Methanol & Hydrogen combustion in marine diesel engines

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X MARITIME SAFETY RESEARCH CENTER

GREATER CHALLENGE

UNITED NATIONS PARIS CLIMATE AGREEMENT SIGNING CEREMONY 22 APRIL 2016

IMO

CO_2 emissions

- **40%** ↓ by 2030
- **0%** ↓ by 2050

INDICATORS →

Carbon Intensity Index

$$CII = \frac{FC \times EF_{CO_2}}{d \times dwt}$$

Energy Efficiency Design Index

$$EEDI = \frac{Power\ Installed \times sfc \times EF_{CO_2}}{Capacity \times Speed}$$

GREATER CHALLENGE

From Conventional

	CO_2 EF
HFO:	3.11 $\frac{g_{CO_2}}{g_{fuel}}$
MDO:	3.20 $\frac{g_{CO_2}}{g_{fuel}}$

To Alternative

Potential renewable production

	CO_2 EF
H_2:	0 $\frac{g_{CO_2}}{g_{fuel}}$
NH_3:	0 $\frac{g_{CO_2}}{g_{fuel}}$
CH_3OH:	1.37 $\frac{g_{CO_2}}{g_{fuel}}$
LNG:	2.75 $\frac{g_{CO_2}}{g_{fuel}}$

Medium-Long term solution

Short term solution

METHANOL CHALLENGES

- High auto-ignition temperature, resulting to enormous CR needed.
- Increased Toxicity.
- Increased storage tank capacity comparing to diesel but still less than other alternative fuels.
- Updated regulatory framework.
- It has lower kinematic viscosity than diesel, so lubrication additives have to be used with methanol.
- Safety precautions due to low flammability.

HYDROGEN CHALLENGES

- Current production methods are very energy intensive.
- For compressed liquid storage, requires 10 times more space than diesel.
- Explosion risk of high-pressure hydrogen tank.
- Low flammability

According to Literature:

**for heavy-duty diesel-H_2 dual fuel engines*

-Higher burning rate → Increased in-cylinder P

-Lower CR, leaner mixtures, injection timing → Knock mitigation

-Longer combustion duration

-While CO and HC reduce significantly, high T is required → Increased NOx

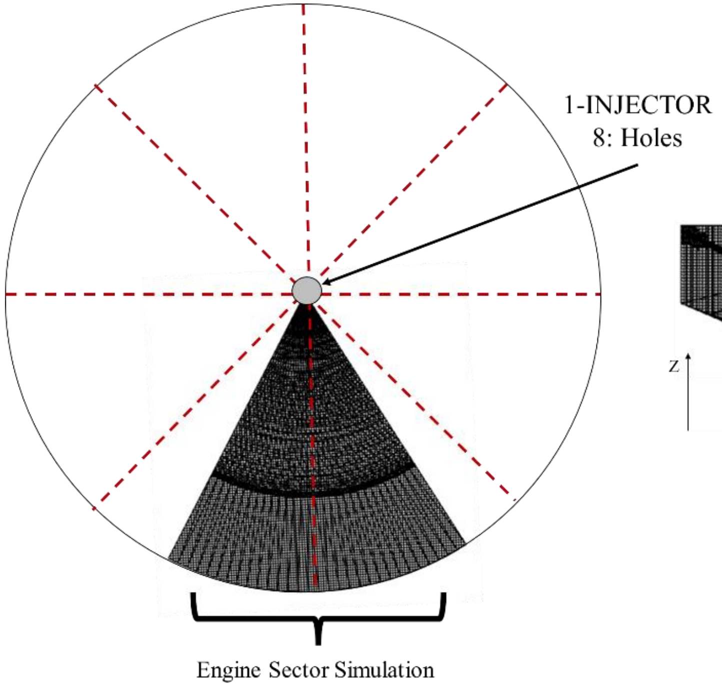
Dimitriou, P., & Tsujimura, T. (2017). A review of hydrogen as a compression ignition engine fuel. *International Journal of Hydrogen Energy*, *42*(38), 24470-24486

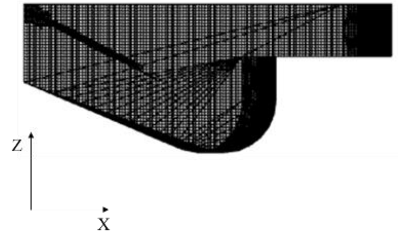
Kumar, V., Gupta, D., & Kumar, N. (2015). Hydrogen use in internal combustion engine: A review. *International Journal of Advanced Culture Technology*, *3*(2), 87-99

MARINE ENGINE

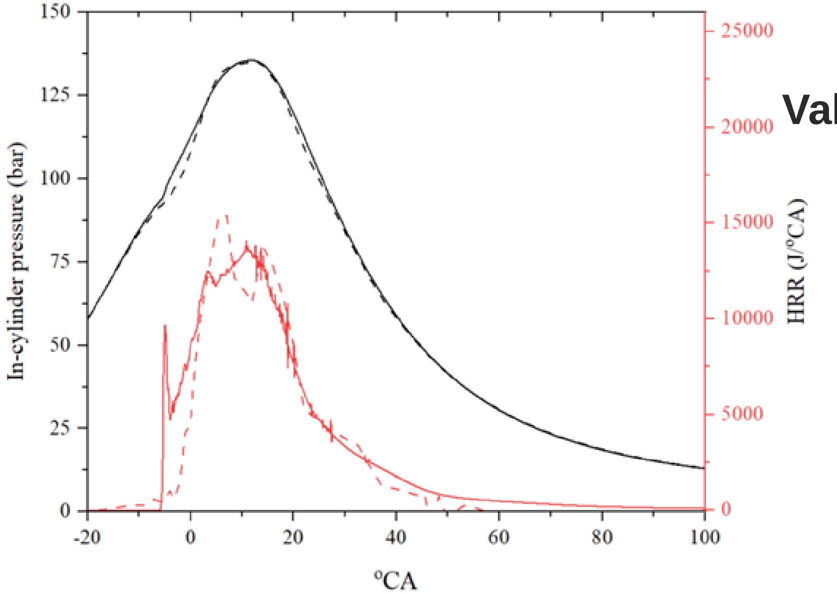
Parameter	Value
Type	Wartsila 9L46C
Max Power Output [kW]	10500
Maximum Speed [rpm]	500
Number of Cylinders	9
Compression Ratio	14.0:1
Bore x Stroke [mm]	460 x 580

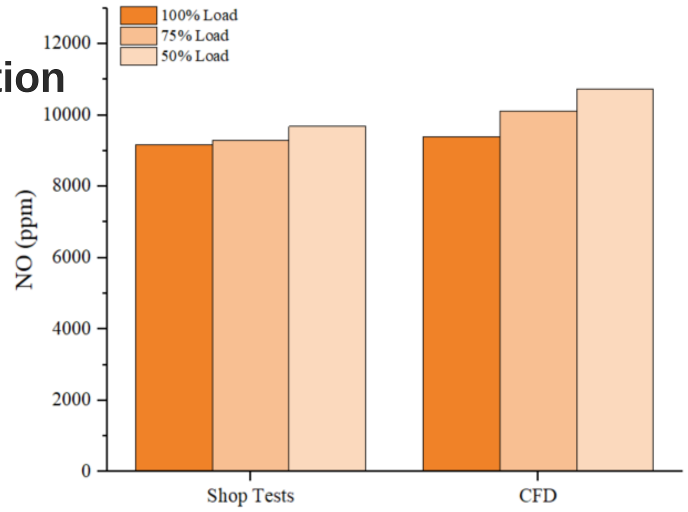
CFD MODEL





Validation



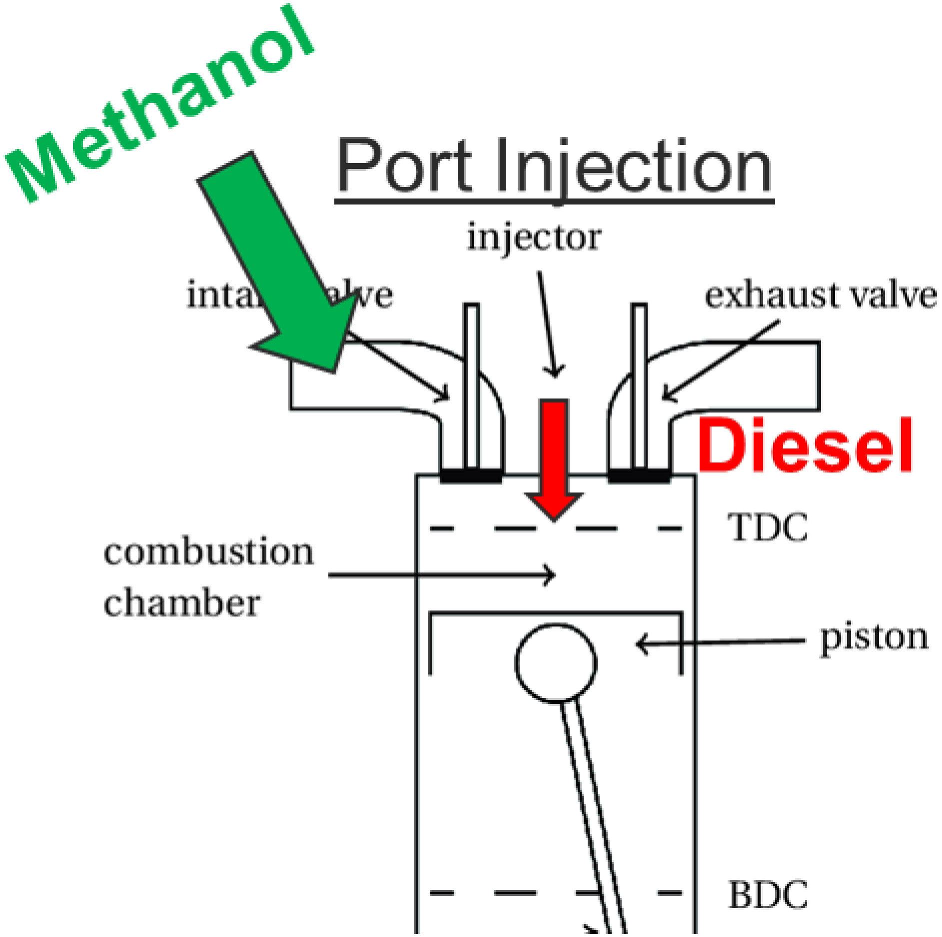


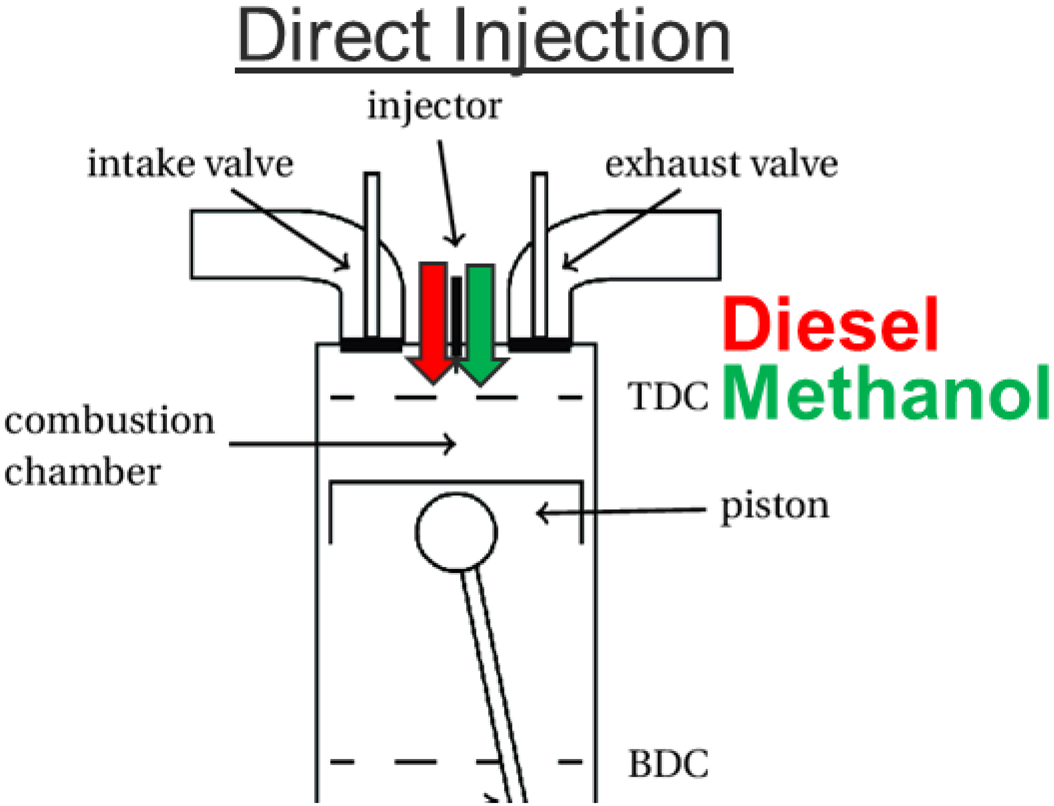
MAIN AIM

Deliver a comprehensive understanding of methanol & hydrogen combustion in marine engines under various conditions

METHANOL COMBUSTION

STUDY-1
Port VS Direct Injection of Methanol





METHANOL COMBUSTION

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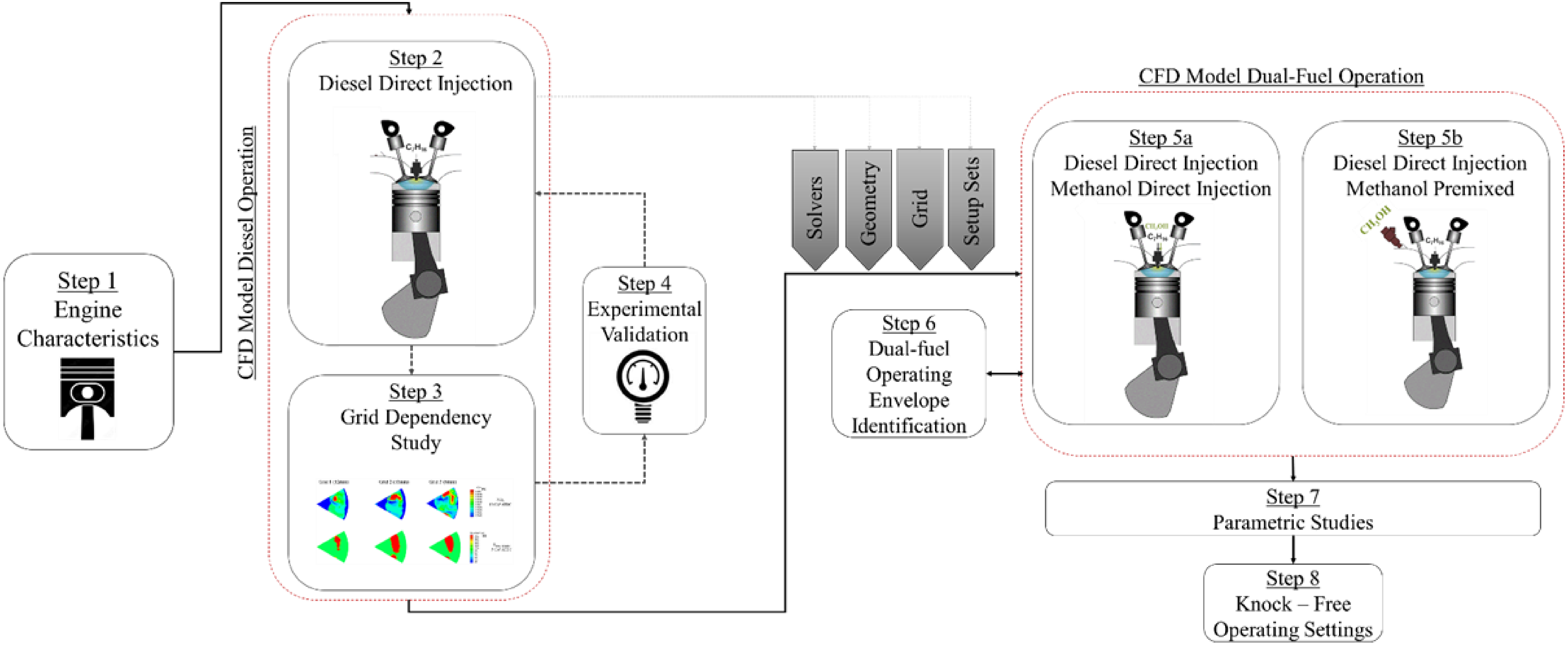
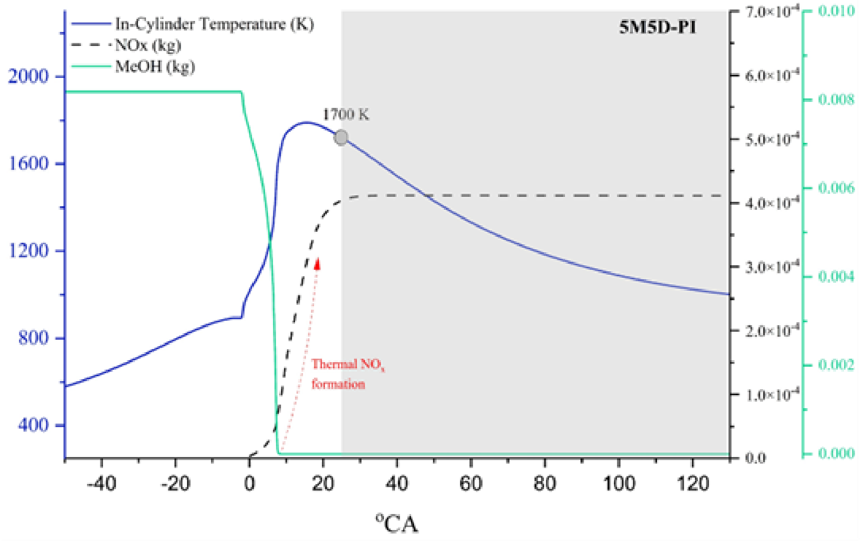
METHODOLOGY



METHANOL COMBUSTION

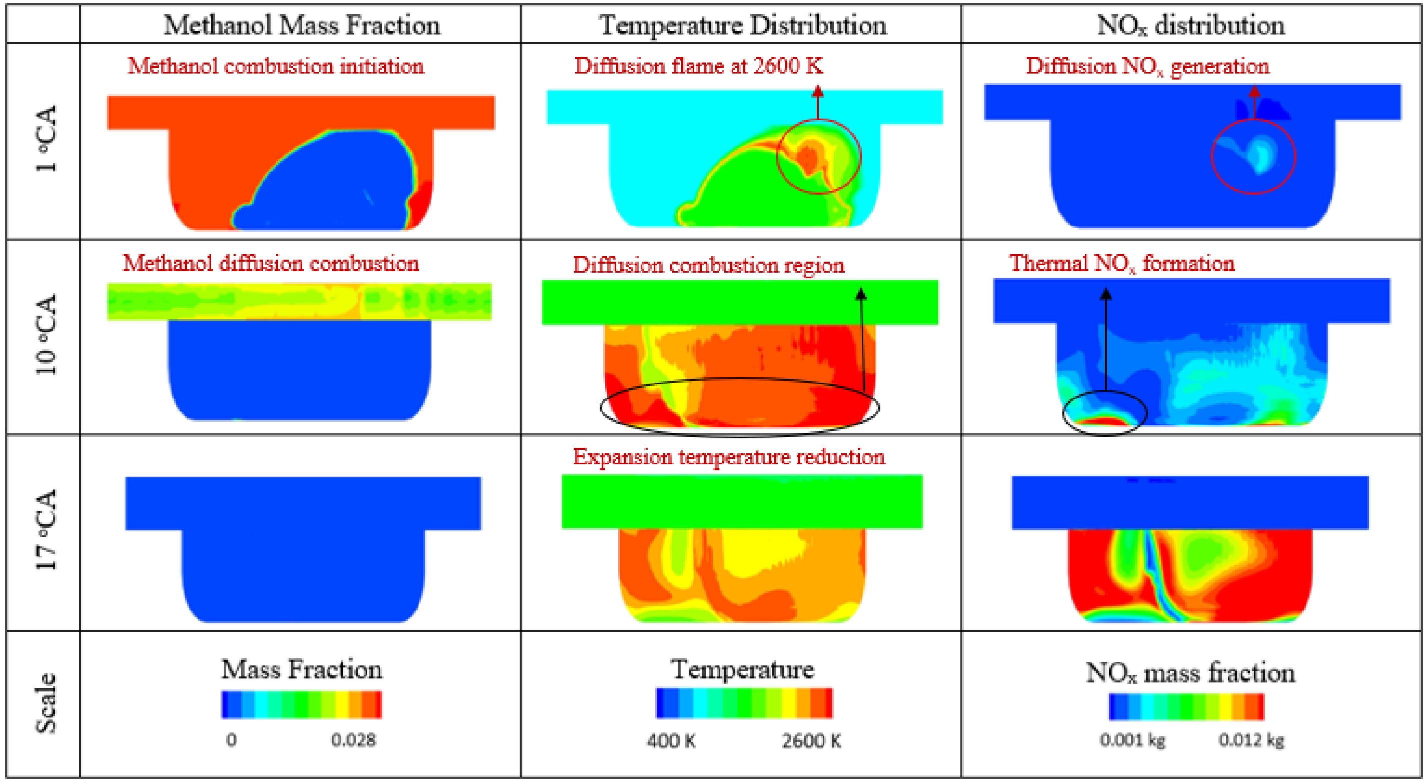
RESULTS

NO$_x$ formation tendency for 50% MEF



(a)

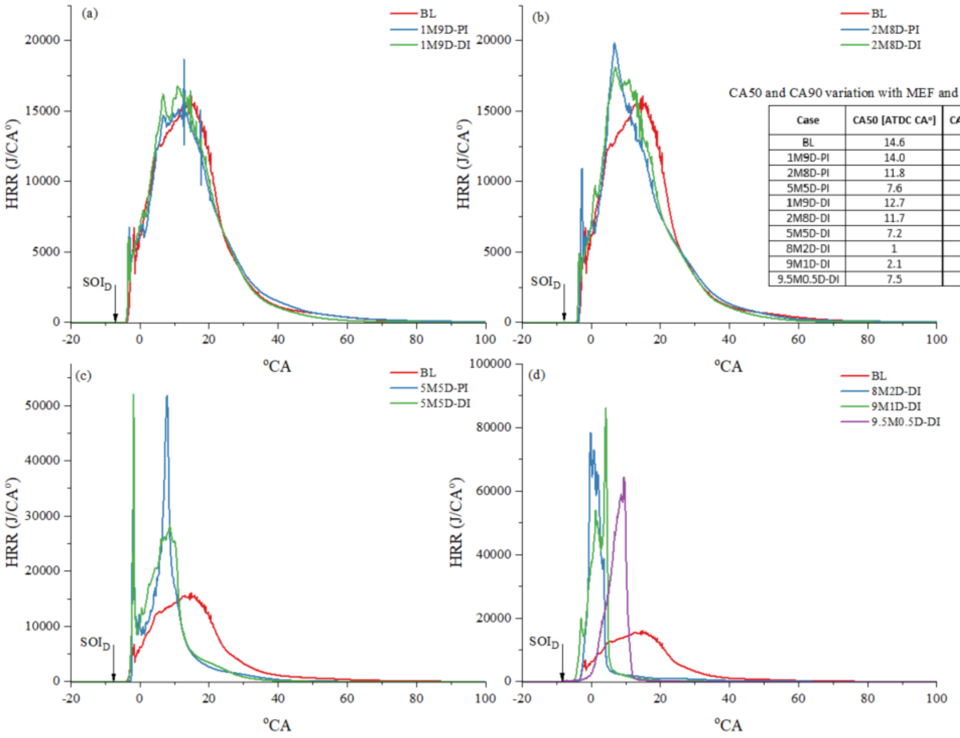
Combustion propagation and NO$_x$ generation contours for 50%M-PI case



METHANOL COMBUSTION

RESULTS

HRR for different cases

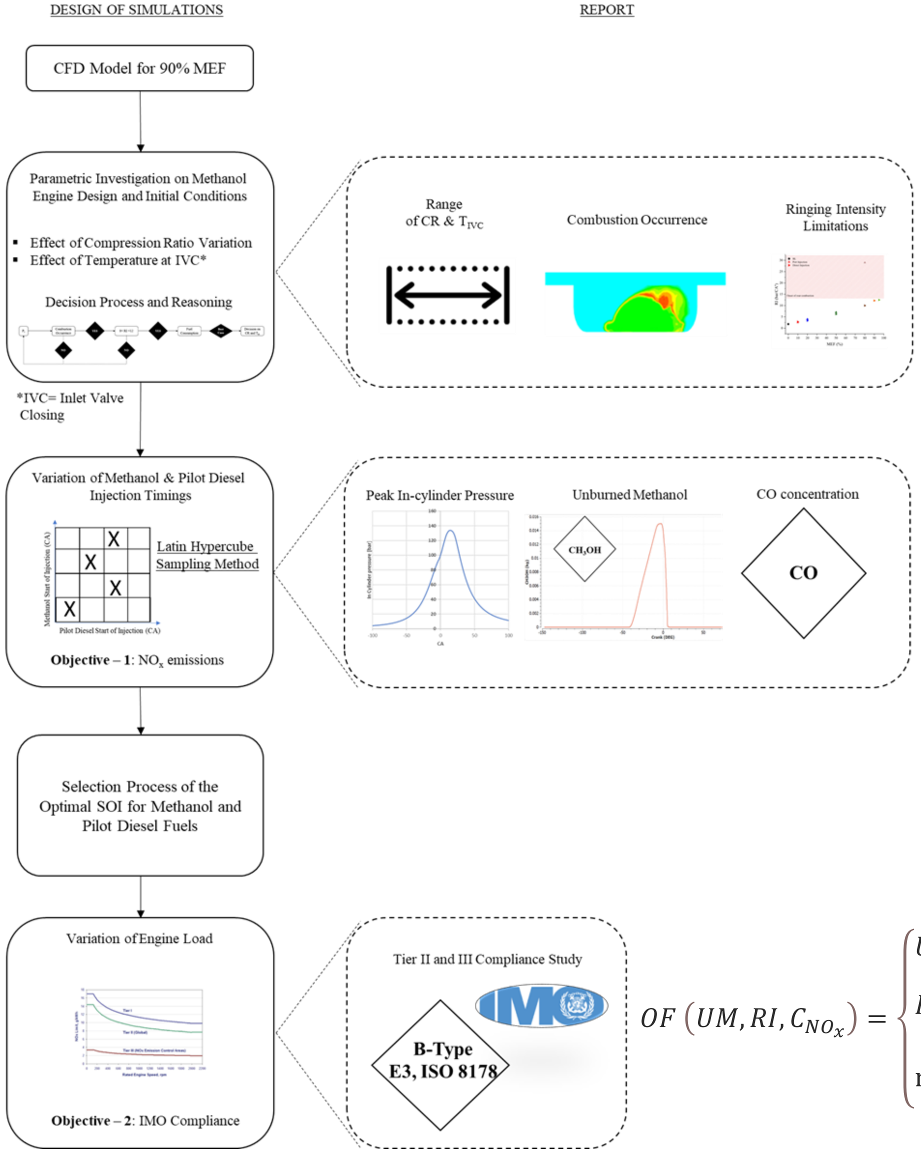


CA50 and CA90 variation with MEF and combustion regime.

Case	CA50 [ATDC CA°]	CA90 [ATDC CA°]
BL	14.6	30.8
1M9D-PI	14.0	31.3
2M8D-PI	11.8	30.6
5M5D-PI	7.6	18.1
1M9D-DI	12.7	27.7
2M8D-DI	11.7	27.7
5M5D-DI	7.2	17.4
8M2D-DI	1	6.2
9M1D-DI	2.1	4.7
9.5M0.5D-DI	7.5	10.1

- For premixed combustion cases, increased in-cylinder pressure and unstable combustion were exhibited with MEF, limiting the upper MEF to 50%.
- Marine engines operating with port methanol injection at 50% MEF present significant benefits reducing NOx emissions by 30.5% compared to the diesel mode.
- For premixed combustion cases, the marine engine exhibited lower thermal efficiency pertinent to diesel operation (41.6% for 50% MEF).
- Premixed combustion method is preferred for retrofitting existing engines as fewer modifications are required in the engine head and manifolds.
- Direct methanol injection demonstrates stable combustion (RI within the acceptable limits) behaviour at 95% MEF, and hence it is preferred when higher decarbonisation levels are required.

STUDY-2
90% Methanol Marine Engines - Optimisation



$$OF\left(UM, RI, C_{NO_x}\right) = \begin{cases} UM < 5 \times 10^{-5} & [kg] \\ RI < 4 & \left[\frac{MW}{m^2}\right] \\ \min\left(C_{NO_x}\right) & \left[\frac{g}{kWh}\right] \end{cases}$$

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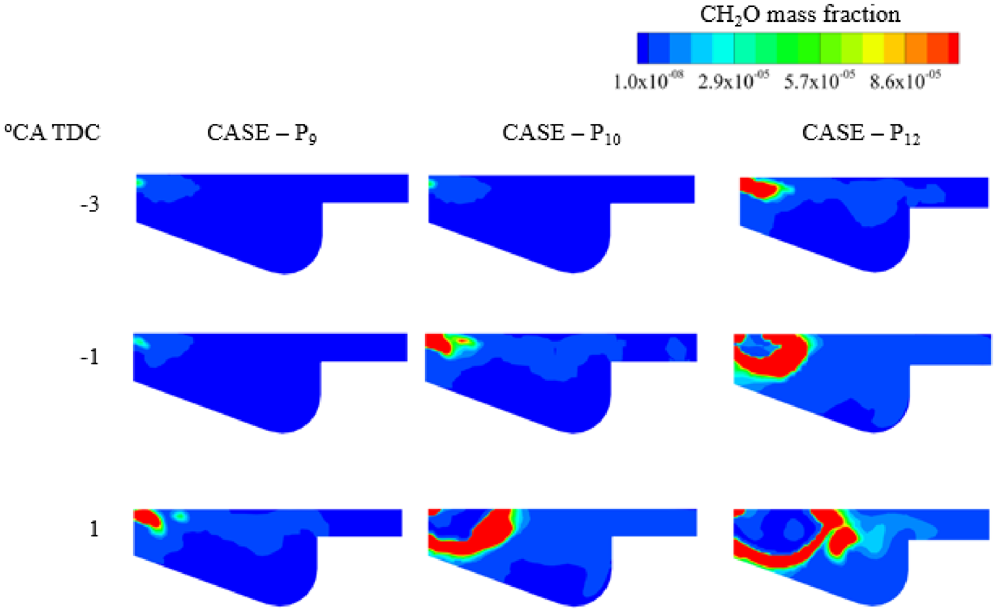
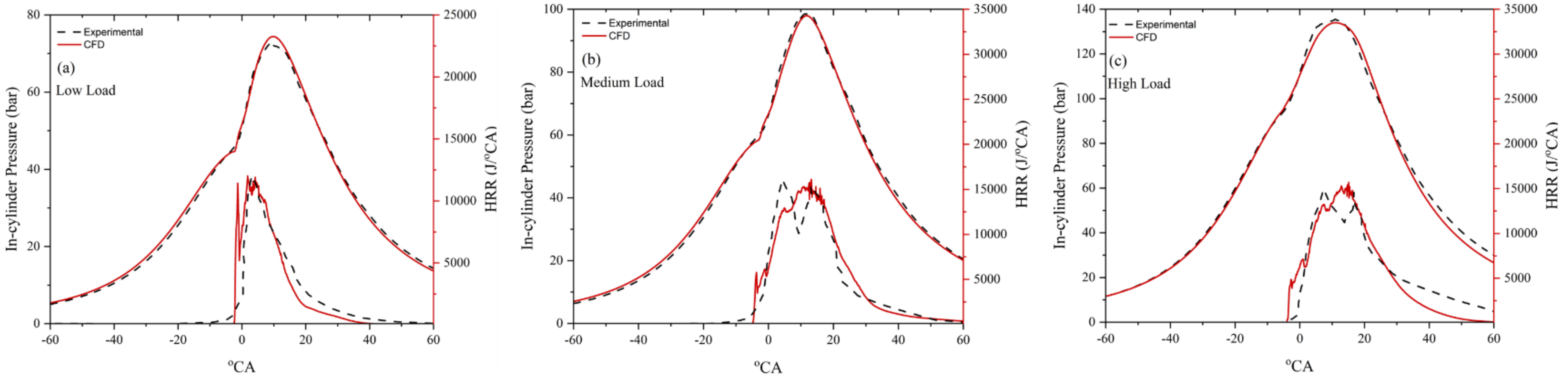
RESULTS

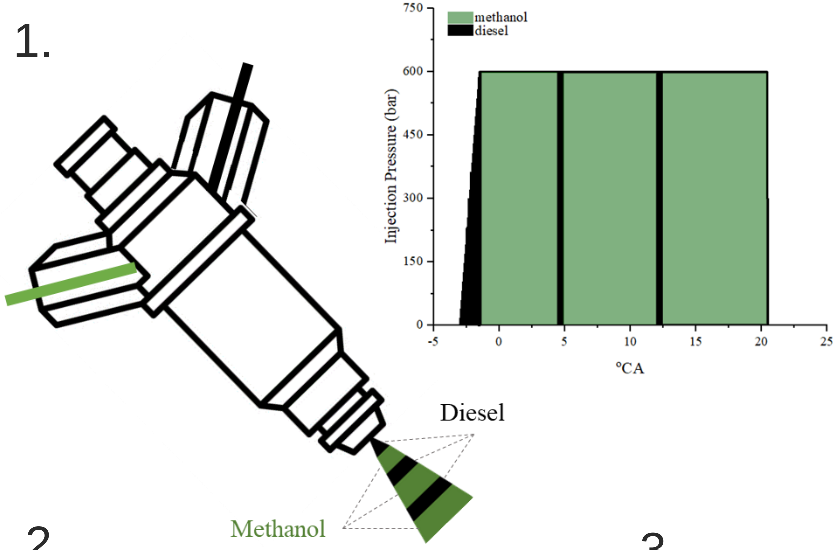


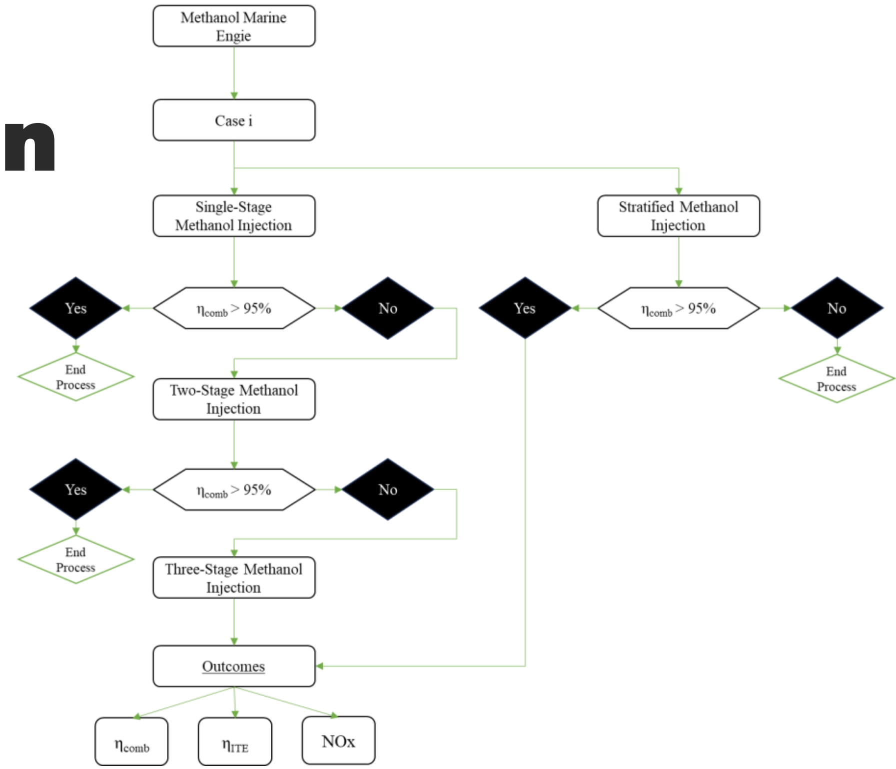
- *Optimal Injection Settings:*
  - Pilot Diesel: -12 CA TDC
  - MeOH: -80 CA TDC



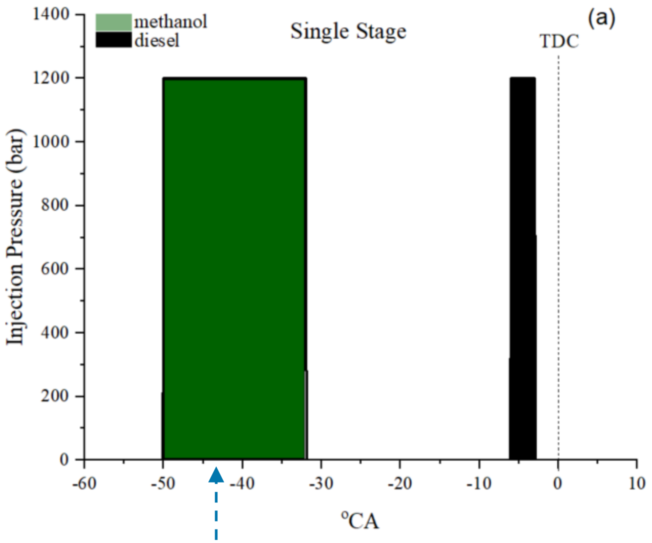
STUDY-3
Low Load Methanol Combustion

1.



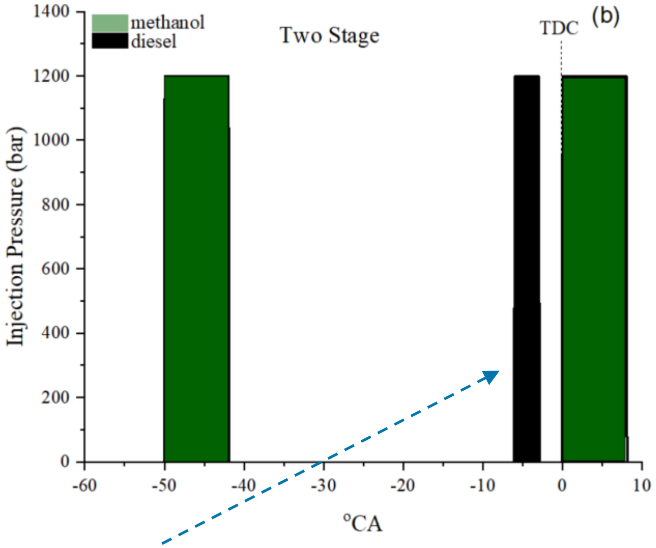


2.



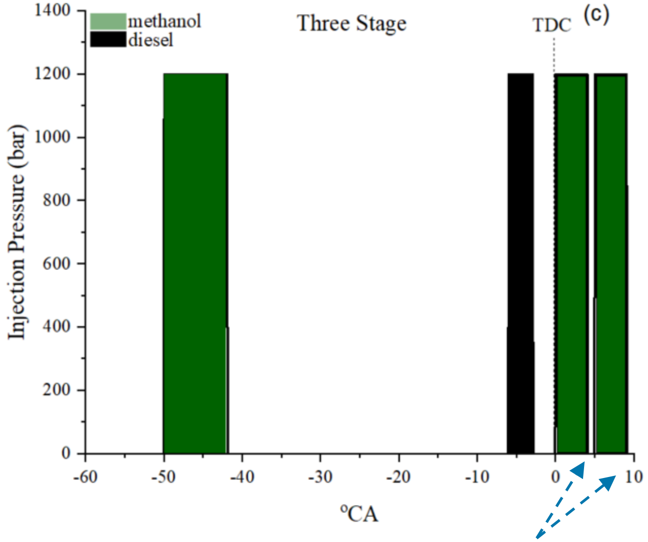
Methanol Injection
During Compression

3.



High Pressure
Pilot Fuel Injection

4.



High Pressure
Methanol Fuel Injection

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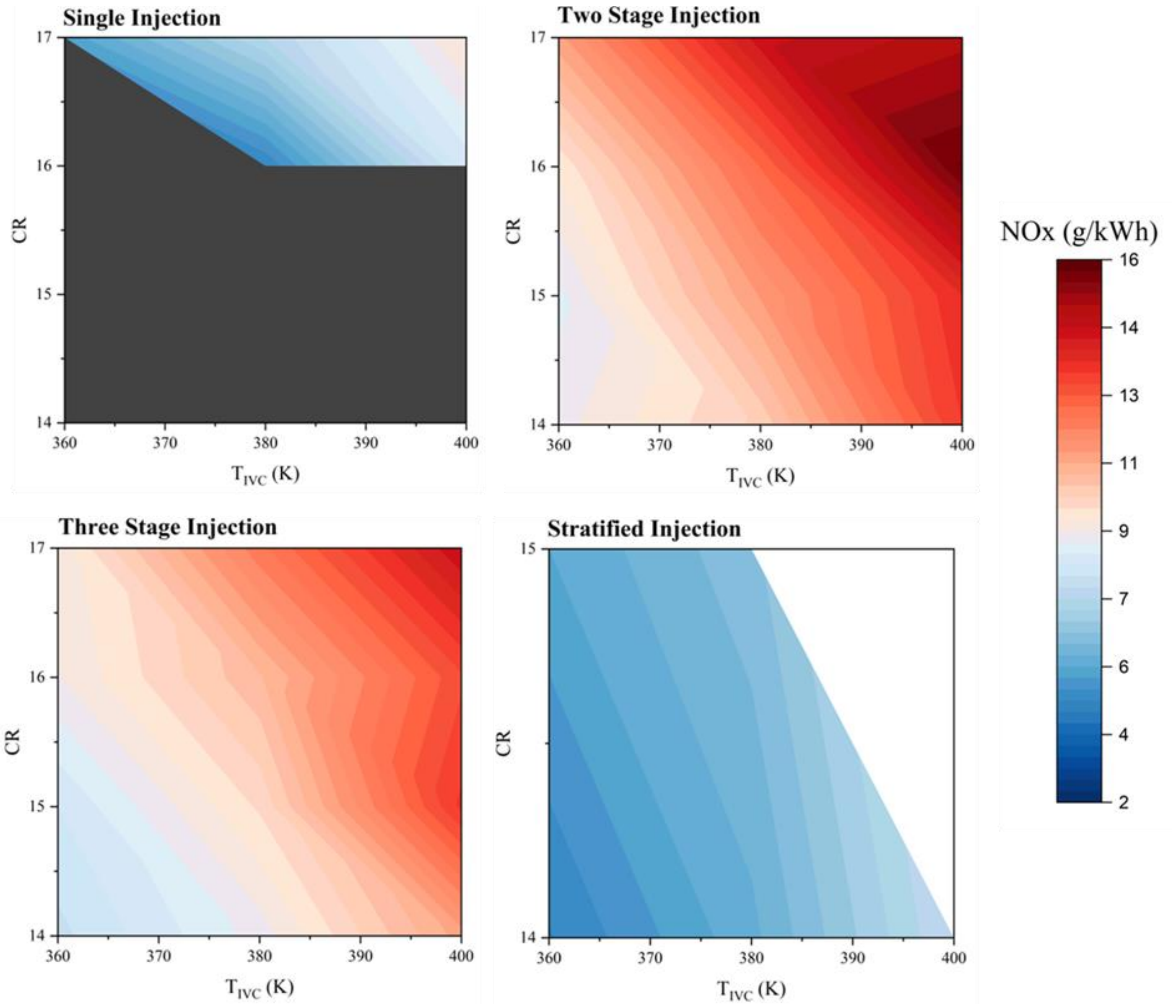
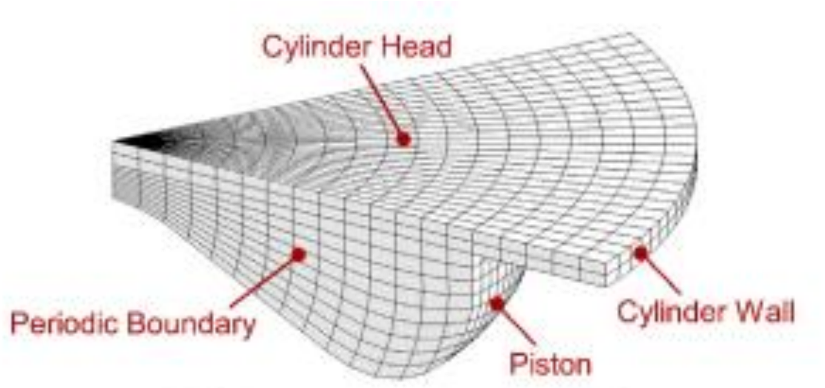
RESULTS

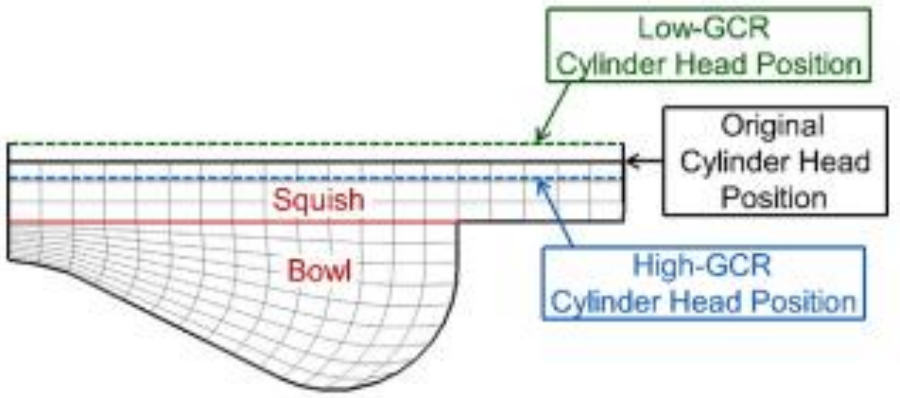


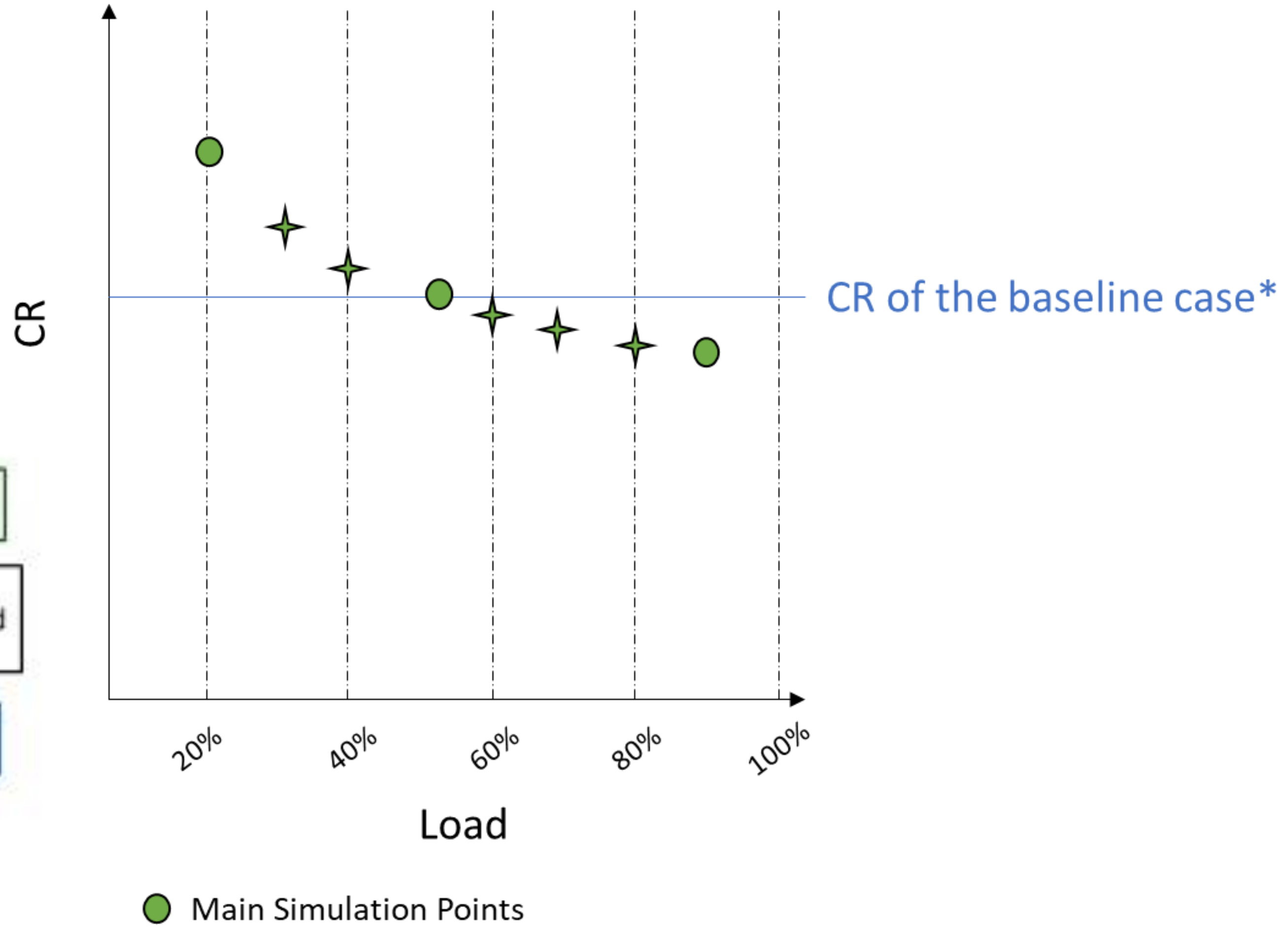
- Stratified Injection offers Ultra-low NOx emissions
- Two-stage injection strategy allows complete combustion and accepted ITE for initial temperature > 370 K or CR > 16
- Three-stage injection strategy is non practical as NOx emissions increase significantly due to combustion duration increase.

STUDY-4
Variable Compression Ratio



(a) 3D computational mesh at TDC





* BL case is the DF operation under fixed CR.

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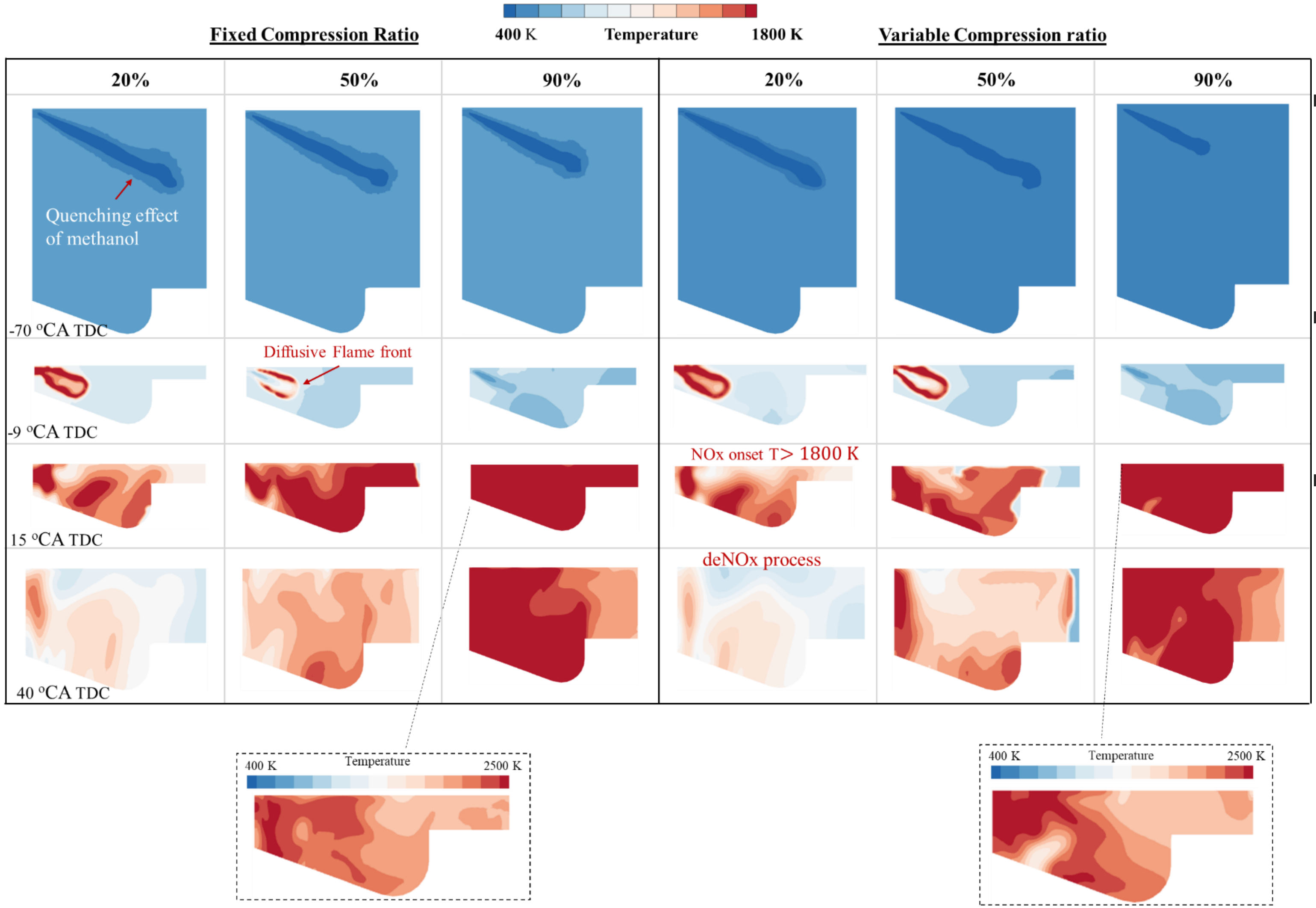
METHANOL COMBUSTION

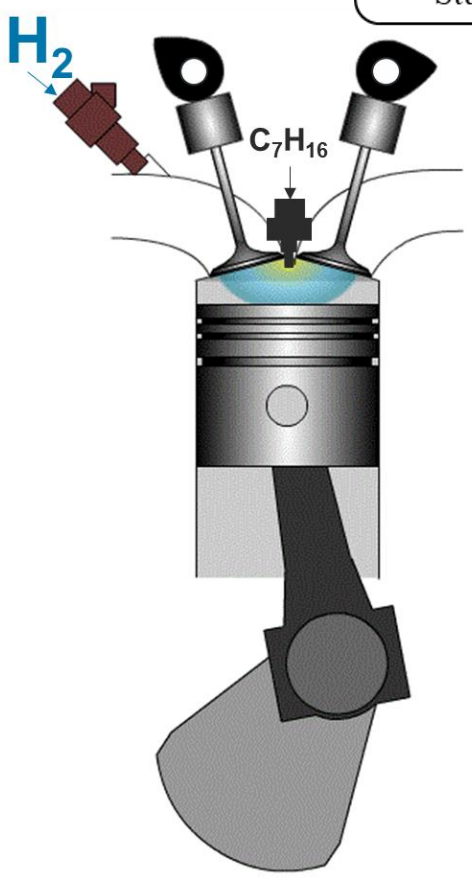
RESULTS

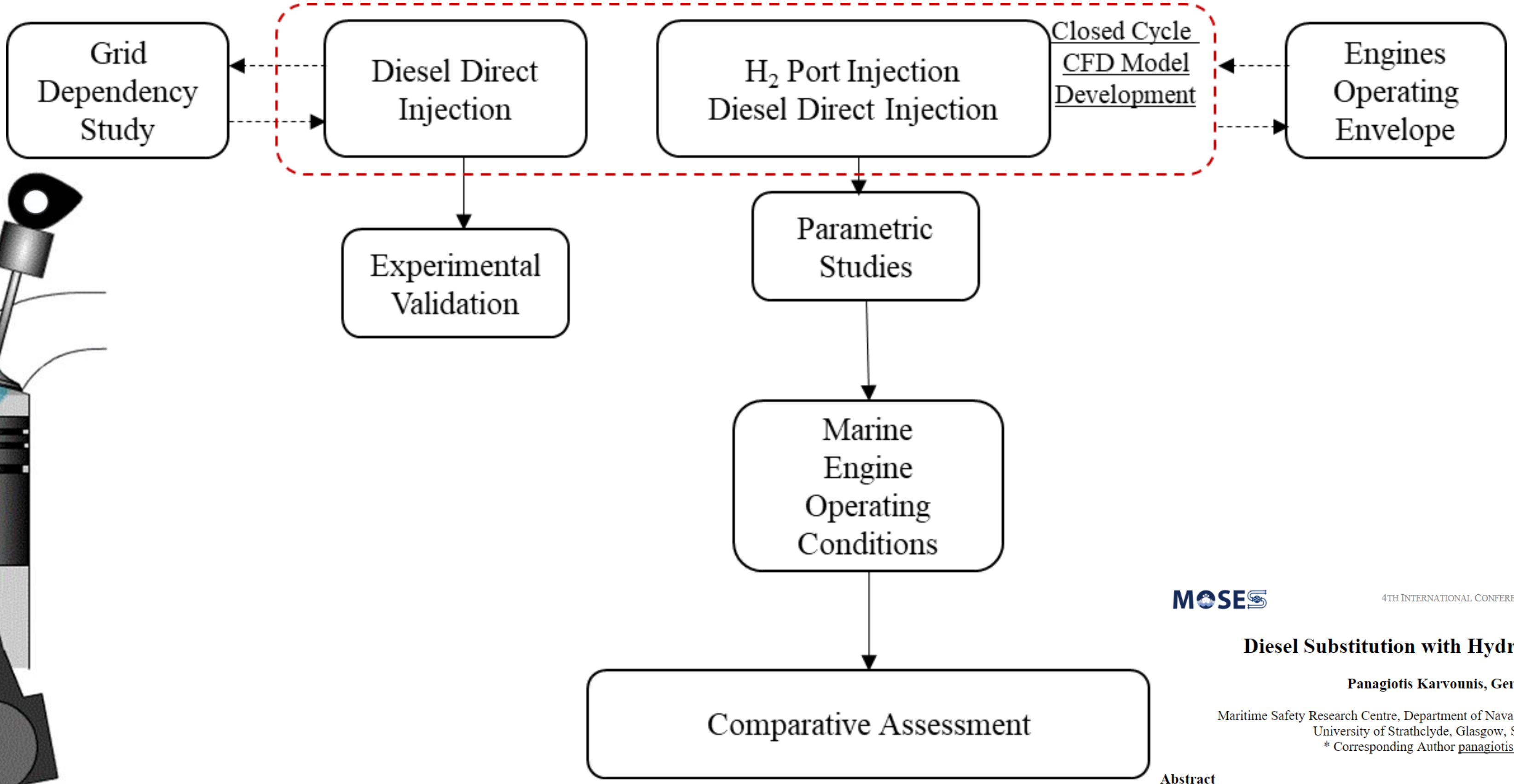


- Variable compression ratio engine provides improved thermal efficiency across all examined loads.
- NOx emissions of the VCR engine increase at medium and high loads.
- EGR of 20% at high load, allows compliance with IMO, Tier III limits.

HYDROGEN COMBUSTION

STUDY-1
20% H_2 in marine diesel engines





PROCEEDINGS OF MOSES2023 CONFERENCE
4TH INTERNATIONAL CONFERENCE ON MODELLING AND OPTIMISATION OF SHIP ENERGY SYSTEMS
26-27 OCTOBER, DELFT, NETHERLANDS

Diesel Substitution with Hydrogen for Marine Engines

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Abstract

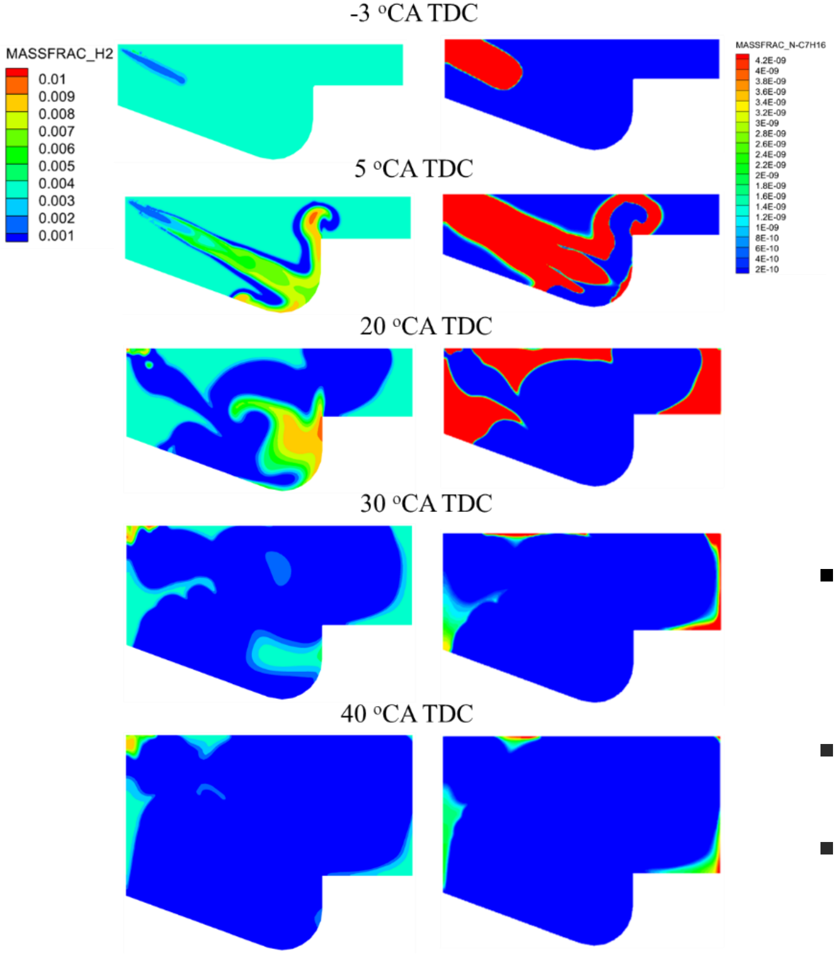
Zero-carbon fuels are expected to catalyse the decarbonisation of the maritime industry, with hydrogen being considered a long-term solution. This study aimed to investigate the feasibility of using hydrogen as a secondary fuel in marine diesel engines. A marine four-stroke engine with a nominal power output of 10.5 MW at 500 rpm was investigated, whereas the hydrogen injection at the engine port was considered. A CFD model was set up in CONVERGE for both diesel and the diesel-hydrogen operating modes to investigate the effects of 20% hydrogen fuel fraction (by energy) on engine performance, emissions, and combustion characteristics. This model was validated against experimental data for the diesel operating mode. Based on a parametric study, the mesh characteristics were selected to compromise between the prediction error and the computational effort. The impact of 20% hydrogen energy fraction on the heat release rate (HRR) and NO_x emissions is comparing with the diesel mode. The results demonstrate that despite the reduction in carbon emissions when using hydrogen, the NO_x emissions increase by 2.5 times, whereas the lower compression ratio allows for engine free-knock operation. This study contributes to the identification of efficient and reliable combustion conditions for diesel-hydrogen dual-fuel marine engines.

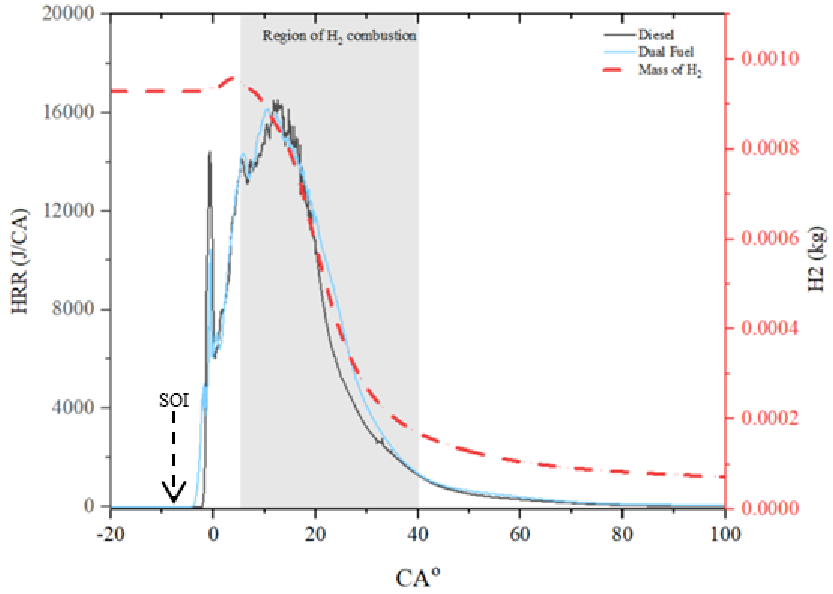
Keywords: CFD model, Hydrogen, Combustion, Marine engines, Decarbonisation.

HYDROGEN COMBUSTION

RESULTS

In-cylinder hydrogen and diesel mass fraction variations.





- Hydrogen knock free combustion is plausible under reduced CR in marine engines
- Hydrogen combusts after the diesel start of combustion
- Temperature in-cylinder remains above the NOx cutoff threshold for longer time increasing NOx concentration
- Indicated thermal efficiency reduces by 2% as heat transfer losses increase under hydrogen operation

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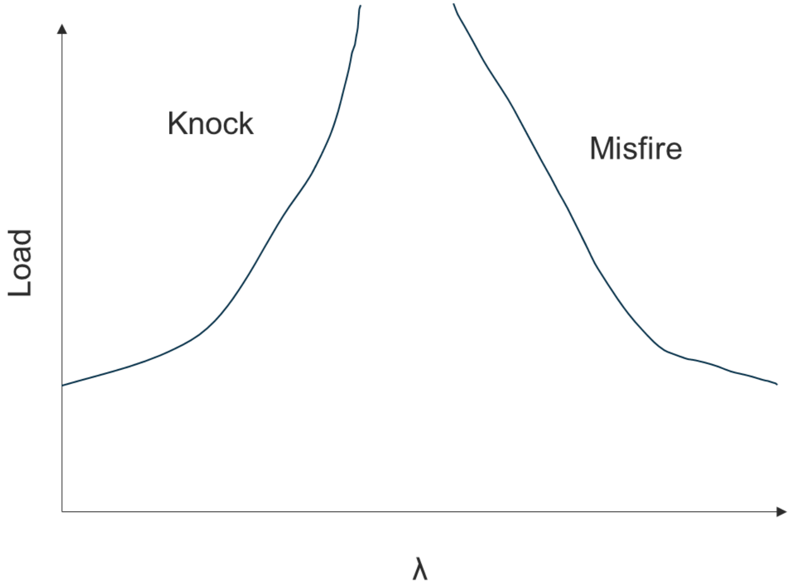
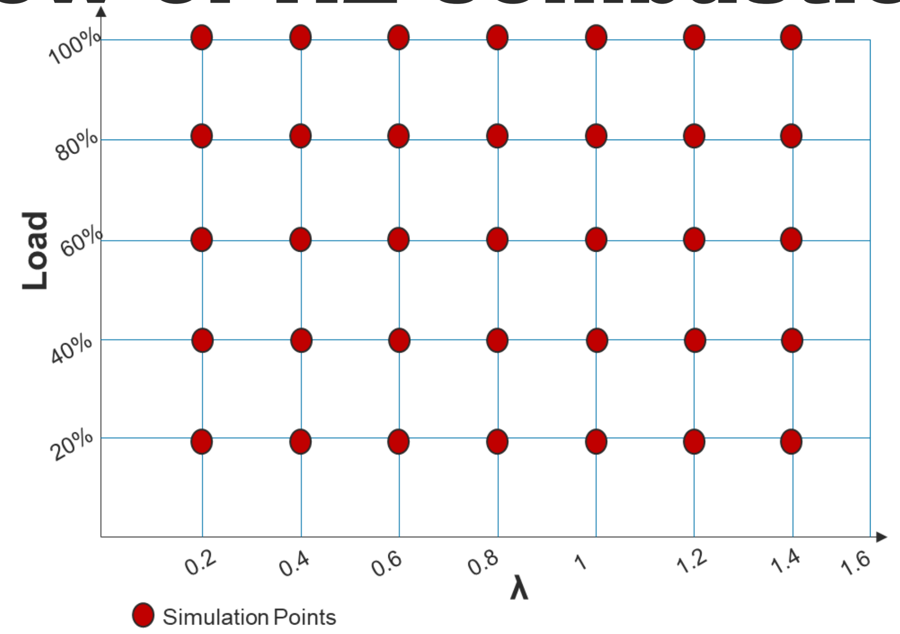
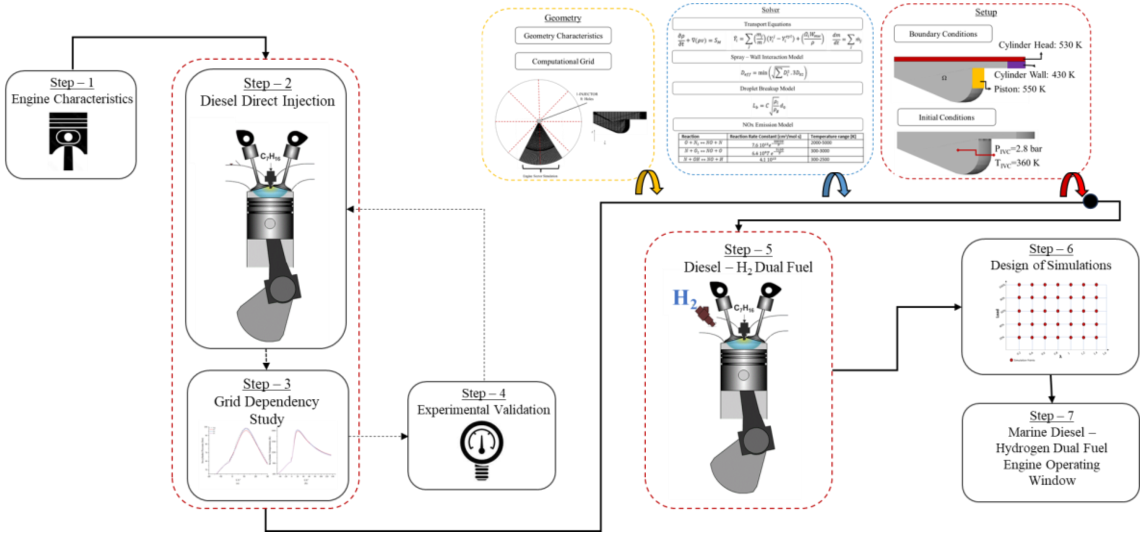
STUDY-2
Operating Window of H2 combustion







Collaborations

WIN GD Winterthur Gas & Diesel

Harbin Engineering University 1953

University of Strathclyde Glasgow

UNIVERSITY of STRATHCLYDE MARITIME SAFETY RESEARCH CENTRE

Publications

Contents lists available at ScienceDirect
International Journal of Hydrogen Energy
journal homepage: www.elsevier.com/locate/he
ELSEVIER

Environmental-economic sustainability of hydrogen and ammonia fuels for short sea shipping operations

Panagiotis Karvounis *, Gerasimos Theotokatos, Evangelos Boulougouris
Maritime Safety Research Centre, Department of Naval Architecture, Ocean, and Marine Engineering, University of Strathclyde, Glasgow, G4 0LZ, United Kingdom

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Review

Methanol Combustion Characteristics in Compression Ignition Engines: A Critical Review

Panagiotis Karvounis [1], Gerasimos Theotokatos [1,*], Ioannis Vlaskos [2] and Antonios Hatziapostolou [3]

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Article

Environmental-Economic Analysis for Decarbonising Ferries Fleets

Gerasimos Theotokatos *, Panagiotis Karvounis and Georgia Polychronidi

Journal of *Marine Science and Engineering* MDPI

Article

Ship Power Plant Decarbonisation Using Hybrid Systems and Ammonia Fuel—A Techno-Economic–Environmental Analysis

Panagiotis Karvounis, João L. D. Dantas, Charalampos Tsoumpris and Gerasimos Theotokatos *

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Recent advances in sustainable and safe marine engine operation with alternative fuels

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