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Clean, green ammonia
engines for maritime

Megawatt Scale Dual-Fuel Compression Ignition Engines Using Premixed Ammonia or Direct In-Cylinder Injection of Liquid Ammonia

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- Introduction
- 3D Dual Fuel Engine Model
- 0/1D Dual Fuel Engine Model
- Summary

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Ammonia as marine fuel

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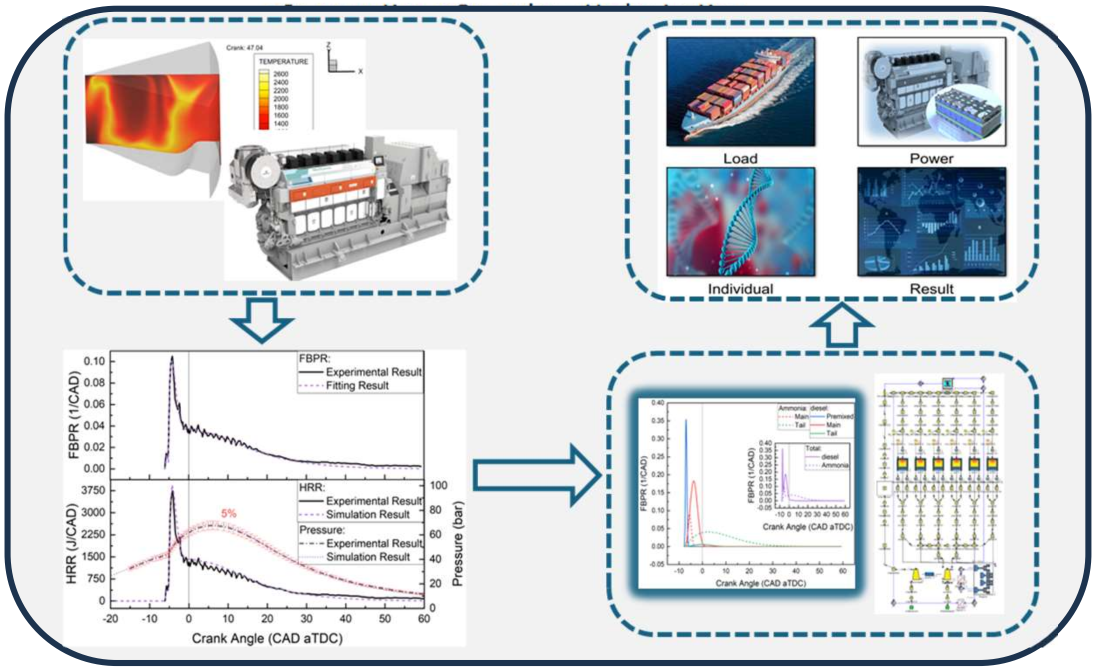
Rationale

- According to DNV's May 2025 report, there are currently three ammonia-fuelled vessels in operation, with more than 30 additional ships on order.
- Accurate engine model and ammonia powertrain case studies underpin decision making of ship owners and operators.
- We are responsible to deliver a new comprehensive ammonia engine model library and various powertrain case studies (WP10) for both research community and industry stakeholders.



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3D
4-stroke
compression ignition
engine model

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Case engine

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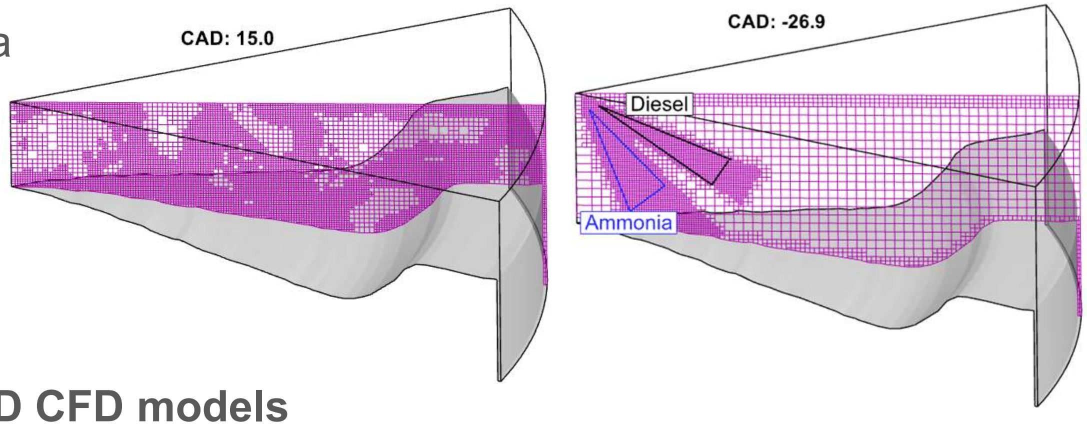
Wärtsilä DF32 Engine, 3.48 MW

- Dual fuel engine retrofit 1 – premixed ammonia
- Dual fuel engine retrofit 2 – direction injection

Bore × Stroke	320 mm × 400 mm
Connecting Rod	848 mm
Compression Ratio	16:1
Number of cylinders	6
Displacement volume	32.2 L/cyl
Cylinder output power	580 kW/cyl
Engine speed	750 rpm
Piston speed	10.0 m/s
Intake valve close	-225 CA aTDC
Exhaust valve open	140 CA aTDC



3D CFD models

- Number of cells 1 million per sector; mesh refinement scale 4.
- Skeletal chemical kinetic mechanism for ammonia/n-heptane combustion (Lund University 2023)

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Premixed ammonia

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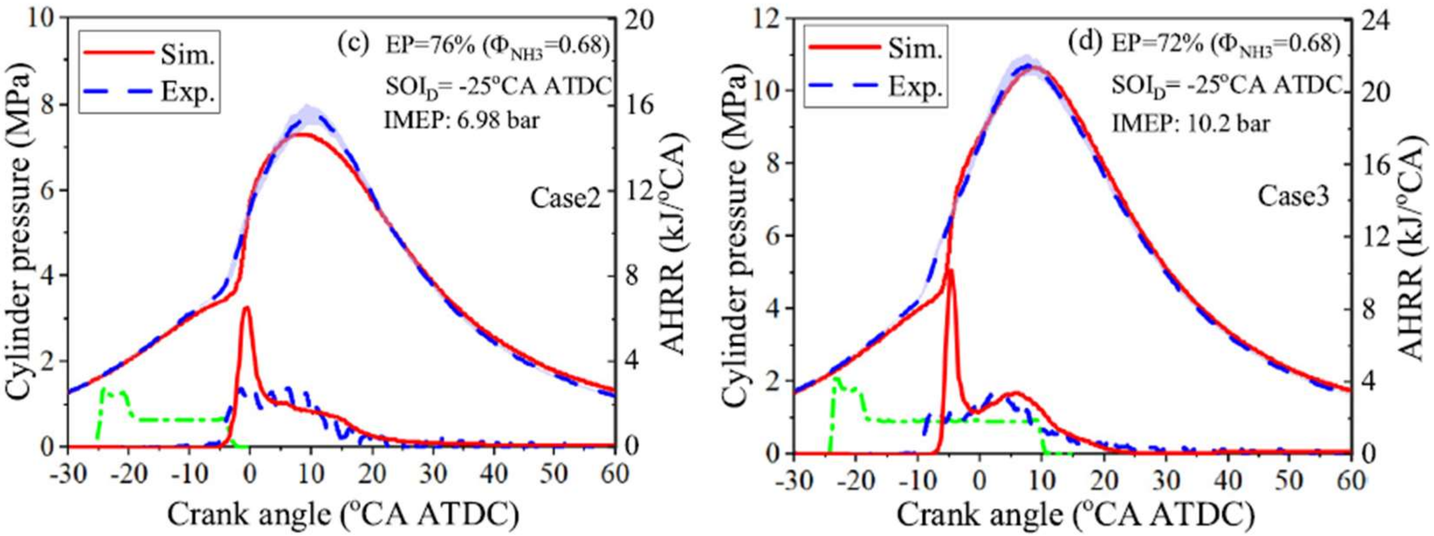
Dual Fuel Engine – premixed NH3

- Early diesel injection (-25 CAD aTDC) to compensate ignition delay of ammonia compared to the methane-diesel benchmarking case (-20 CAD aTDC).
- A second peak of HRR in a long duration due to lower reactivity and slower flame propagation of NH3.

Main fuel	CH4	NH3	NH3
IMEP (bar)	7.4	7.0	10.2
Fuel mass (g/cycle)	1.2/ 0.13	2.8/ 0.35	3.8/ 0.61
Sol_D (CA)	-20	-25	-25
Inj. press. (MPa)	90	150	190
Duration (CA)	16	33	49



Direct injection

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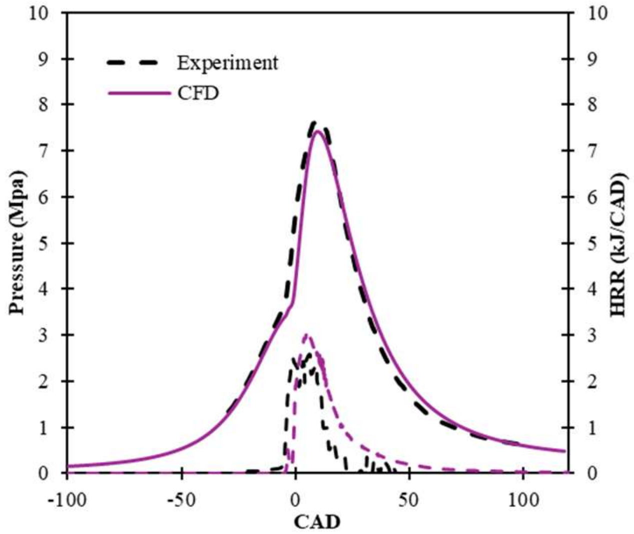
Dual Fuel Engine, direct injection of liquid ammonia

- Impact of energy share ratio of liquid ammonia
- Impact of fuel injection timing

Cases	AES	SOI NH3	m diesel	m NH3	Indicated power
	%	CAD	kg/h	kg/h	kW
1	0	-40	35.17	0.00	182.06
2	25	-40	26.38	20.46	186.83
3	50	-40	17.59	40.91	198.40
4	77	-40	7.90	63.45	198.36
5	77	-50	7.90	63.45	177.72
6	77	-40	7.90	63.45	198.36
7	77	-35	7.90	63.45	193.65
8	77	-30	7.90	63.45	177.59
9	77	-25	7.90	63.45	173.20
10	77	-15	7.90	63.45	151.20



Validation

- CFD results can accurately predicate HRR and in-cylinder pressure with less than 3.36% error.

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Direct injection

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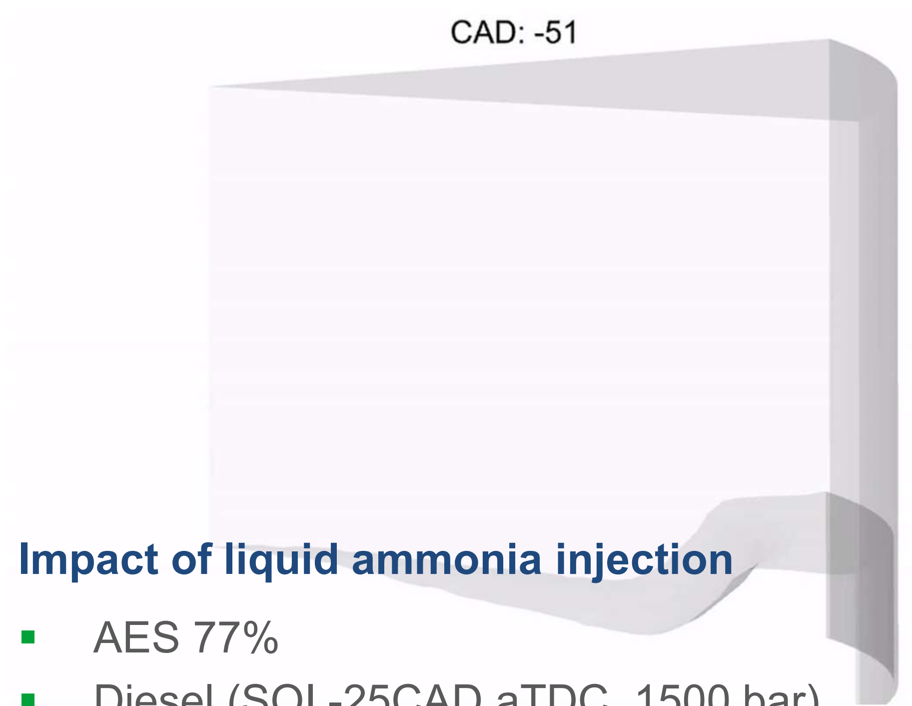
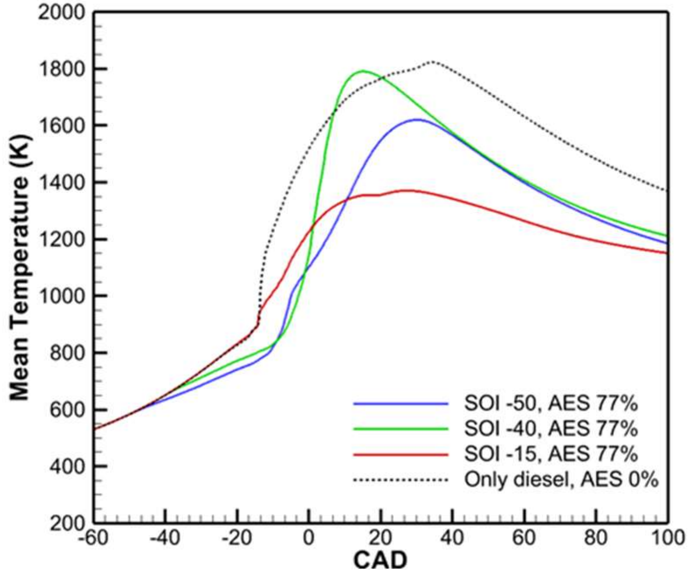


Impact of liquid ammonia injection

- AES 77%
- Diesel (SOI -25CAD aTDC, 1500 bar)
- Ammonia (SOI -40CAD aTDC, 200 bar)

- Ammonia evaporation causes low temperature of the spray and piston crown.
- Early injection reduced compression temperature by more than 125°C.



Direct injection

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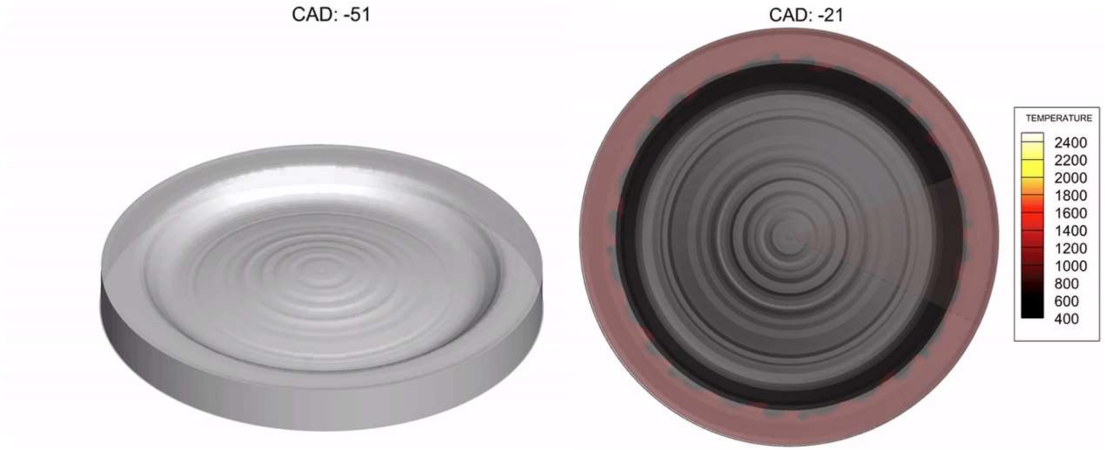
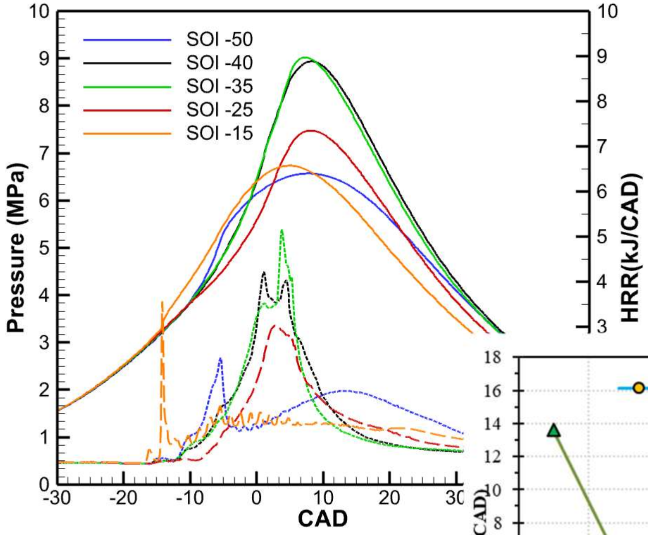
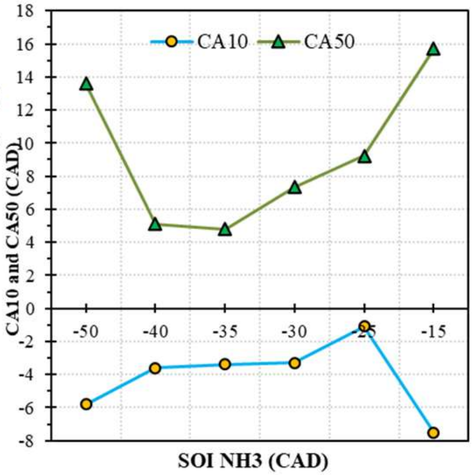
Combustion characteristics

- Late NH3 injection has a prolonged tail combustion.
- Early ammonia injection causes low in-cylinder temperature, late ignition and HRR peak.
- Optimal injection (NH3 SOI -35/40CAD aTDC)







Direct injection

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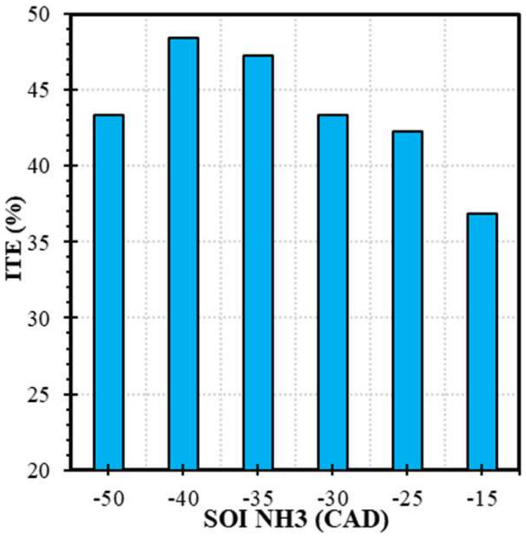
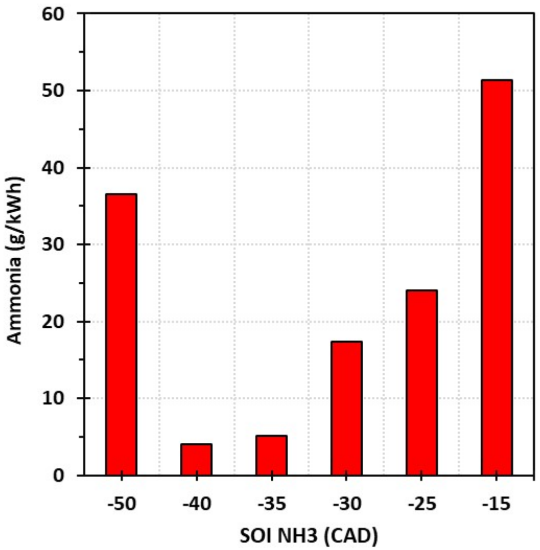
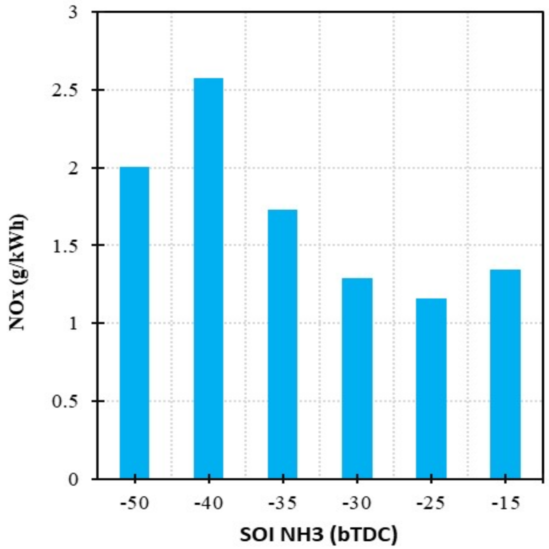
Performance and emissions

- Early (premixed) and late injection of NH3 increased unburn NH3 emission.
- Late injection of ammonia decreases NOx emissions due to decrease in local and peak cylinder temperature.







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Comparison

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Emission result comparison

- Direct injection of liquid ammonia considerably reduced ammonia slip from 10000 to 1638 ppm compared to PFI.
- At optimal injection timings, liquid ammonia reduced the peak of in-cylinder temperature; as a result, NO emissions were reduced considerably.
- Improved combustion also reduce CO emission in direct injection.

	Port injection (Premixed) - Gaseous ammonia	Direct injection - Liquid ammonia
AES	76%	77%
Load percent.	30%	30%
IMEP	6.98 bar	9.8 bar
Sol_diesel	-25 CAD aTDC	-15 CAD aTDC
Sol_NH3	-	-40 CAD aTDC
CO	3318 ppm	584 ppm
NO	2000 ppm	583 ppm
NO2	50 ppm	100 ppm
NH3	10000 ppm	1638 ppm

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0/1-D
4-stroke compression ignition engine model

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0/1-D 4-stroke CI engine model

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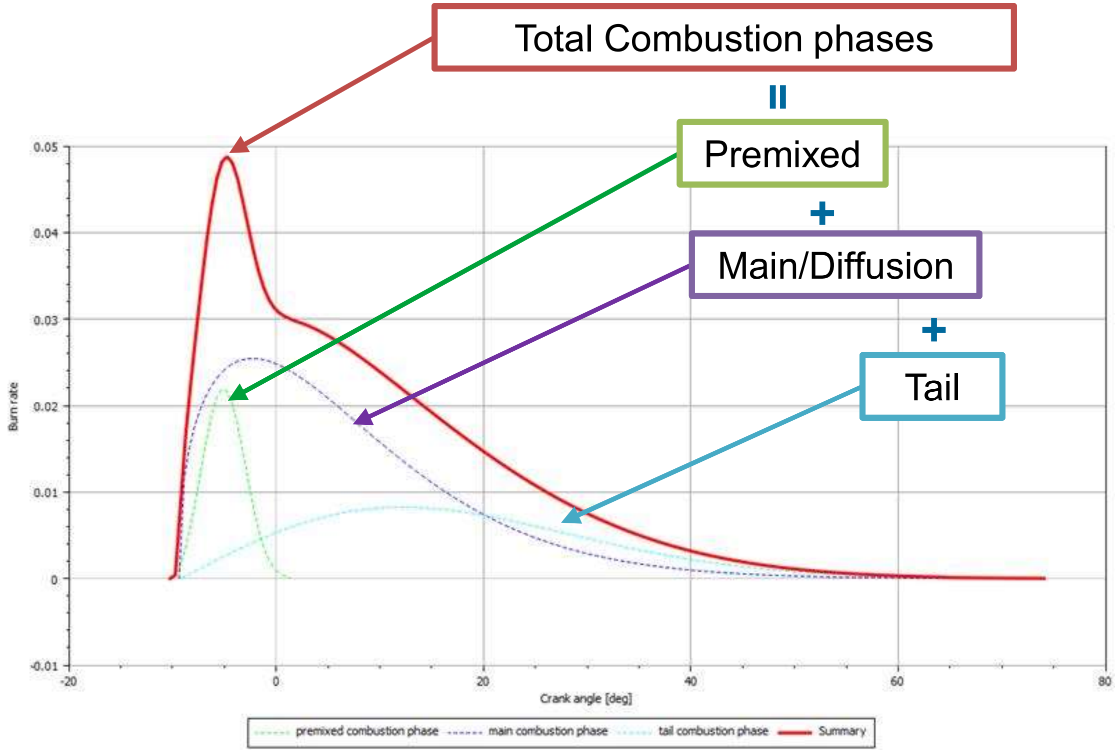
- **Multi-Wiebe combustion (MWC) model**

A fast and cost-effective approach for engine development and system integration.

Capture the heat release characteristics of combustion

$$x_b(\theta) = \sum_i^n C_i \left(1 - \exp\left(-a_i \left(\frac{\theta - \theta_{0,i}}{\Delta\theta_i} \right)^{m_i+1} \right) \right)$$

1. Start of Combustion / Ignition Delay
2. Combustion Fraction
3. Combustion Duration
4. Combustion Quality



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0/1-D 4-stroke CI engine model

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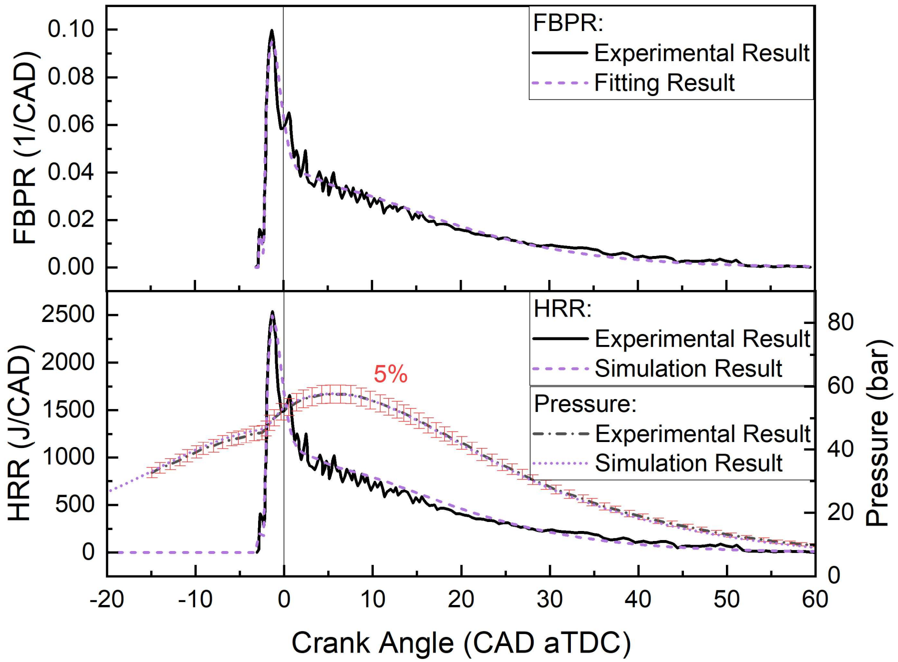
- **MWC model for ammonia-diesel dual-fuel engine**

1. Premixed ammonia + direct injection of diesel: 15 Wiebe parameters
2. Direct injection of ammonia + direct injection of diesel: 18 Wiebe parameters

⇩

Non-dominated Sorting Genetic Algorithm II (NSGA-II) assisted to find the optimal solution of Wiebe parameters



Comparison of FBPR, HRR and pressure among experimental results, simulation results and fitting results

Premixed ammonia

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- **Change SOI_{diesel}: ignition delay**

SOI of diesel from -20 CAD aTDC to -10 CAD aTDC:

1. Reduced the ignition delay of both diesel and ammonia by more than 42%
2. Reduced the gap between the SOC of diesel and ammonia.

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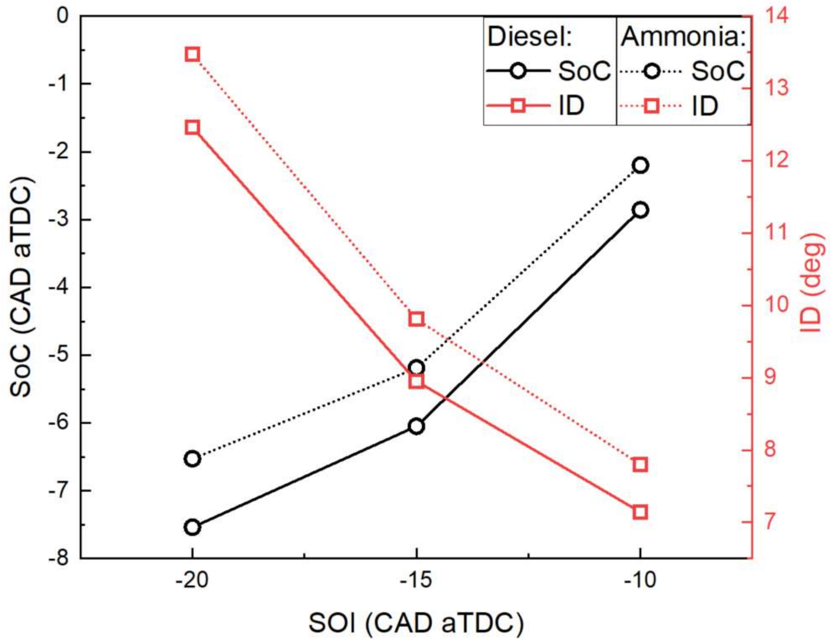
Ammonia ignites faster when the SOI of diesel is delayed.



SOC and ID of ammonia and diesel under varying SOI of diesel (SOI of ammonia = -350 CAD aTDC, Energy share ratio of ammonia = 91.85%)

Premixed ammonia

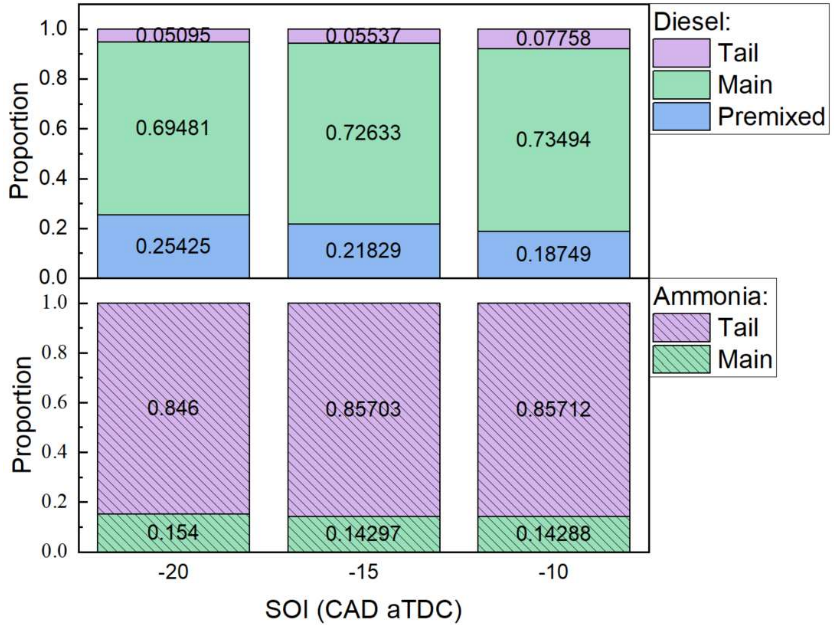
- **Change SOI_{diesel}: fuel burned proportion**

SOI of diesel from -20 CAD aTDC to -10 CAD aTDC:

1. Weakened the main combustion of ammonia while enhancing its tail combustion phase.

⇩

More percent of ammonia burned near the end of combustion when SOI of diesel is delayed.



Fuel burned proportion of ammonia and diesel under varying SOI of diesel (SOI of ammonia = -350 CAD aTDC, Energy share ratio of ammonia = 91.85%)

Premixed ammonia

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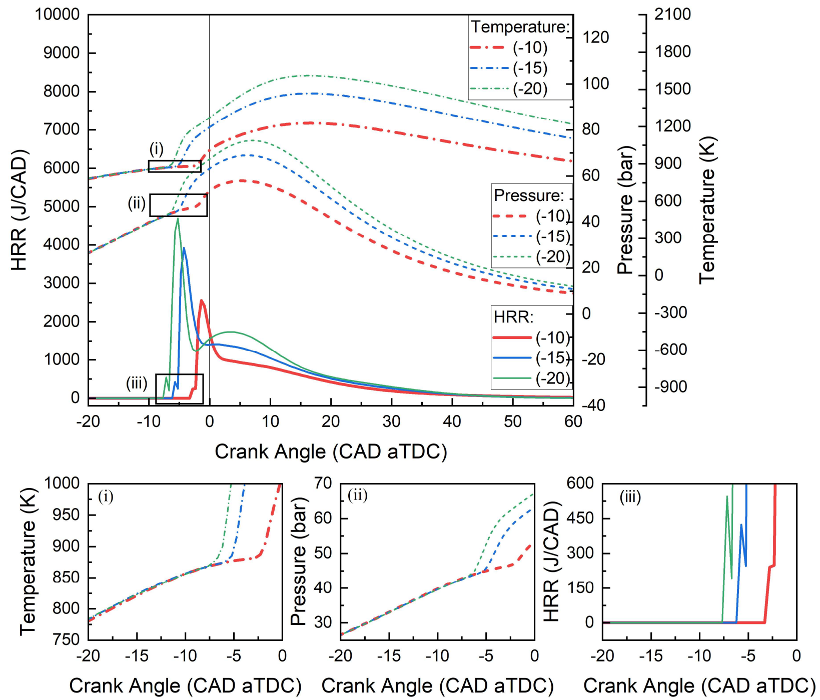
- **Change SOI$_{diesel}$: temperature, pressure and HRR**

SOI of diesel from -20 CAD aTDC to -10 CAD aTDC:

1. Lower in-cylinder pressure, temperature and HRR.

⇩

Lower efficiency, higher unburned ammonia when SOI of diesel is delayed.



Temperature, pressure and HRR under varying SOI of diesel
(SOI of ammonia = -350 CAD aTDC, Energy share ratio of ammonia = 91.85%)

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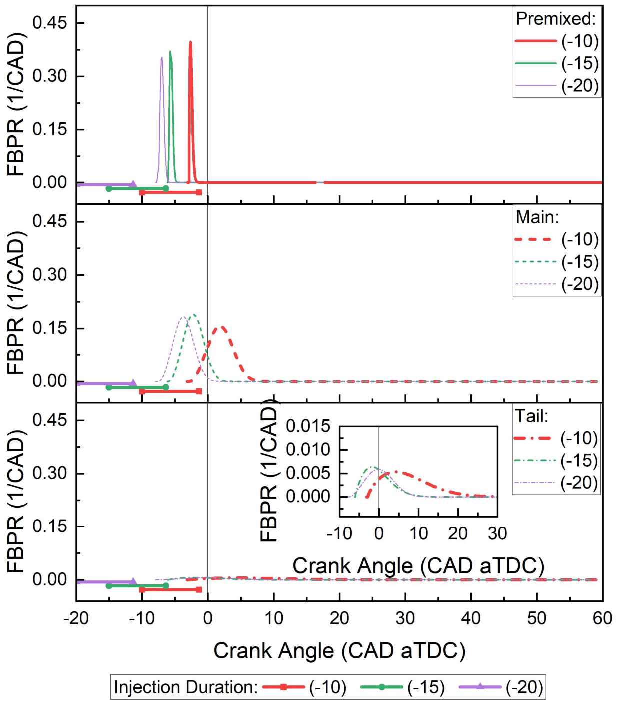
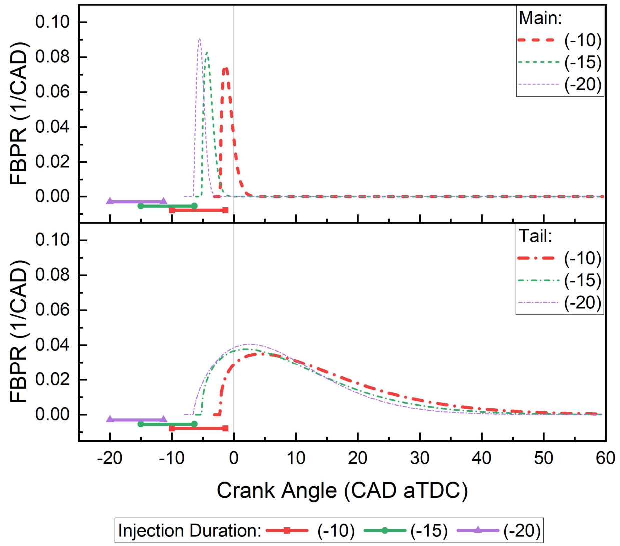
Premixed ammonia

- **Change SOI_{diesel}: Wiebe combustion curves**

Ammonia main combustion was weakened and more ammonia was burned near the end of combustion

Cause higher heat exhaust loss





Combustion curves of diesel and ammonia across various SOIs during the premixed, main, and tail combustion phases (SOI of ammonia = -350 CAD aTDC, Energy share ratio of ammonia = 91.85%)

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Direct injection of ammonia

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- **SOI_{diesel} = $SOI_{ammonia}$: ignition delay**

SOI from -17.5 CAD aTDC to -10 CAD aTDC:

1. Reduced the ignition delay of both diesel and ammonia, especially for diesel
2. Increased the gap between the SOC of diesel and ammonia.

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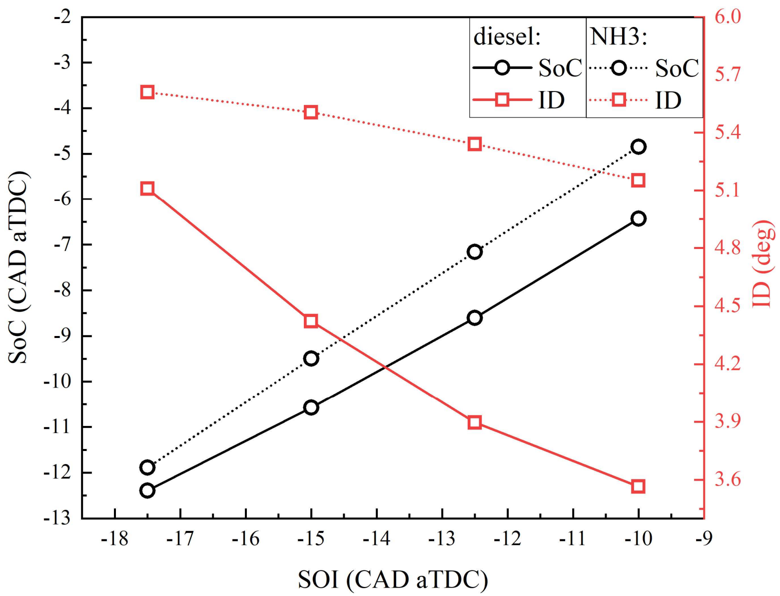
Ammonia ignites slower when the SOI is delayed.



SOC and ID of ammonia and diesel under varying SOI of diesel
(SOI of ammonia = SOI of diesel, Energy share ratio of ammonia = 40%)

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Direct injection of ammonia

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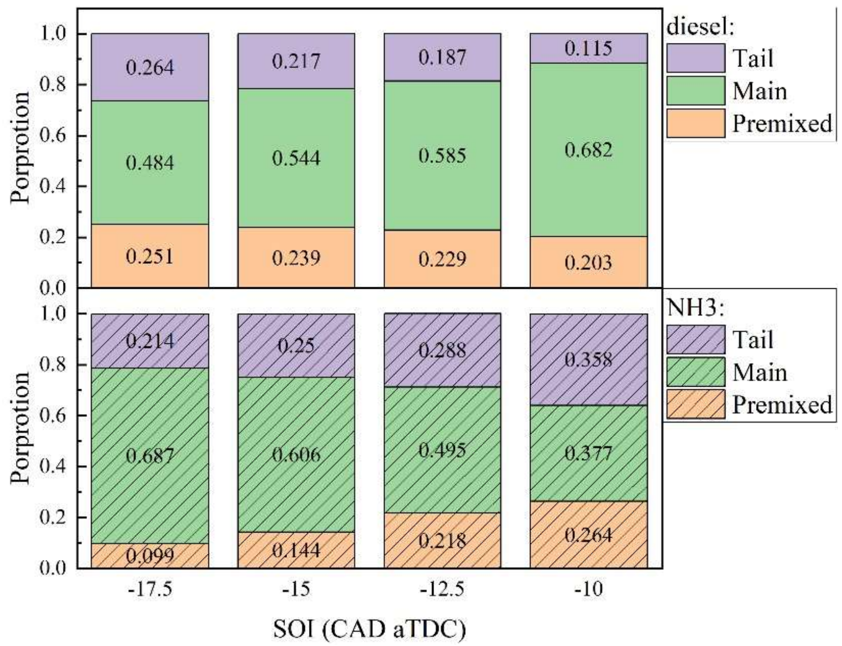
- **$SOI_{diesel} = SOI_{ammonia}$: fuel burned proportion**

SOI from -17.5 CAD aTDC to -10 CAD aTDC:

1. Weakened the main combustion of ammonia while enhancing its premixed and tail combustion phase.

⇩

More percent of ammonia burned near the start and end of combustion when the SOI is delayed.



Fuel burned proportion of ammonia and diesel under varying SOI of diesel
(SOI of ammonia = SOI of diesel, Energy share ratio of ammonia = 40%)

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Direct injection of ammonia

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- **SOI_{diesel} = $SOI_{ammonia}$: temperature, pressure and HRR**

SOI from -17.5 CAD aTDC to -10 CAD aTDC:

1. Lower in-cylinder pressure and higher HRR.
2. Drop of temperature at the SOC of combustion

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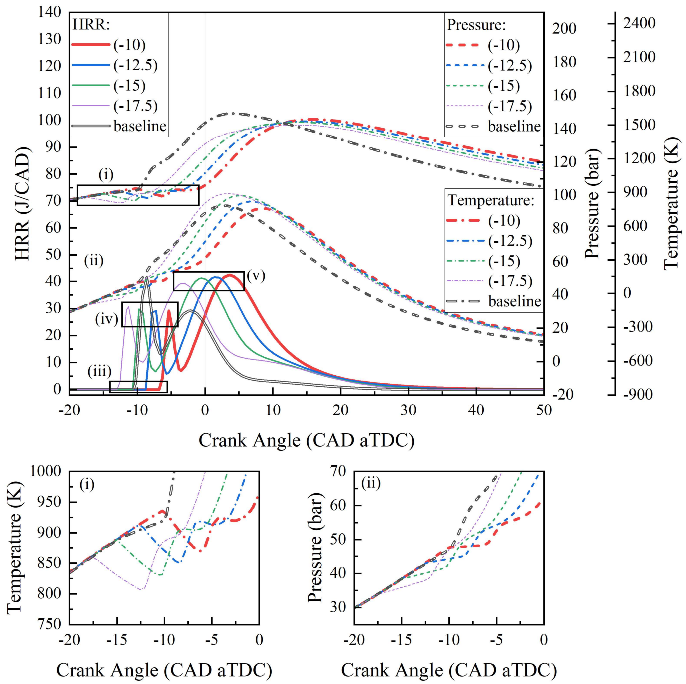
Vaporization of liquid ammonia causes a drop of the in-cylinder temperature.



Temperature, pressure and HRR under varying SOI of diesel
(SOI of ammonia = SOI of diesel, Energy share ratio of ammonia = 40%)

Direct injection of ammonia

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- **SOI_{diesel} = $SOI_{ammonia}$: Wiebe combustion curves**

1. Ammonia main combustion was weakened when the SOI is delayed

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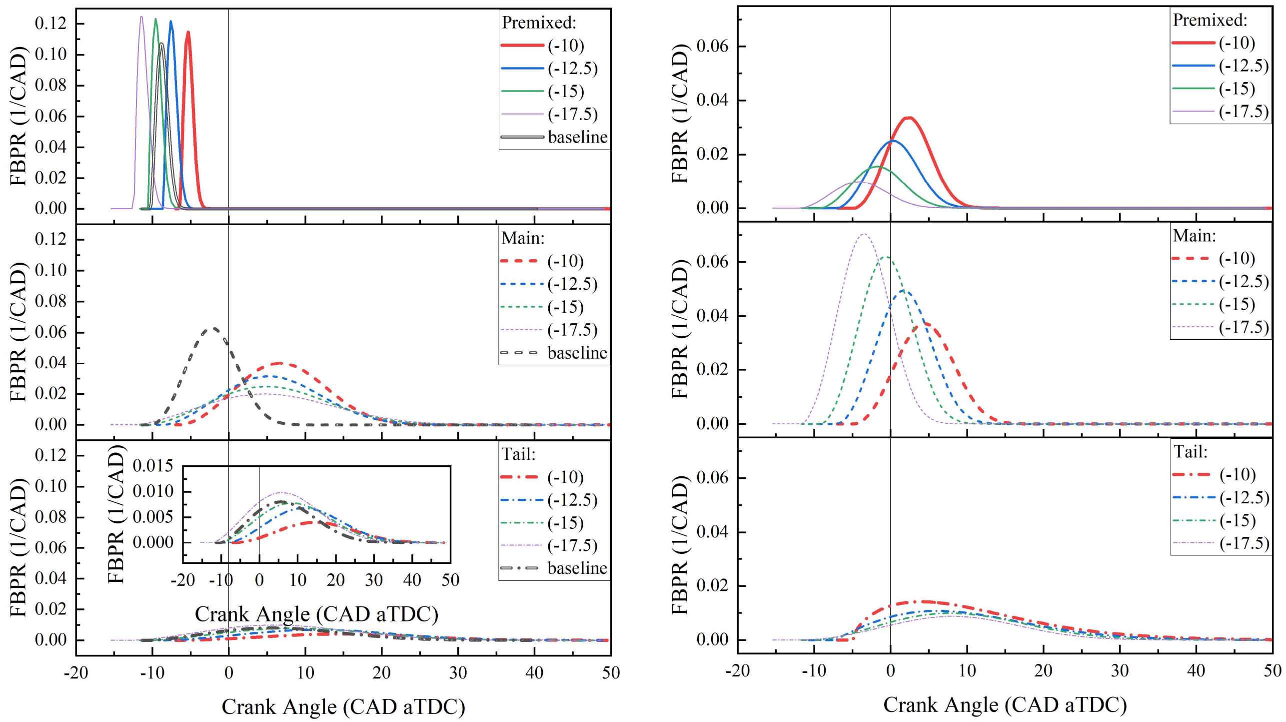
Balance the fuel combustion percent and the fuel combustion timing to get the best efficiency.



(a) Diesel (b) ammonia

Combustion curves of diesel and ammonia across various SOIs during the premixed, main, and tail combustion phases (SOI of ammonia = SOI of diesel, Energy share ratio of ammonia = 40%)

Direct injection of ammonia

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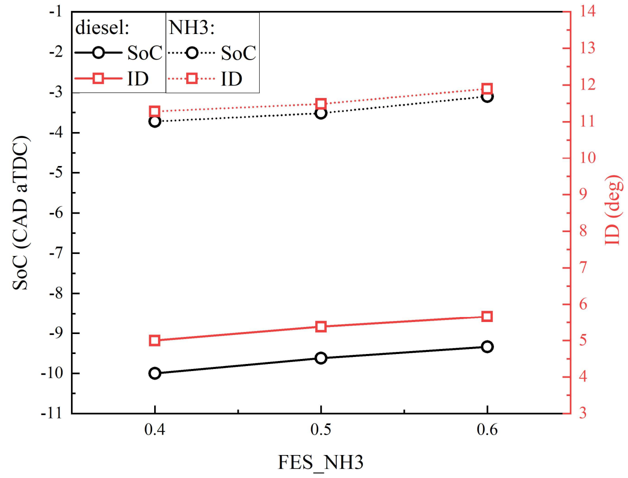
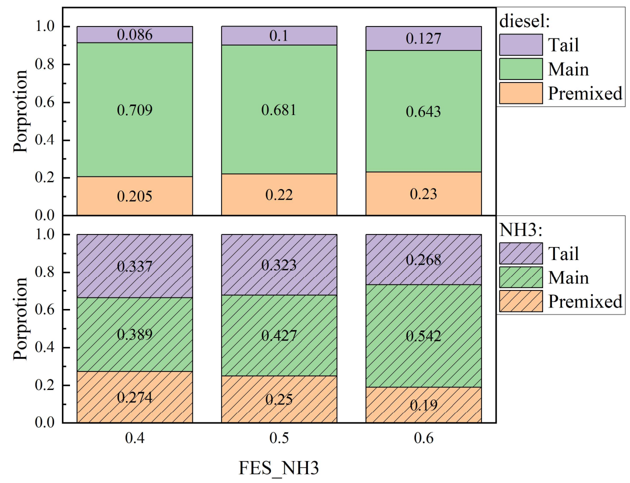
- **Change energy share ratio of ammonia**

Energy share ratio of ammonia from 40% to 60%:

1. Increased ignition delay of both diesel and ammonia
2. Weakened ammonia premixed combustion while enhancing ammonia main combustion





SOC, ID and fuel burned proportion of ammonia and diesel under varying energy share ratio of ammonia (SOI of ammonia = -20 CAD aTDC, SOI of diesel = -15 CAD aTDC)

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Publications

1. 0/D Simulation research on MW scale direct-injection ammonia-diesel dual fuel engines
   - Genetic algorithm-assisted multi-objective optimization for developing a Multi-Wiebe Combustion model in ammonia-diesel dual fuel engines, ***Energy***, doi.org/10.1016/j.energy.2025.136181
   - MW scale premixed ammonia-diesel dual fuel engine study was presented at ***CIMAC 2025***.
2. Hybrid marine powertrain system fuelled with ammonia.
   - Ammonia-fuelled hybrid marine powertrains study has been accepted by ***ECCE Europe 2025***.【*IEEE Energy Conversion Congress& EXPO (ECCE)】
   - Integration of Alternative Fuels in Deep-Sea Shipping study has been accepted by ***APEN-Disco HIS 2025***.【The 1st Applied Energy Discovery Workshop on System integration of Hydrogen】

Ammonia powertrains

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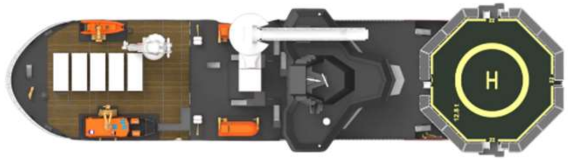
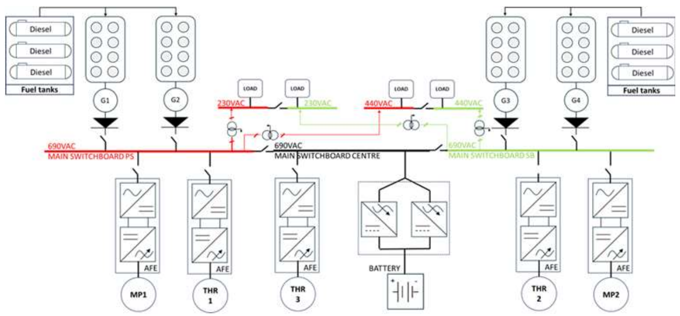
Case studies

- Neo-Panamax Containership – 42 MW
- Offshore wind farm Service Operation Vessel (SOV) – 5 MW

Ship Technical Details
Neo-Panamax Containership
12,000 TEU
132,000 DWT

Base Case	NH3-ICE	NH3-FC
2 stroke main engine 42,000 kWh MCR 4 stroke auxiliary engines 2 x 4,000 kWh 2 x 3,500 kWh	Matching the base case powertrain	Solid oxide fuel cells 57,000kWh combined generation
IFO-380 fuel oil	Blue ammonia IFO-380 pilot fuel (5% MCR)	Blue ammonia





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