Variable Valve Actuation enabled Reactivity-Controlled Compression Ignition in a Natural-Gas/Diesel Marine engine

1. Background & Motivation

- RCCI combustion is very **sensitive to in-cylinder thermodynamic conditions (for instance, IVC temperature).**
- **Variable valve actuation (VVA)** adjusts these conditions flexibly which could extend the operation limits of stable and efficient RCCI operation.

WHAT? Investigating **two VVA strategies**: *early intake valve closing (**EIVC**)* and *second exhaust valve re-opening (**2EVO**)* on NG-diesel RCCI combustion

HOW? **Model-based investigation** under fixed total fuel energy condition

GOALS? **G1.** Evaluate the model's sensitivity to VVA
G2. Influence on RCCI combustion / engine performance

2. Methodology

- **1D engine simulation** (*GT-SUITE*) was performed on **single-cylinder version of large bore medium-speed marine engine platform**

Table 1. Engine specifications and simulation condition

Engine	Wärtsilä 31 DF
Displacement & nominal speed	32.45 L & 720 rpm (4-stroke)
Stroke / bore	1.39
High reactivity fuel (HRF)	$nC_{12}H_{26}$ (ISO 8217 LFO) I Direct-injection
Low reactivity fuel (LRF)	Natural-gas (MN=80) I Port-injection
Valvetrain	Four valves with swirl & tumble ports
Reference operating point	50% load I 0.108 (m/m) HRF/LRF I 49 AFR

- **Predictive RCCI combustion model: in-house physic-based chemical kinetic multizone model, *UVATZ*** *(University of Vaasa Advanced Thermo-kinetic multi-Zone model)*

Table 2. Governing assumptions of in-house multizone model (UVATZ)

Source code	C++ & Cantera (thermo-kinetic library)
Reaction mechanism	Yao et al. [1] ; 54 species and 269 reactions
Zonal configuration	Onion-skin (BL zone + crevice zone)
Interzonal mixing	Diffusion-based, predictive turbulence model
Wall heat loss	Chang et al. [2] ; zone dependent
Simulation time	< 3.5 min / cycle (coupled with GT)
HRF stratification	Generated from CFD simulations

- **Validation** with experimental data (fixed VVA): **< 2%** (in-cylinder/air-path pressure & performance parameters) [3,4]

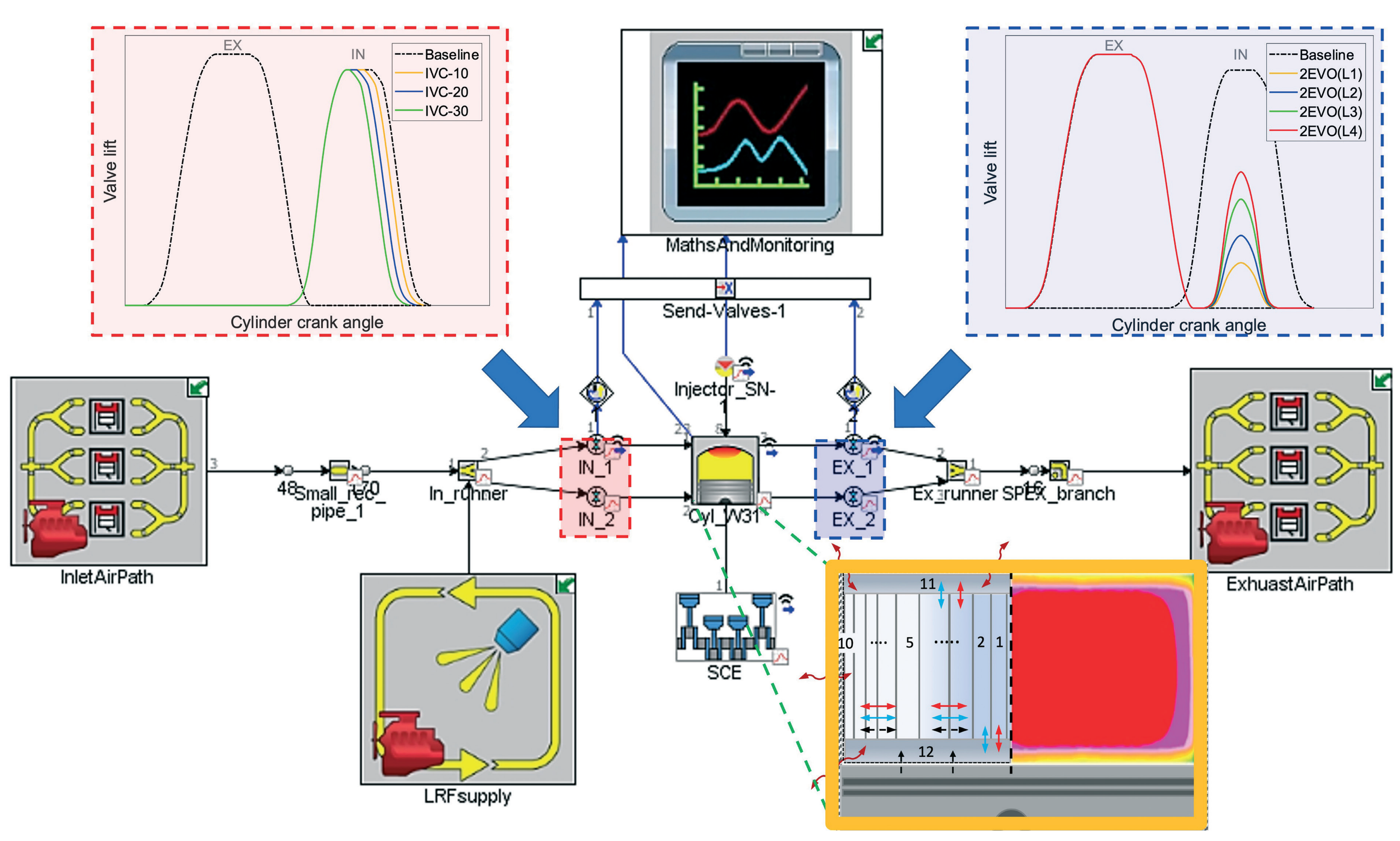

Figure1. 1D engine model coupled with in-house multizone model (UVATZ)

3. Simulation results

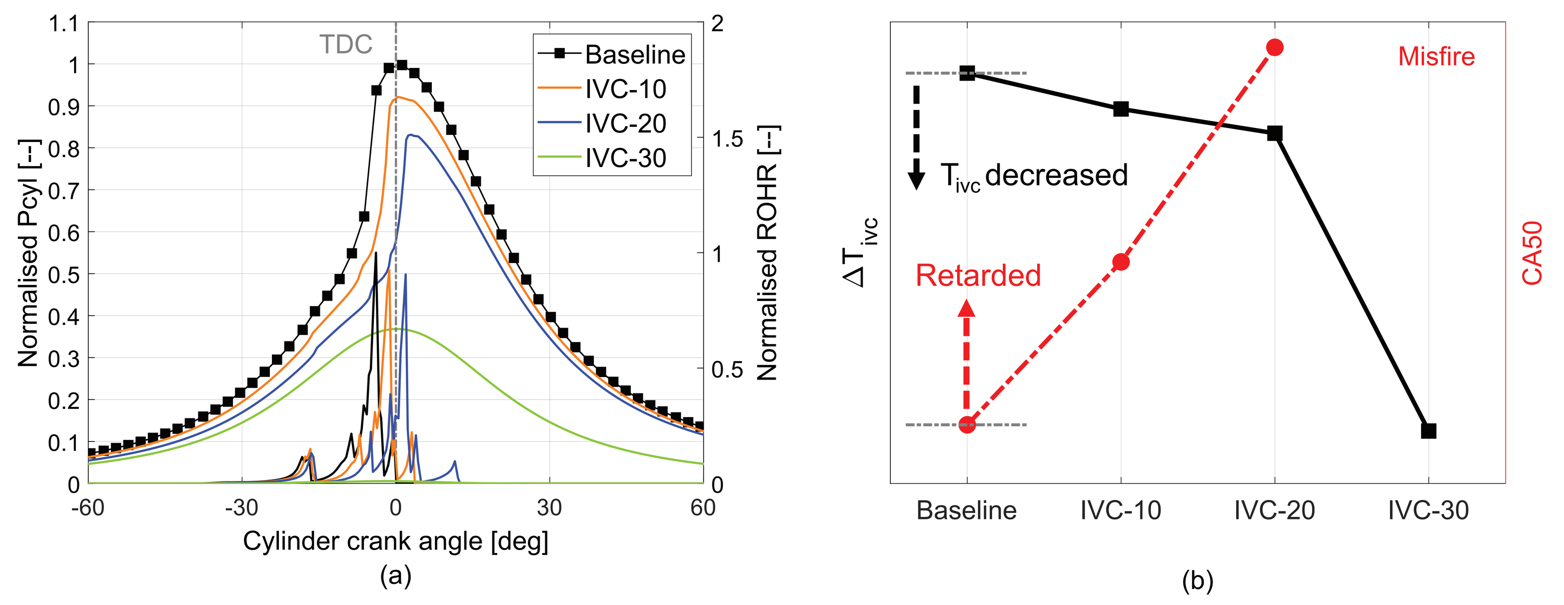

Figure2. Simulation results of EIVC: (a) normalised in-cylinder pressure (Pcyl) and rate of heat release rate (ROHR); (b) IVC temperature and CA50

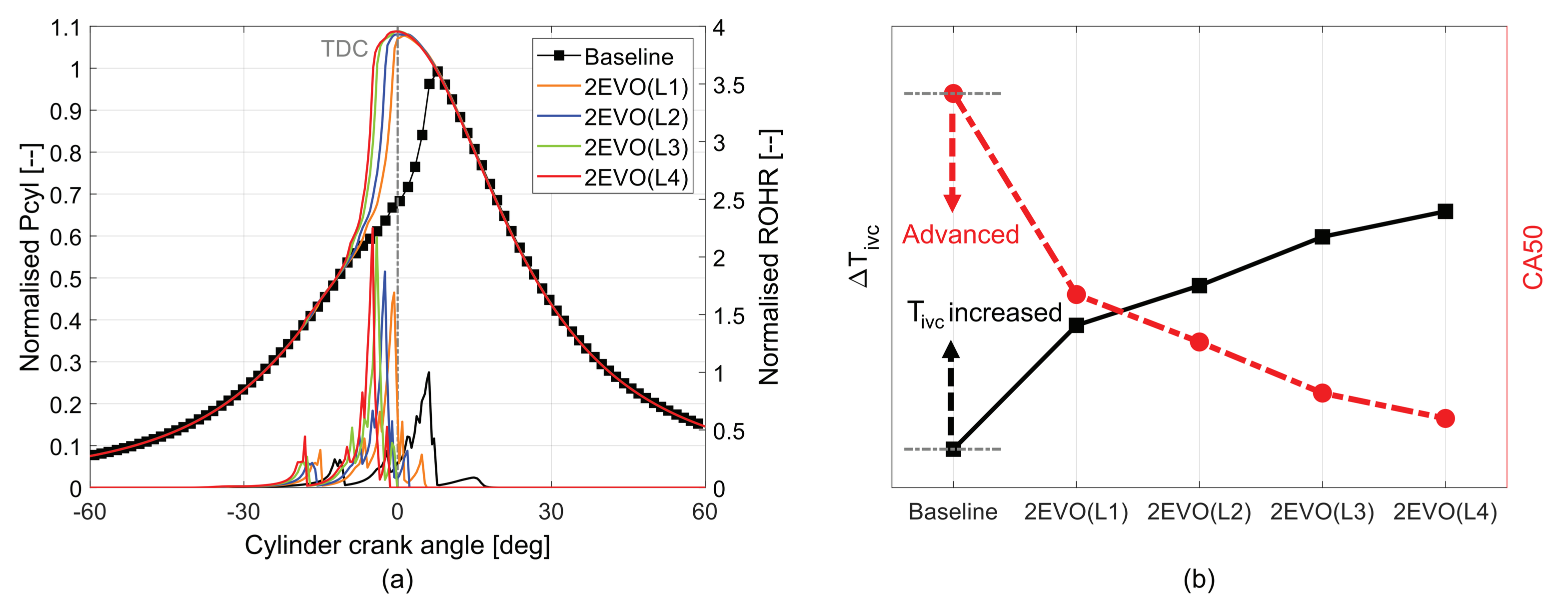

Figure3. Simulation results of 2EVO: (a) normalised in-cylinder pressure (Pcyl) and rate of heat release rate (ROHR); (b) IVC temperature and CA50

Key findings of EIVC:

- Reduced effective compression ratio (ECR) → lower compression temp (T_{ivc}) → long ignition delay → retard combustion onset
- P_{max} / pressure rise rate (PRR) is reduced → effective for high load extension
- Extensive EIVC leads to misfire

Key findings of 2EVO:

- Increased internal-EGR → elevated in-cylinder temp (T_{ivc}) → short ignition delay → advance combustion onset
- Supports higher combustion efficiency, particularly at low loads

- Better low/high load performance when these VVA strategies are combined with blend ratio control for maintaining optimum combustion phasing

4. Future works

- Enhance the model: in-cylinder flow motion (turbulence model), NO_x emission & validation, coupling with multi-cylinder platform, parallel processing
- Systematic optimisation: to achieve ultra-efficient RCCI operation
- Further experimental verification with an electronic-hydraulic valve actuation (EHVA) system

5. References

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[4] Kakoee, A. et al. *"A Predictive 1D Modeling Framework for Reactivity-Controlled Compression Ignition Engines, via a Chemistry-Based, Multizone Combustion Object."* No. 2023-24-0001, SAE Technical Paper (2023).

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Variable Valve Actuation enabled Reactivity-Controlled Compression Ignition in a Natural-Gas/Diesel Marine Engine

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Abstract. The present study numerically investigated two variable valve actuation (VVA) strategies – early intake valve closing (EIVC) and second exhaust valve re-opening (2EVO) with a large bore marine engine operating under natural-gas/diesel RCCI mode. A fully calibrated and validated 1D engine model was utilized for VVA simulation via commercial software, GT-Power. In order to capture RCCI combustion behaviour on VVA, a physic-based chemical kinetic multizone model (UVATZ) was directly coupled with GT-Power. The simulation results revealed that EIVC and 2EVO could control combustion phase and extend load range to some extent by controlling in-cylinder thermal condition right before the combustion initiates. EIVC retards combustion phase by decreasing compression temperature while 2EVO advances combustion onset by increasing in-cylinder temperature by trapping hot residual gases.

1. Introduction

Reactivity-controlled compression ignition (RCCI) is a promising option for maritime decarbonization, offering over 50% thermal efficiency and ultra-low emissions of NO_x and soot [1]. This is achieved through lean combustion, rapid heat release, reduced heat rejection, and low combustion temperatures [1]. RCCI, a dual-fuel concept, can adapt to various zero-carbon fuels and is controlled by thermo-kinetic reactions and in-cylinder fuel stratification. Despite its advantages, RCCI faces challenges in real-world implementation due to limited load range, combustion stability, difficult transients, and poor exhaust thermal management [2]. Adjusting blend ratios or pilot injection timing can mitigate some issues, but RCCI remains sensitive to in-cylinder thermodynamic conditions, especially intake valve closing temperature. Variable valve actuation (VVA) enables ultra-efficient RCCI operation by regulating in-cylinder thermodynamic conditions flexibly [3]. This research examines two VVA strategies: EIVC and 2EVO and their impact on combustion using 1D engine simulation with a predictive multizone, kinetic-based combustion model.

2. Methodology – 1D engine simulation with multizone model (MZM)

The study is based on single cylinder version of a large bore medium speed marine engine. The engine specifications are presented in Table 1.

Table 1. Specifications of research engine and simulation condition

Engine	Wärtsilä 31 DF
Displacement & nominal speed	32.45 L & 720 rpm (4-stroke)
Stroke / bore	1.39
High reactivity fuel (HRF)	$nC_{12}H_{26}$ (ISO 8217 LFO) I Direct-injection
Low reactivity fuel (LRF)	Natural-gas (MN=80) I Port-injection
Valvetrain	Four valves with swirl & tumble ports
Reference operating point	50% load I 0.108 (m/m) HRF/LRF I 49 AFR

Since there is no commercial predictive combustion model for RCCI, a physic-based chemical kinetic multizone model (MZM) was utilized. In-house MZM code, known as UVATZ was originally developed by Vasudev et al. [1]. The UVATZ conceptual framework is illustrated in Figure 1 which is coupled with a one-dimensional (1D) engine model. The initial engine model was developed by Wärtsilä. Its general assumptions are listed in Table 2.

Table 2. Governing assumptions of in-house MZM (UVATZ)

Source code	C++ & Cantera (thermo-kinetic library)
Reaction mechanism	Yao et al. [4]
Zonal configuration	Onion-skin (BL zone + crevice zone)
Interzonal mixing	Diffusion-based, predictive turbulence model
Wall heat loss	Chang et al. [5]; zone dependent
Simulation time	< 3.5 min / cycle (coupled with GT)
HRF stratification	Generated from CFD simulations

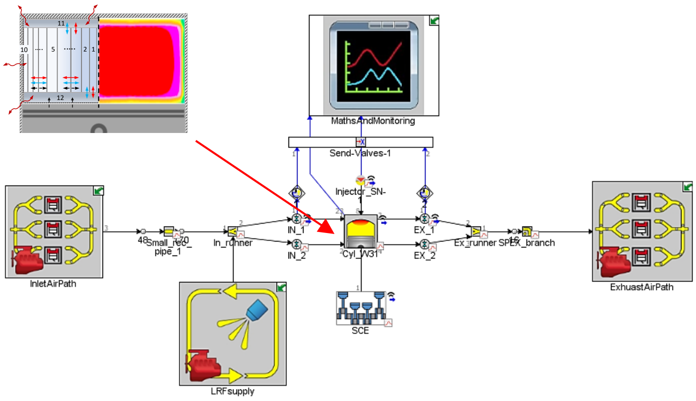

Fig. 1. 1D engine model coupled with in-house MZM (UVATZ)

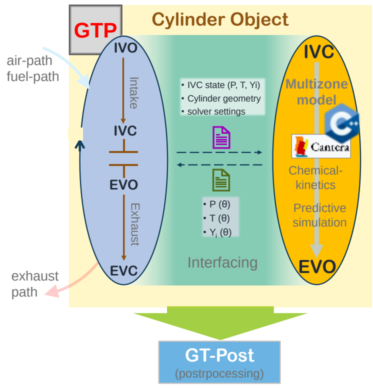

Fig. 2. *Coupling methodology between GT-Power and MZM [6]*

Figure 2 depicts how two models are coupled. From the perspective relevant to the present study, GT-Power handles airpath dynamics and gas exchange process during open cycle (IVO to IVC and EVO to EVC). It enables accurate estimation of in-cylinder conditions at IVC, while changing the valve profiles. UVATZ handles the combustion progress and emission calculation in the closed loop cycle (IVC to EVO), which affect the residual mass temperature and composition. The coupled simulation runs for several cycles until convergence in IMEP and CA50 is reached. The engine model was calibrated and validated with experimental data by Kakoee et al. [6]. The model presented less than 2% error in terms of in-cylinder/ air-path pressure and performance parameters. A mid-load RCCI operating point (where the model was calibrated) was used as reference for the present variable valve actuation study.

Two VVA strategies was investigated as shown in Figure 3. EIVC was realized by advancing IVC timing while maintaining IVO timing and exhaust profile. Three different IVC timings were examined by shifting -10/-20/-30 CAD from the baseline as shown in Figure 3-(a). 2EVO was implemented by re-opening exhaust valves during intake stroke as shown in Figure 3-(b). The opening duration was maintained (100 CAD) but the maximum lift was only varied to adjust hot residual fraction. During VVA simulation, only valve profiles were varied. The other parameters such as injection timing, amount of each fuel, and boost remain unchanged.

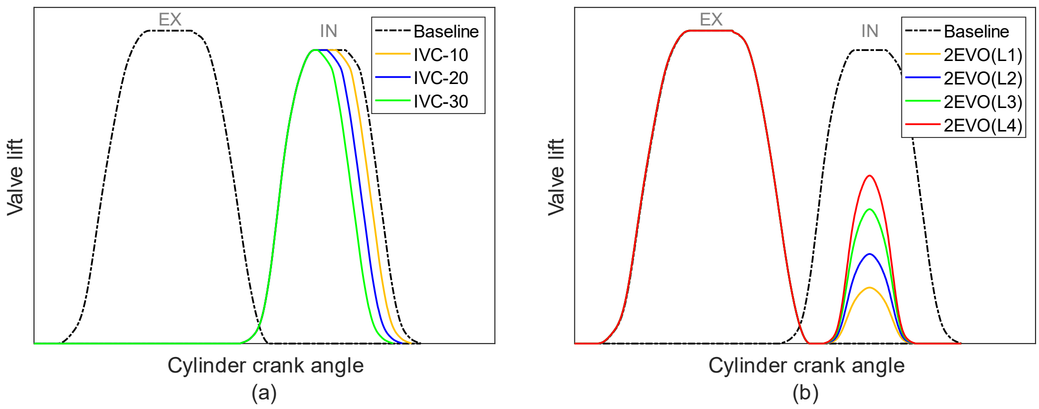

Fig. 3. *Simulated VVA profiles: (a) EIVC; (b) 2EVO*

3. Simulation results and discussions

3.1 Effect of EIVC

Figure 4 shows simulation results of EIVC. With advancing IVC timings, peak of in-cylinder pressure (P_{max}) was reduced. It is mainly attributed to low effective compression ratio where compression pressure and temperature are decreased as shown in Figure 4-(a). In addition, low compression temperature leads to long ignition delay which could promote premixed combustion. However, CA50 is retarded due to delayed combustion onset due to low in-cylinder temperature. This relationship is clearly visible in Figure 4-(b). This also partially contributes to reducing peak of combustion pressure. However, IVC-30 incurs misfire since too low in-cylinder temperature is not able to initiate chemical reaction. For this reason, IVC modulation should be carefully implemented under safe boundary.

EIVC is more effective at high load where there is high temperature margin instead of low and mid load. In addition, the reduced P_{max} and delayed combustion by EIVC allow to increase engine load further without exceeding P_{max} limit. However, EIVC results in trapping less fresh charge by a short intake duration. In order to provide enough oxygen for high load operation, additional boost is necessary to maintain same lambda.

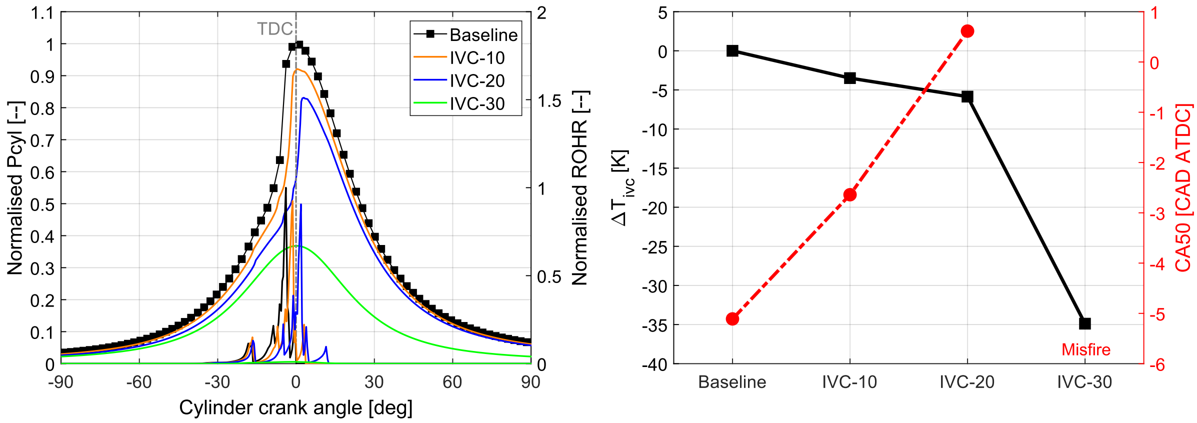

Fig. 4. *Simulation results of EIVC: (a) in-cylinder pressure (P_{cyl}) and rate of heat release rate (ROHR); (b) temperature at IVC (T_{ivc}) and CA50*

3.2 Effect of 2EVO

Figure 5 presents simulation results of 2EVO. Unlike EIVC, 2EVO increases P_{max} as shown in Figure 5-(a). This is associated with increasing in-cylinder temperature. During 2EVO, there is backflow from exhaust to combustion chamber due to high back pressure (P_{ex}>P_{in}). This backflow allows to trap hot exhaust gases, known as internal EGR. The trapped hot exhausts gases elevate in-cylinder temperature directly. The higher lift admits more backflow and raises in-cylinder temperature (T_{ivc}) as shown in Figure 5-(b). In the end, this triggers early ignition and advances combustion phase (CA50) so that P_{max} is increased.

Similar to EIVC, 2EVO also reduces intake fresh charge since the backflow suppresses incoming fresh charge during intake stroke. For this reason, this strategy is applicable at low load where there is less oxygen demand and could improve combustion capability suffering from relatively low in-cylinder thermal status. The improved combustion behaviour could reduce methane slip by improving combustion efficiency. Also, low trapped air mass could increase exhaust temperature due to reduced heat capacity effect [7] which is beneficial to increase conversion efficiency of aftertreatment system at low load operation.

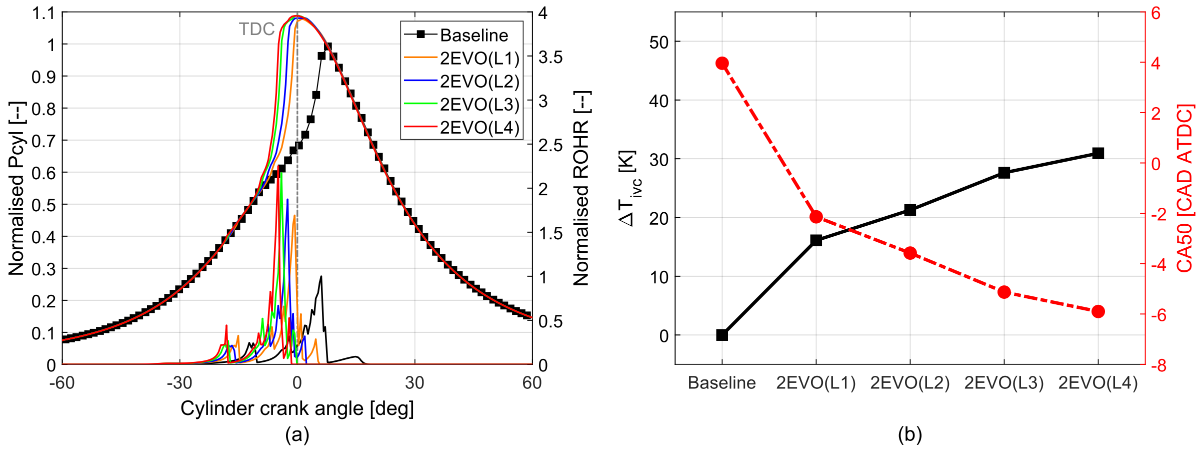

***Fig. 5.** Simulation results of 2EVO: (a) in-cylinder pressure (P_{cyl}) and rate of heat release rate (ROHR); (b) temperature at IVC (T_{ivc}) and CA50*

Conclusions

Two VVA strategies, EIVC and 2EVO were numerically examined with a large bore medium speed marine engine platform operating under natural-gas and diesel RCCI mode. The numerical simulation was conducted with GT-Power coupled with in-house multizone model (UVATZ). The multizone model is essential in this research to predict and capture RCCI combustion behavior with varying in-cylinder thermodynamic conditions by VVA. Both VVA strategies could be effective measures to control combustion and load extension by adjusting in-cylinder thermodynamic conditions. EIVC reduces in-cylinder temperature by reducing effective compression ratio which delay ignition and combustion. The reduced P_{max} and pressure rise rate can be used for high load extension. 2EVO increases in-cylinder temperature by trapping hot exhaust gases which promote ignition and advance combustion onset. The capability to improve combustion is beneficial for low load operation/ extension. The additional benefit is low methane slip and better exhaust thermal management.

Future works

Since the current study was carried out numerically, further experimental verification is required. This will be considered with an electronic-hydraulic valve actuation (EHVA) system in on-going research. Furthermore, systematic optimization will be performed for efficient RCCI operation.

References

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