



VVA-enabled Ultra-Efficient RCCI Combustion Development in a Medium Speed Marine Engine Platform

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1. Background & motivation

- Reactivity controlled compression ignition (RCCI), dual-fuel concept, achieves high thermal efficiency (~55%) & ultra-low NO_x and Soot and adapts various low or zero carbon fuels
- Challenges:** limited-load range, combustion stability, excessive hydrocarbon emissions → *limit efficient RCCI operations*
- Variable valve actuation (VVA)** addresses these challenges by flexibly regulating in-cylinder thermodynamic and mixing conditions [1] → *unlock a broader operating window of ultra-efficient RCCI combustion* [2]
- However, VVA's potential has not been fully investigated in the marine engine platform (efficient turbocharging system and high thermal inertia) + VVA significantly increases calibration and optimization complexity.

What?

- Investigate how each valve timing influences RCCI combustion and emissions
- Utilize VVA to achieve ultra-efficient RCCI combustion

How?

- Experimental investigation with fully-flexible valve train system + model-assisted optimization with NSGA-III Genetic Algorithm

Objectives?

- Identify VVA's RCCI combustion control mechanism
- Extend RCCI load limit up to IMEP 3 bar and 25 bar
- ITE > 50% and ISNO_x < 0.4 g/kWh (EU Stage-V NO_x limit)

2. Methodology

Experimental platform :

Wärtsilä 4L20 multi-cylinder research engine

Numerical platform : One-dimensional GT-Power engine model coupled with in-house developed thermochemical multizone model (UVATZ) [3]

Multi-objective optimization

- Objective:** Max. ITE and Min. ISNO_x
- Constraints:** P_{max} < 225 bar, MPRR < 10 bar/deg

GT Technologies

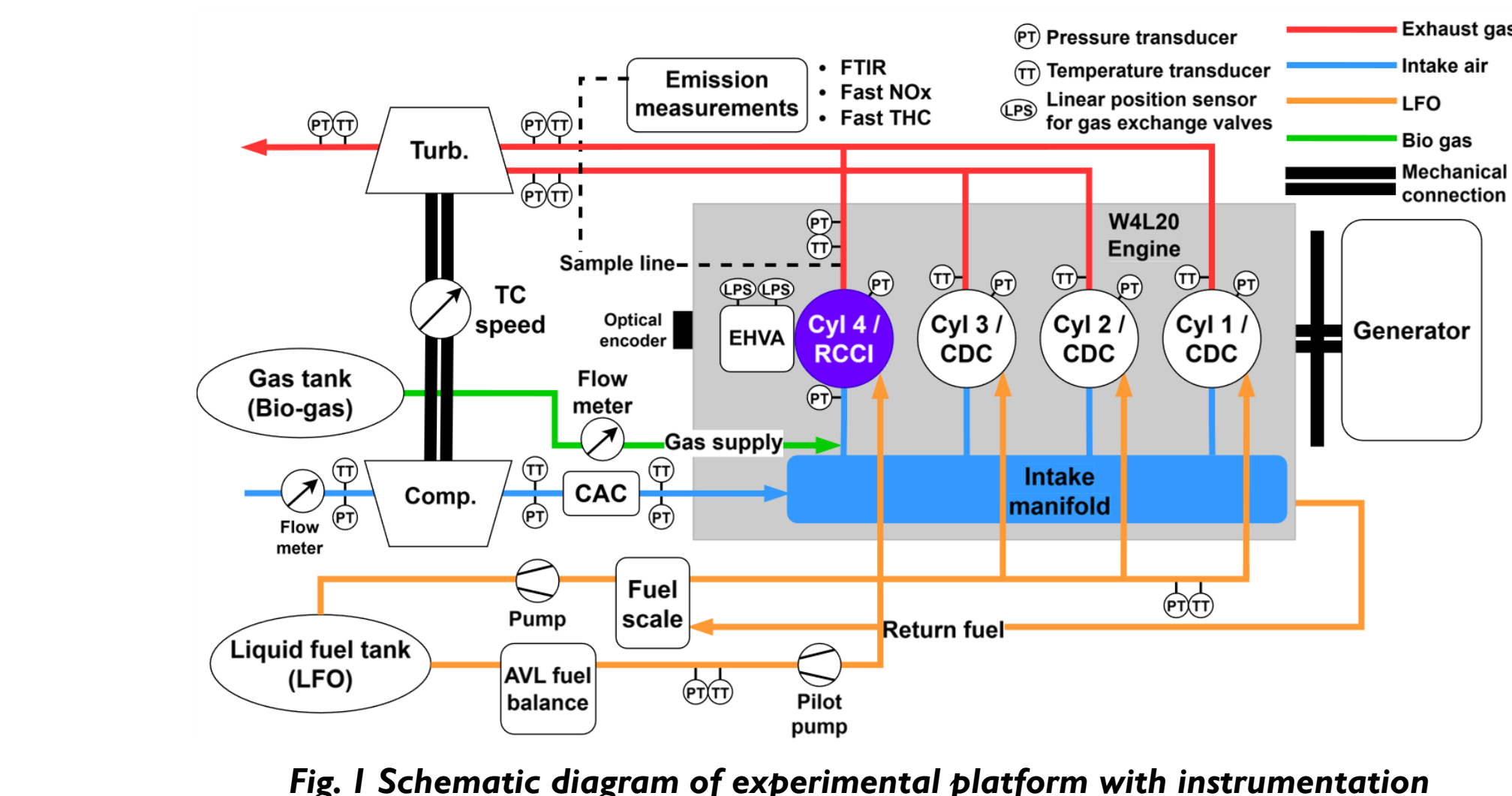


Fig. 1 Schematic diagram of experimental platform with instrumentation

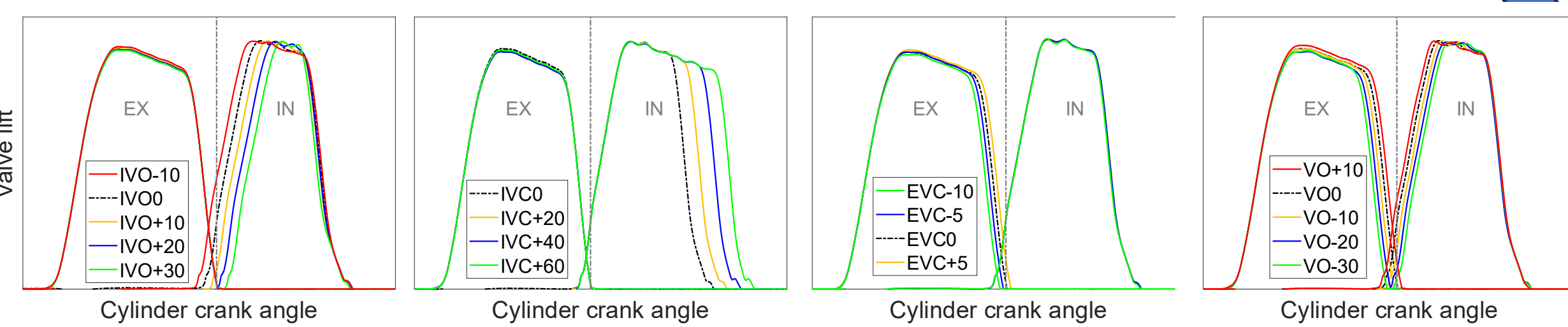


Fig. 2 Valve Profiles investigated using EHVA

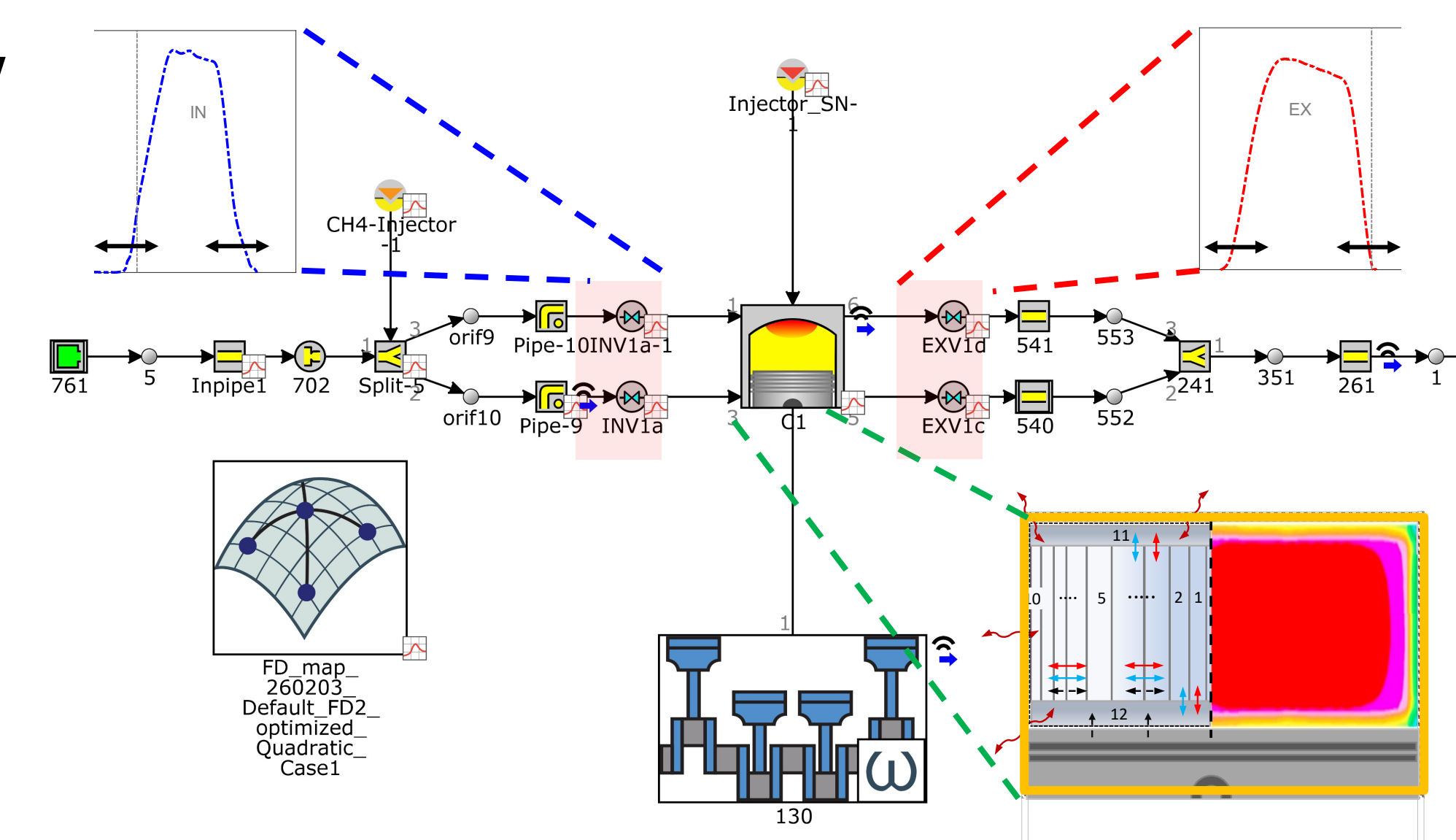
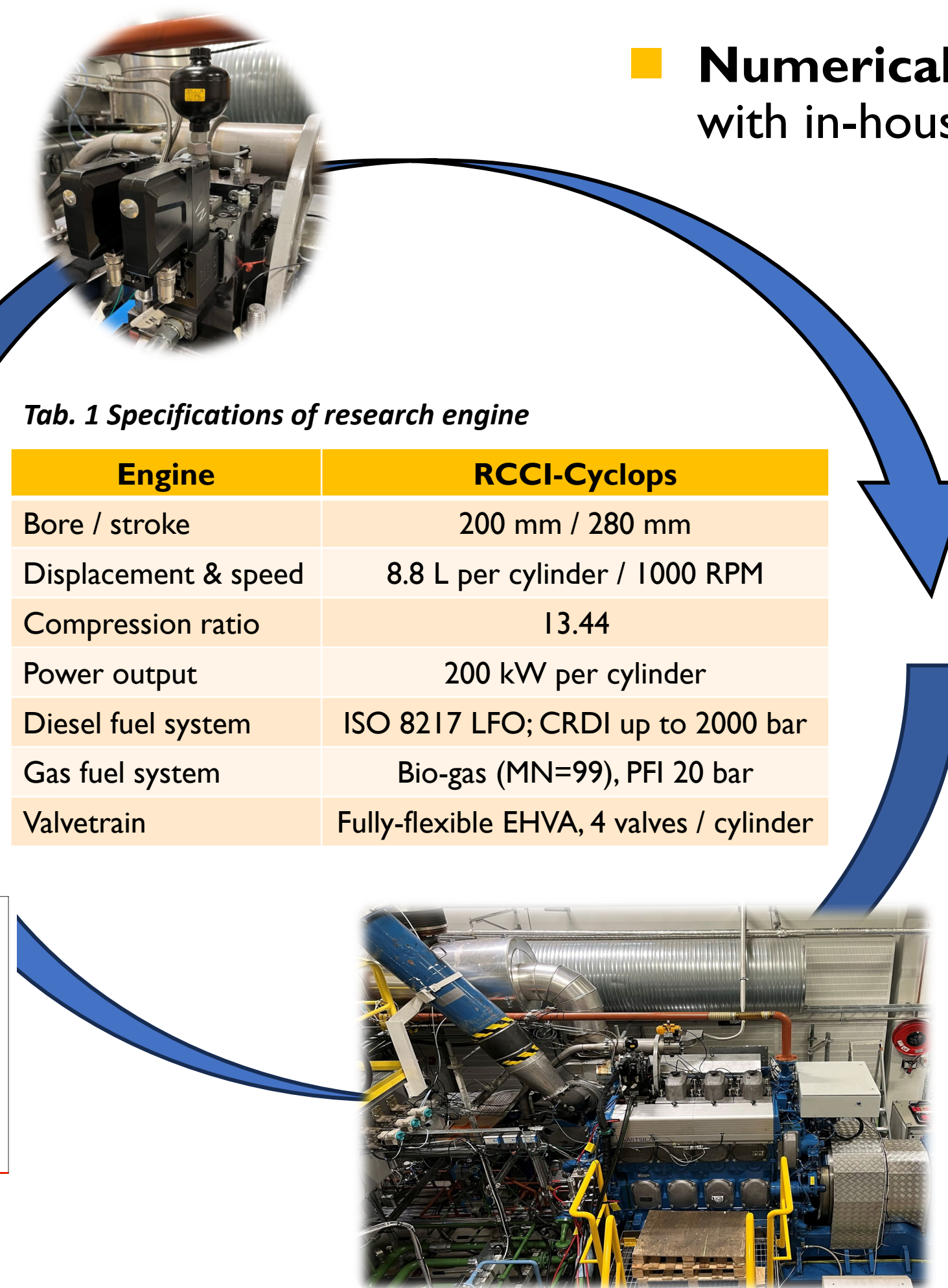


Fig. 3 1D GT-Power engine model coupled with multizone model (UVATZ)

3. Results and discussion

VVA's combustion control mechanism (experiment) [4]

VVA enabled load extension (experiment) [2]

RCCI optimization with VVA (simulation)

In-cylinder temperature and charge density control

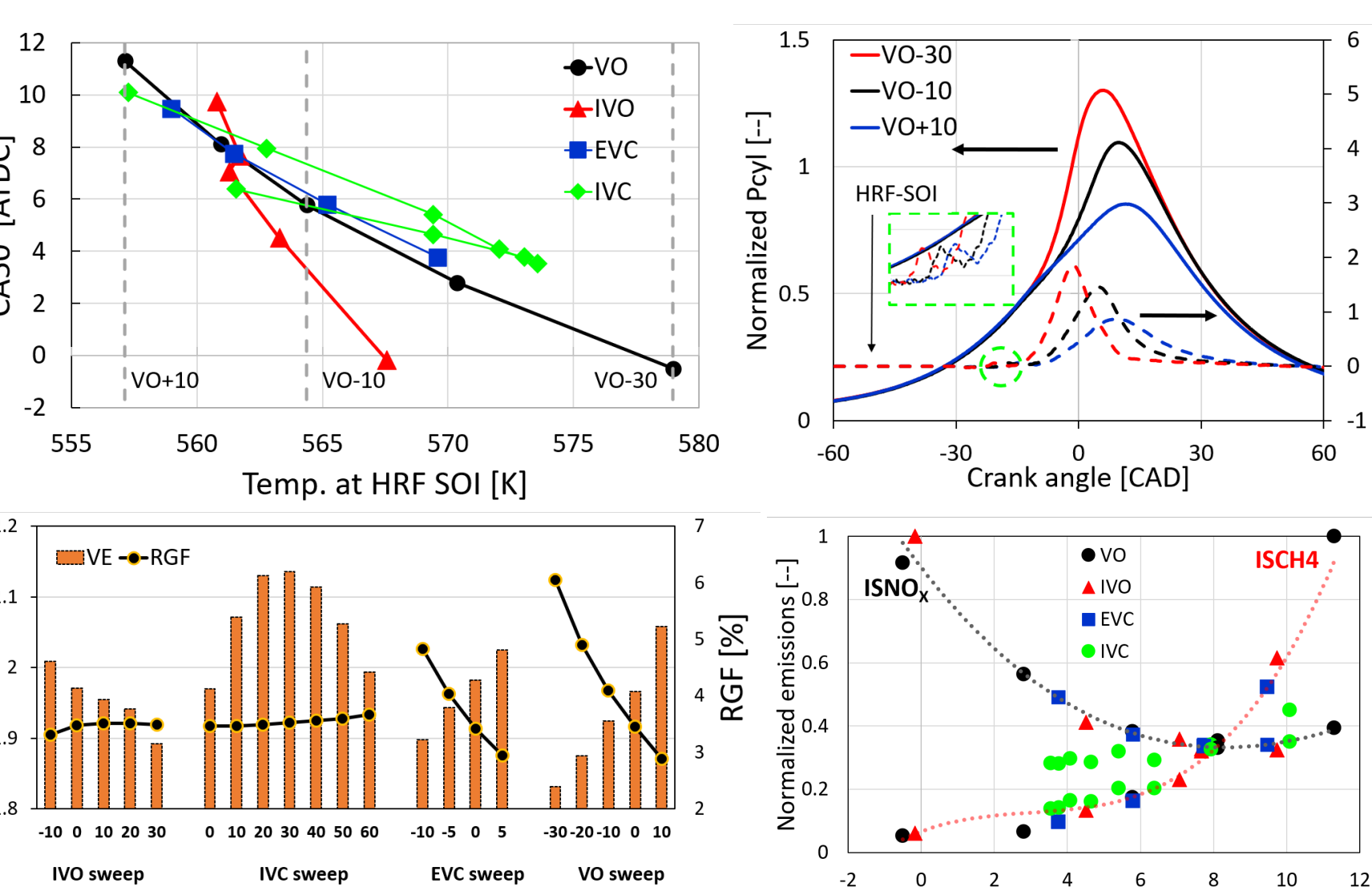


Fig. 4 Experimental results of VVA sweeps (IVO, IVC, EVC, VO) on RCCI combustion

Low load extension up to IMEP 2.96 bar with NVO High load extension up to IMEP 25.4 bar with EIVC

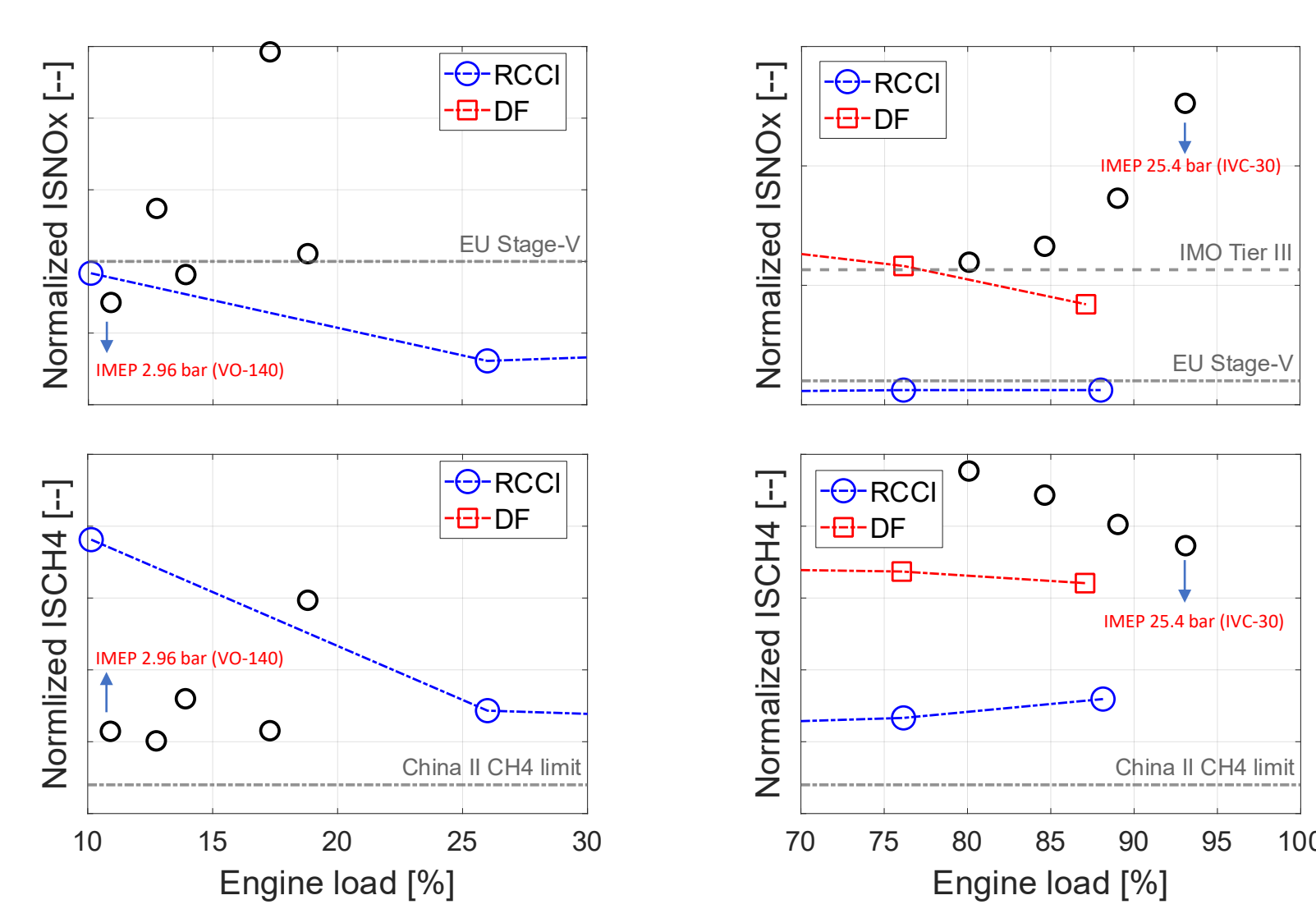


Fig. 5 Emissions benchmarking against the current best technology

50, 75% load points : ITE > 50% by optimizing combustion phase Ultra low NO_x emissions < EU Stage-V by high boost (high dilution) VVA provided additional efficiency gain (+0.8%) compared non-VVA optimization case

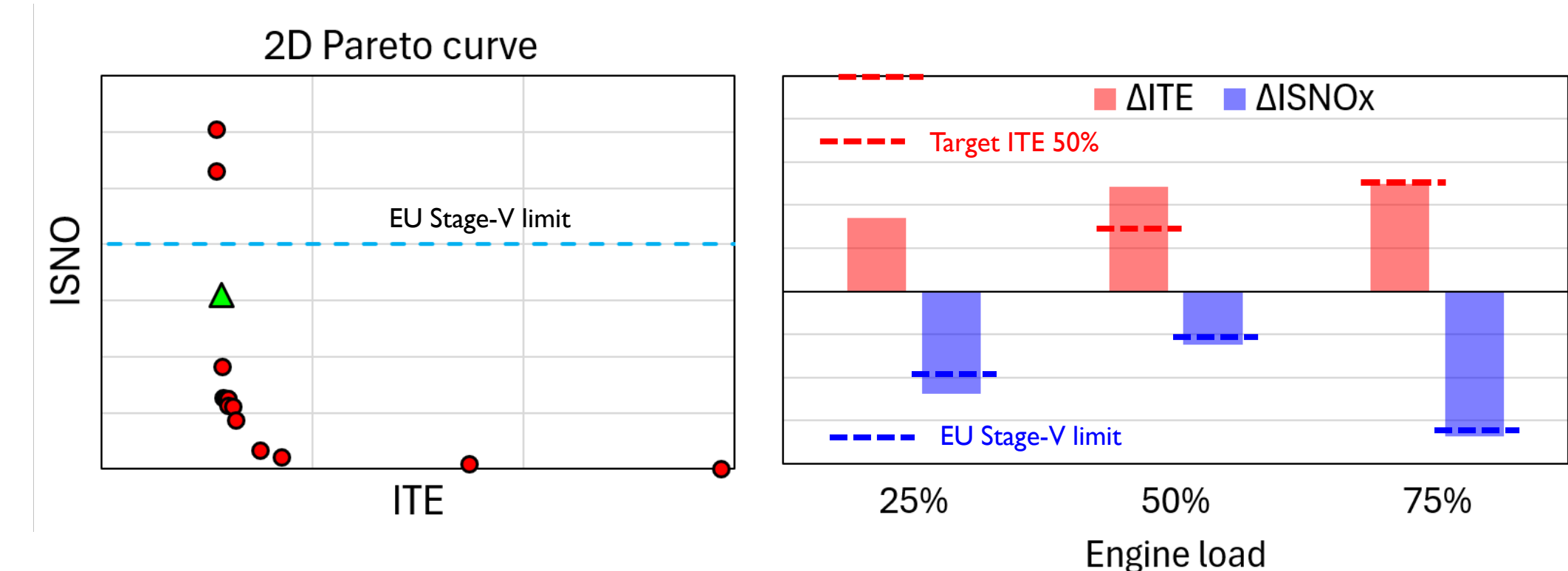


Fig. 6 Optimization results at three different load points

4. Conclusions

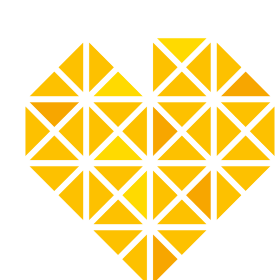
- Fully-flexible VVA system demonstrated to control RCCI combustion effectively via rapid in-cylinder thermal and charge control.
- VVA extended efficient and clean RCCI operation up to IMEP 3 bar and 25 bar.
- VVA enabled ultra-efficient RCCI operation (ITE > 50%) with relatively low NO_x emissions (< EU-Stage V NO_x limit).
- There is room to improve the efficiency further by optimizing piston and injector geometry which are not explored in the present study.
- VVA can be integrated with conventional control parameters (BR, HRF-SOI, lambda), expanding the control space. The enhanced control authority provides greater flexibility in engine calibration and optimization even with different fuels and fuel blends, supporting sustainable transition toward net-zero GHG emissions in maritime sector.

5. Acknowledgements

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6. References

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