMO's fourth GHG report
- EFs of H2 and NH3 for CO2, CH4, CO, SOX, PM, black carbon are zero
- EFs of N2O, NOX, unburned NH3 & H2 are from literatures.

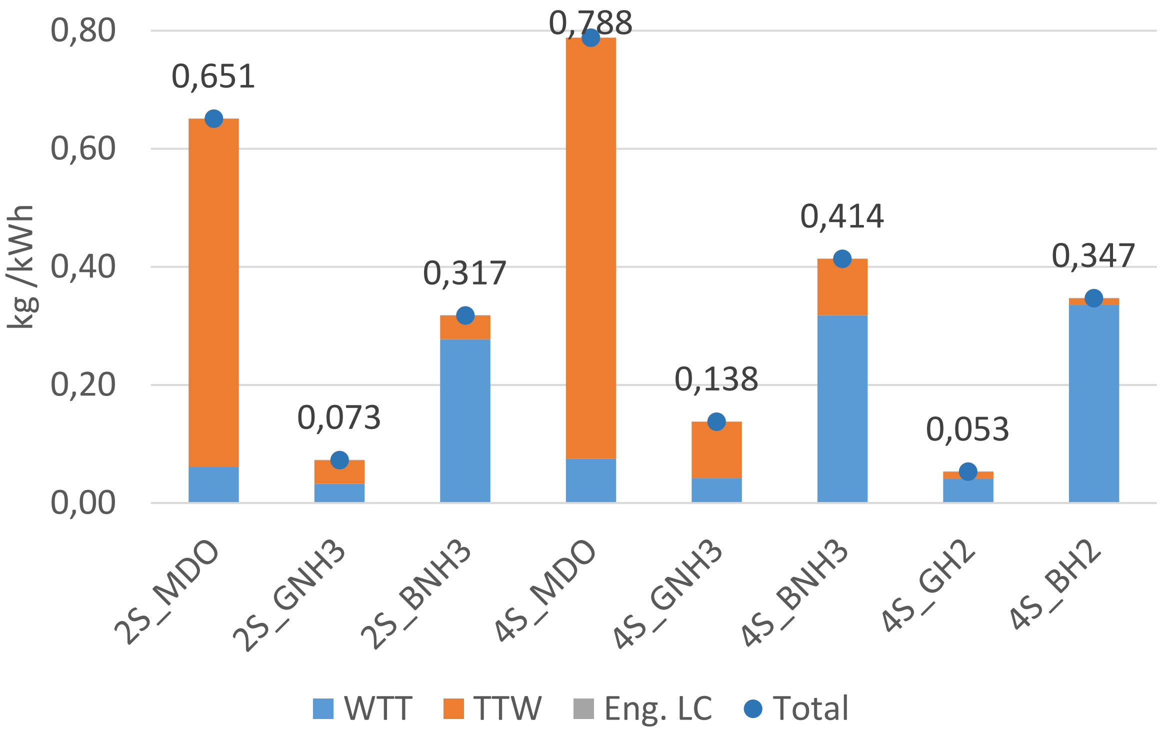
Database and software

- LCA-FE-Sphera
- Database/Data are available in the software and data providers

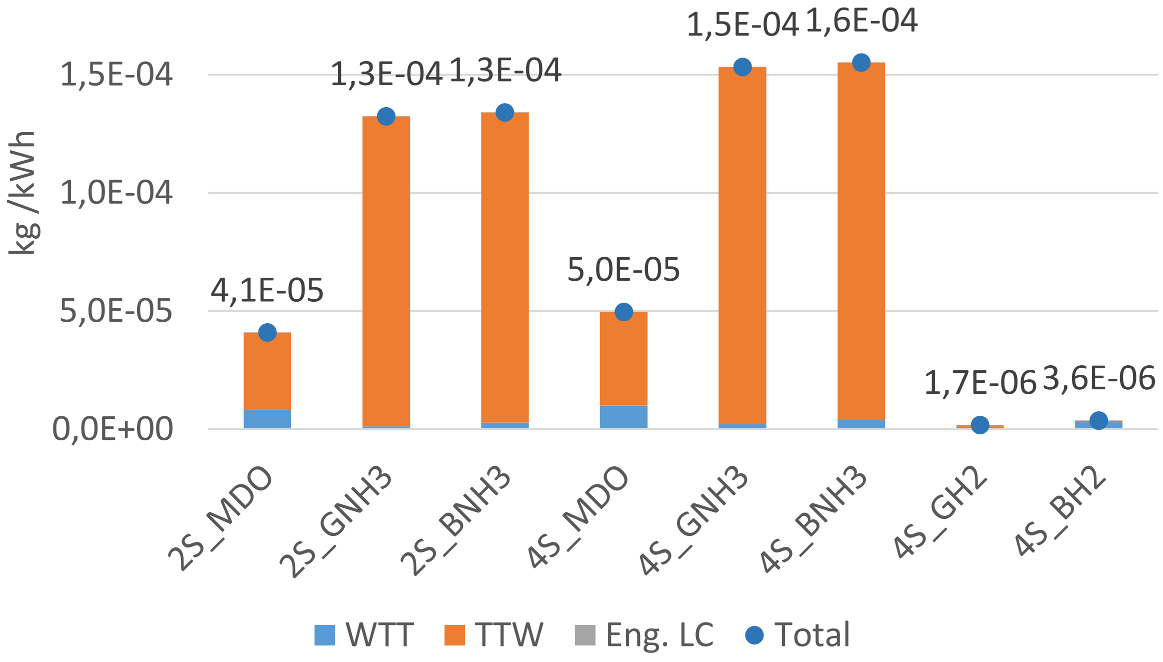
Table. Tank-to-wake emission factors (kg emission/kg fuel)

Emissions	MDO	H2	NH3
CO2	3.20600	0.00000	0.00000
CH4	0.00001	0.00000	0.00000
N2O	0.00018	0.00015	0.00033
NOx	0.05671	0.02333	0.02033
CO	0.00259	0.00000	0.00000
NMVOC	0.00240	0.00000	0.00000
SOX	0.00137	0.00000	0.00000
PM10	0.00090	0.00000	0.00000
PM2.5	0.00083	0.00000	0.00000
Black carbon	0.00038	0.00000	0.00000
H2 slip	0.00000	0.00800	0.00000
NH3 slip	0.00000	0.00000	0.00950

Life cycle emissions – GHG emissions



CO2 emissions

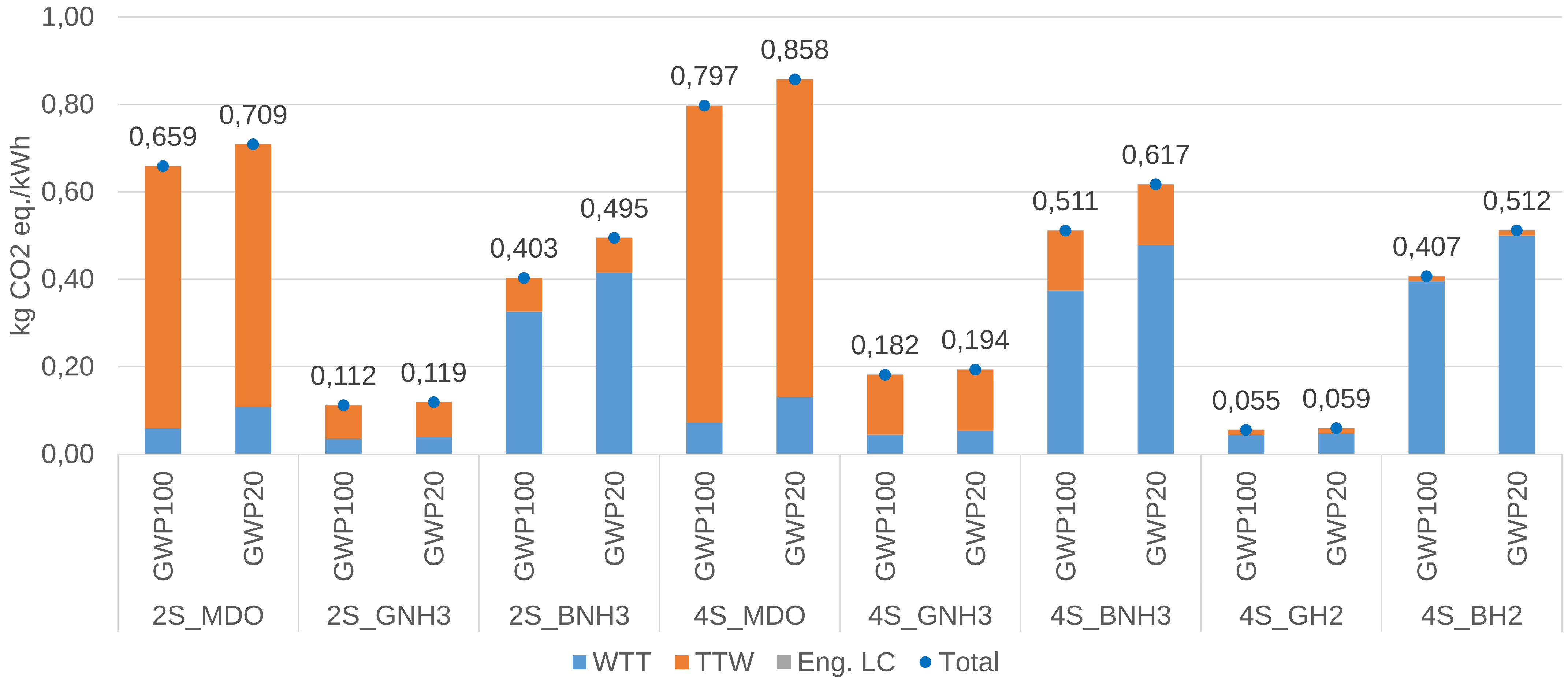


N2O emissions

2S: 2-stroke
4S: 4-stroke
G: green fuel
B: blue fuel
WTT: well-to-tank

WTW: well-to-wake

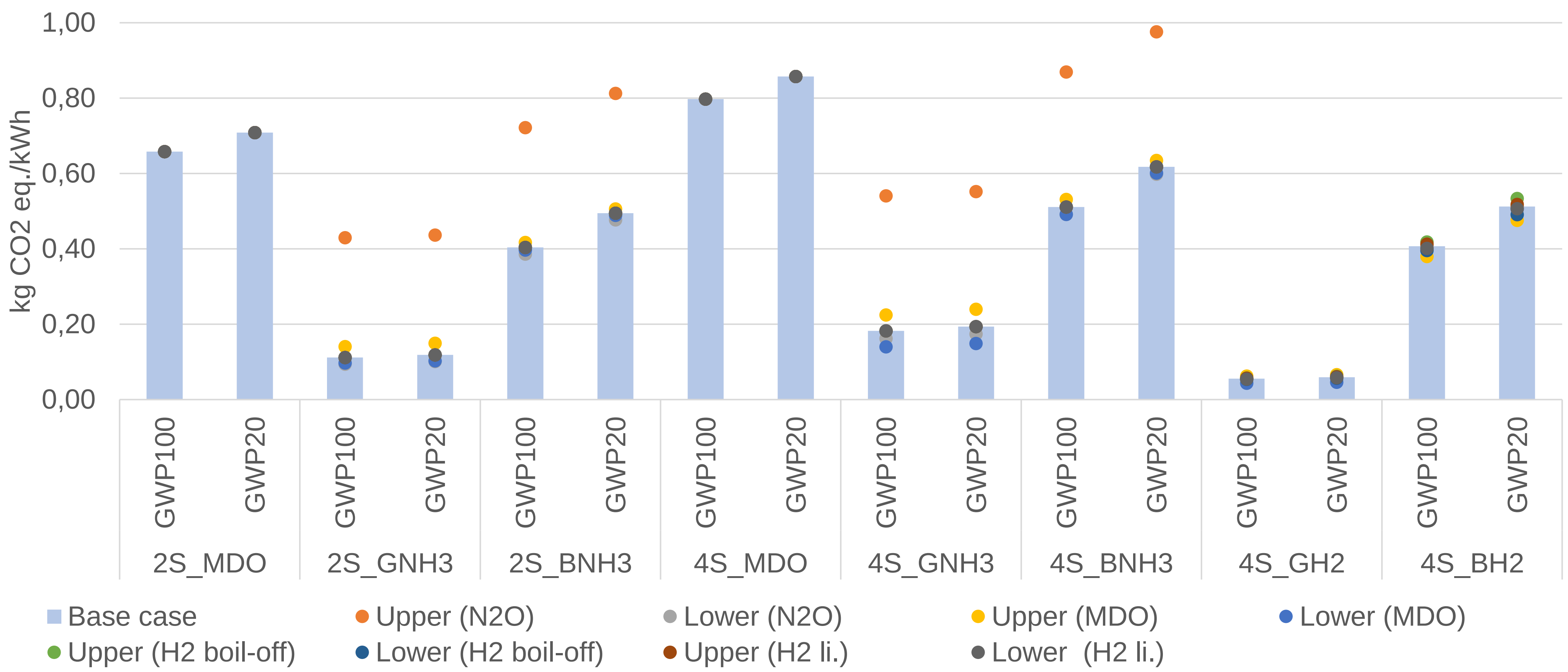
GWP100 & GWP20



2S: 2-stroke
4S: 4-stroke
G: green fuel
B: blue fuel

WTW: well-to-wake

Sensitivity Analysis



2S: 2-stroke
4S: 4-stroke
G: green fuel
B: blue fuel
WTT: well-to-tank

WTW: well-to-wake

LCA - results

Environmental indicators. Units: GWP100 (kg CO2 eq./kWh), GWP20 (kg CO2 eq./kWh), AP (kg SOX eq./kWh), EP (kg phosphate eq./kWh), ODP (kg R11 eq./kWh), POCP (kg ethene eq./kWh)

Scenarios	GWP100	GWP20	AP	EP	POCP
2S_MDO	6.59E-01	7.09E-01	1.15E-03	2.11E-04	1.80E-04
2S_GNH3	1.12E-01	1.19E-01	6.67E-03	1.48E-03	4.21E-05
2S_BNH3	4.03E-01	4.95E-01	6.81E-03	1.54E-03	8.76E-05
4S_MDO	7.97E-01	8.58E-01	1.40E-03	2.54E-04	2.19E-04
4S_GNH3	1.82E-01	1.94E-01	7.62E-03	1.69E-03	6.33E-05
4S_BNH3	5.11E-01	6.17E-01	7.77E-03	1.75E-03	1.15E-04
4S_GH2	5.55E-02	5.94E-02	1.31E-03	2.97E-04	7.14E-05
4S_BH2	4.07E-01	5.12E-01	1.48E-03	3.60E-04	1.26E-04

2S: 2-stroke
4S: 4-stroke
G: green fuel
B: blue fuel
WTT: well-to-tank
TTW: tank-to-wake
WTW: well-to-wake

COST-BENEFIT ANALYSIS

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Method

- **CUMULATIVE COST** includes capital expenditure (CAPEX) and operational expenditure (OPEX)

$$Cumulative\ cost = CAPEX + \sum_{n=1}^{n=25} \frac{OPEX*(1+i)^n}{(1+d)^n}$$

n is the age of the ship from 1 to 25 years, *d* is the discount rate and *r* is the inflation rate

- **CAPEX** is the investment cost

$$CAPEX = (engine\ cost/kW + SCR\ cost/kW) * KW$$

- **OPEX** includes the fuel costs

- **EMISSIONS COSTS**

$$Cm,m',bn,gn,bn',gn',bh,gh = Ec,s,n,p * C'c,s,n,p$$

C are the emission costs. E are the life-cycle emissions per kW. C´ are the emission costs per tonne of emissions

Table. Investment cost (€/kW) Korberg et al. (2021)

Engine type	Fuel	Engine cost/kW
4-stroke (4S)	MDO	240
	NH_3	370
	H_2	470
2-stroke (2S)	MDO	460
	NH_3	600

Table. Fuel prices (€/ton of fuel) (Inal et al., 2022)

Fuel	Fuel price	2036-2050
MDO	550	
Blue NH_3	375	
Green NH_3	750	360
Blue H_2	2200	
Green H_2	5500	2600

Table. Emission costs (Victoria Transport Policy Institute, 2020)

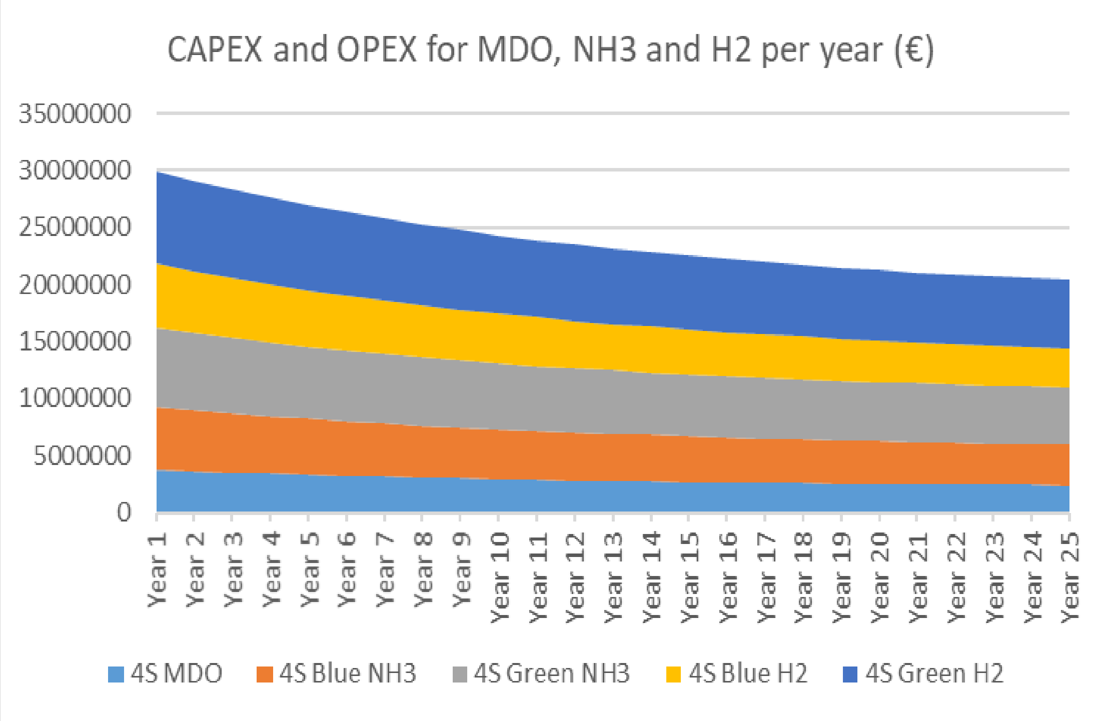
Emissions	**Costs** (€/ton of emission)
CO_2eq.	90
SOX	6500
NOX	4700
PM	2500

Economic cost

- Green hydrogen and ammonia are by far the most expensive fuels with their annual cost decreasing over the years, but still remaining much higher than the cost of MDO and blue hydrogen and ammonia.

- The main reason lies to the high OPEX of green fuels as their price is very high at the moment due to their limited availability and technological maturity for their production.

- Conventional fossil fuels, the employment of hydrogen and ammonia imply additional CAPEX coming from the conversion of existing marine engines



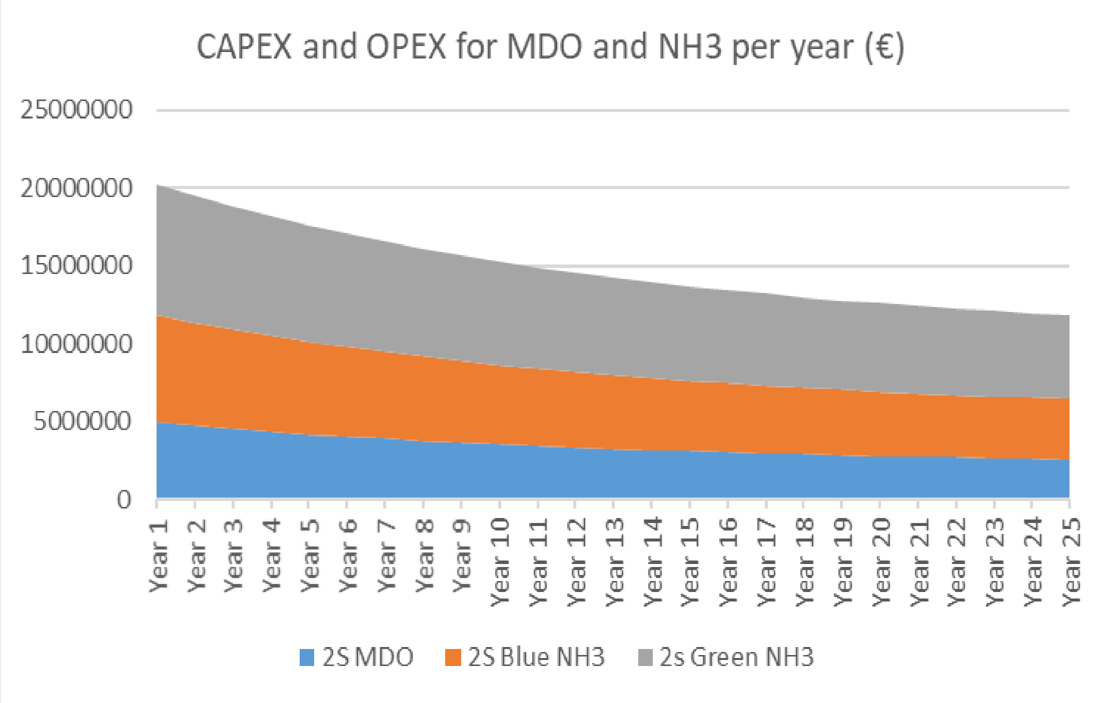


Figure 1: CAPEX and OPEX for different fuels per year (€)

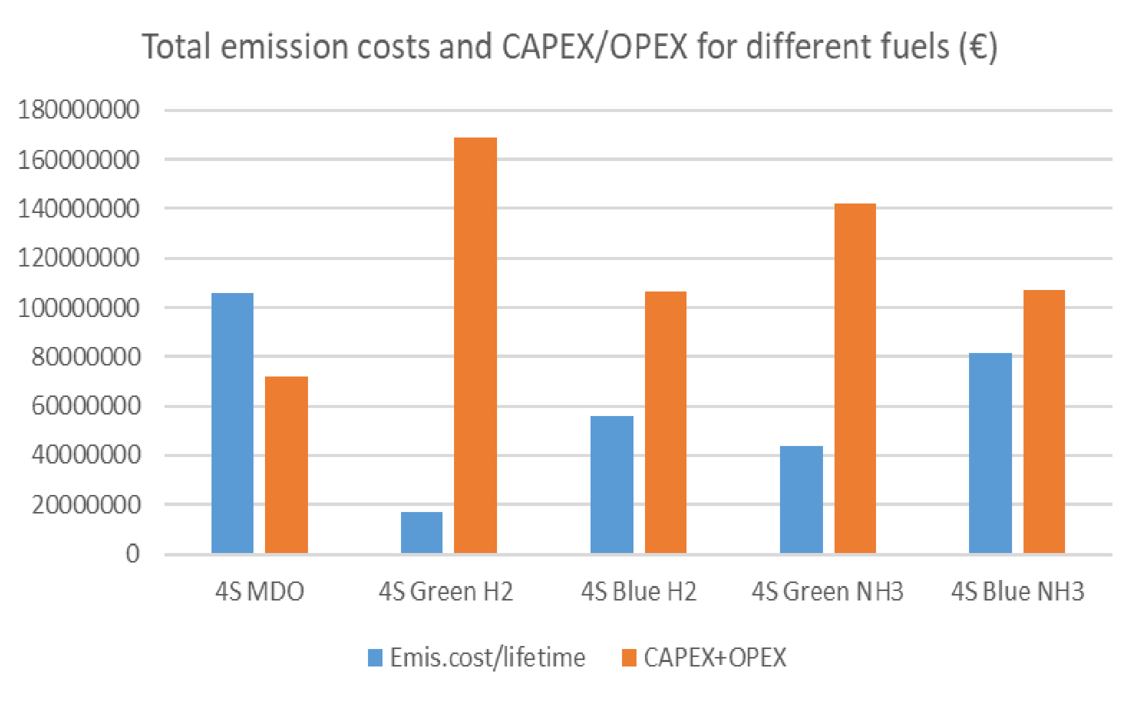
Lifecycle costing

- 4S engines the use of green hydrogen leads to the minimal emissions cost (external cost) compared to all other options accounting for 17 million euros; the most costly option with the total expenditure from its use reaching 170 million euros.

- Green ammonia represents the second best option in terms of external costs (44 million euros), but its use also leads to high CAPEX and OPEX (142 million euros) compared to conventional fuels.

- Blue hydrogen comes third in terms of emissions cost (56 million euros) while blue ammonia comes fourth with an external cost of 81 million euros.

- The use of MDO generates a high external cost of 106 million euros and a low total expenditure of 72 million euros.



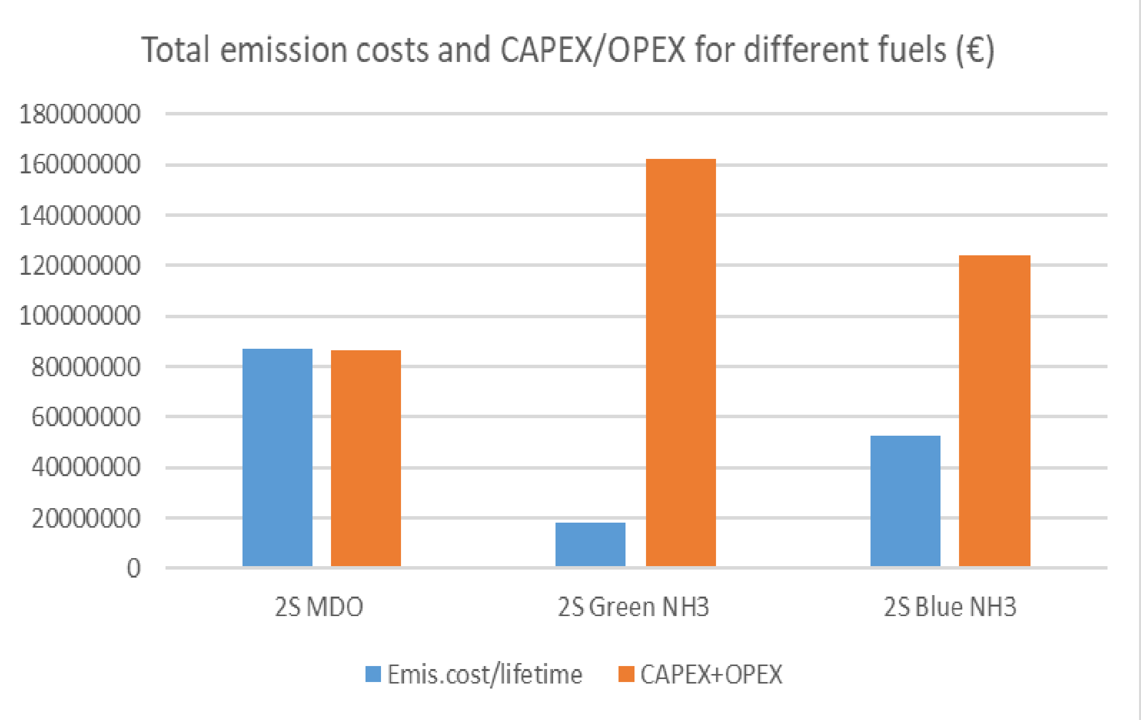


Figure 3: Total emission costs and CAPEX/OPEX for different fuels (€)

Cost-benefit analysis

- The potential of ammonia and hydrogen to decarbonize shipping becomes quite obvious from the analysis undertaken in this research. Their life-cycle GHG emissions are far less than the ones generated from the use of MDO with the relevant external cost from their use also being minimal in comparison to conventional options.
- High total expenditure for their employment also becomes apparent underlining the urgent need to put a cost on GHG emissions to level the playing field for the employment of alternative fuels and accelerate the energy transition of the sector according to the 'polluter pays' principe.

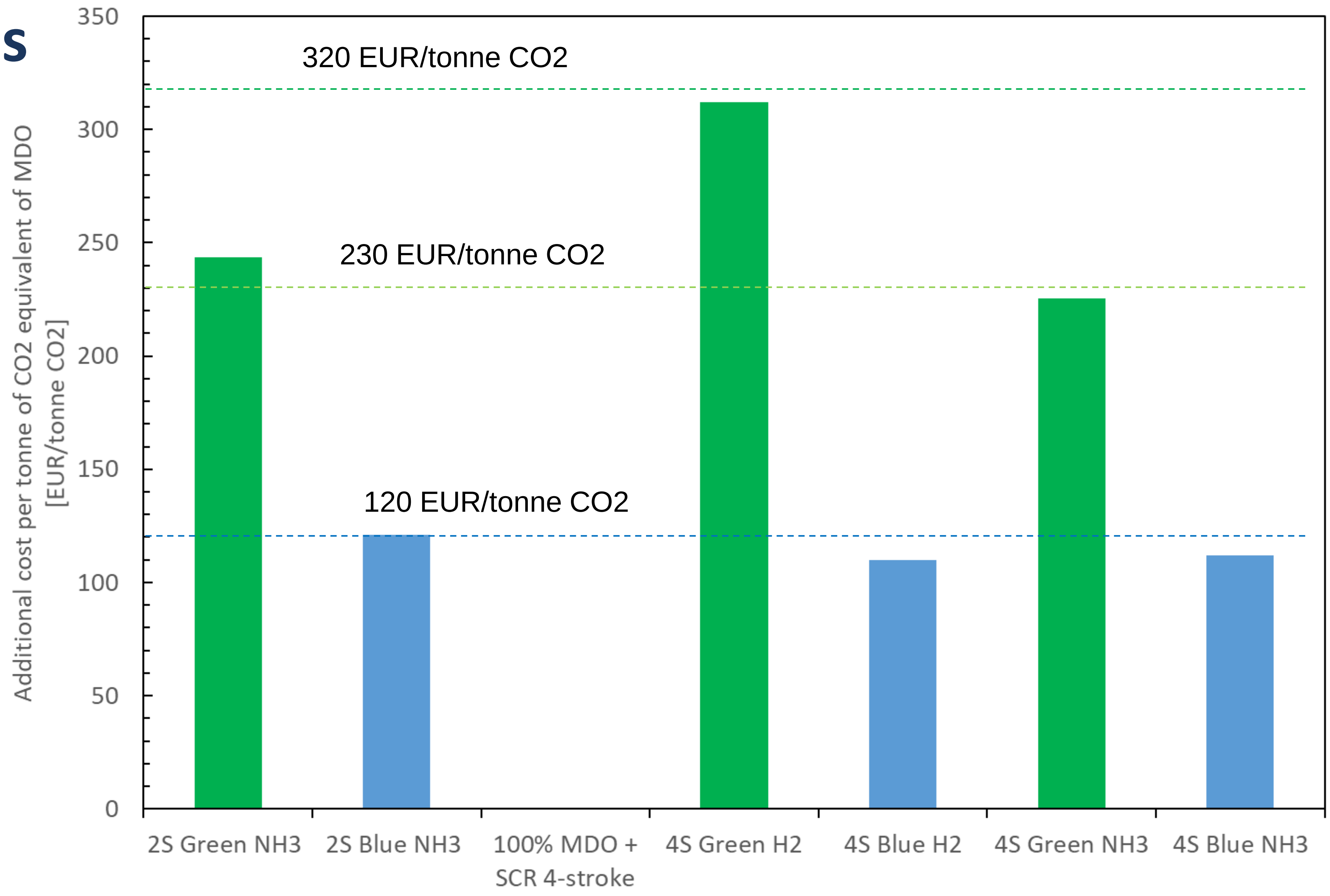


Figure 4: Additional costs per tonne of CO2 equivalent of MDO (€/tonne CO2)

Conclusions and policy implications

- Most emissions come from fuel production and engine operation (fuel use). **The rate of MDO used for pilot injection increases the environmental impacts.**
- **The life-cycle GHG impact of H2 and NH3 is much lower than that of MDO** with the relevant external cost from their use also minimal
- NH3 has higher environmental impacts than H2 (excl. H2 slip), given the higher need for pilot (support) fuel
- The green solutions could significantly reduce emissions more than blue H2 and NH3
- H2 is more suitable for short-voyage and small vessels due to the boil-off
- H2 and NH3 have a higher total expenditure underlining the **urgent need to put a cost on carbon emissions to make alternative fuels competitive and accelerate the energy transition** of the sector.
- Green hydrogen is by far the most costly option as marine fuel followed by green ammonia, blue hydrogen and blue ammonia.
- At the same time, though, the emission costs of green hydrogen (followed by green ammonia) are minimal compared to conventional – and even blue – fuels.
- **The introduction of market-based measures (MBMs) in the form of a global levy on marine fuel or an emissions trading system can internalize the external costs of conventional fuels (at least for the GHG impact) and stimulate the employment of cleaner fuels by applying 'the polluter pays' principle**

https://www.nordicenergy.org/project/cahema/

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