

## Research Paper

# A new control strategy for charge air pressure in a heavy-duty cyclops RCCI test engine

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## ABSTRACT

This study presents a control-oriented strategy for enabling safe and efficient operation of a dual-mode RCCI–diesel research engine using a stock single-stage turbocharger. To the authors' knowledge, the specific challenge of controlling charge-air pressure in a heavy-duty cyclops RCCI–diesel configuration, where one RCCI cylinder and three conventional diesel cylinders share the same stock twin-scroll turbocharger, has not been experimentally addressed in previous RCCI boosting studies. The originality of this work lies in using cylinder-individual combustion control to regulate scroll-wise exhaust energy distribution and turbocharger operation without external boosting hardware or major airpath modification. Conventional low-temperature combustion (LTC) engines often require costly external supercharging systems for sufficient charge air supply, but the proposed approach combines stock turbocharger hardware with a real-time control algorithm to extend the operable load range. Four complementary strategies – advanced start of injection, increased rail pressure, selective activation of the RCCI cylinder and rebalanced diesel injection quantities across cylinders – were coordinated to regulate exhaust thermal load on the twin-scroll turbine. Steady-state experiments at >200 operating points demonstrated successful control of turbocharger operation within surge, choke and thermal limits, while supporting the RCCI cylinder's pressure-ratio demand between 1.0:1 and 3.48:1. The developed algorithm enabled stable engine operation up to 686 kW, with peak turbine inlet temperature constrained to 597 °C, below the 600 °C material threshold. Sensitivity analysis revealed that engine load was the dominant driver of turbine exhaust temperature (42.9% upper case, 27.4% lower case), whereas injection timing and rail pressure provided negative sensitivities, confirming their thermal mitigation role. RCCI cylinder activation and diesel rebalancing strategies effectively redistributed thermal load between turbine scrolls, offering robust scroll-wise management of exhaust asymmetry. The findings highlight a low-cost, software-driven pathway to extend the operability of RCCI engines without hardware modifications, demonstrating practical relevance for marine and large-bore applications. The methodology contributes to the advancement of sustainable, high-efficiency combustion concepts by integrating conventional boosting components with advanced combustion control.

## 1. Introduction

The increasing global demand for energy and the continued reliance on fossil fuels have increased awareness of limited energy resources. The transport sector, in particular, accounts for a significant portion of global energy consumption, leading to serious environmental challenges. Its high energy use generates greenhouse gas emissions, which not only worsen air pollution but also trigger irreversible climate change such as global warming. This underscores the need for urgent adoption of sustainable transport. Electric vehicle technologies have initiated a

major transformation in the automotive sector, but heavy-duty diesel engines continue to play a critical role in the maritime industry, where large-scale propulsion systems are essential for commercial transport and logistics. Full electrification is often considered technically and economically infeasible for power outputs exceeding 360 kW, due to limitations in energy density, battery weight, charging infrastructure and the need for operational flexibility over long distances. Consequently, researchers are expected to continue focusing on internal combustion engines, particularly in the marine sector, developing solutions which operate on alternative fuels with the aim of achieving

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lower emissions, reduced fuel consumption and higher thermal efficiency. They seek to push the boundaries of current engine technologies, exploring new solutions in terms of both performance and environmental sustainability. [1–4].

Conventional spark-ignition (SI) gasoline engines and compression-ignition (CI) diesel engines, while dominant in the transport sector for decades, present significant efficiency and emissions limitations. SI engines typically suffer from throttling losses and operate at lower compression ratios, which restrict thermal efficiency. On the other hand, CI engines, although more efficient due to higher compression ratios and lean operation, are often associated with high levels of nitrogen oxides (NO<sub>x</sub>) and particulate matter (PM) emissions. These drawbacks have intensified the search for alternative combustion strategies able to simultaneously reduce emissions and improve fuel economy. Reactivity-controlled compression ignition (RCCI) engines have emerged as a promising solution. RCCI uses two fuels with different reactivities – typically a low-reactivity fuel such as natural gas or gasoline, and a high-reactivity fuel like diesel or biodiesel – to enable controlled auto-ignition and a highly homogeneous charge. This leads to improved combustion efficiency, lower peak temperatures and thus significant reductions in NO<sub>x</sub> and soot emissions. Furthermore, RCCI demonstrates potential for high thermal efficiency and operational flexibility, making it a strong candidate for next-generation, low-emission internal combustion engine technologies [5–10].

Dual-fuel operation – typically combining diesel and natural gas – and advanced combustion strategies such as RCCI are gaining attention as viable pathways to reduce emissions, while maintaining high power output and fuel flexibility. Operating marine engines in RCCI mode enables cleaner combustion through controlled auto-ignition and improved thermal efficiency, which are vital for meeting stringent emission regulations in emission control areas (ECAs). However, adapting such advanced combustion strategies to large marine engines presents significant research and development challenges, including complex fuel injection control, combustion stability across varying load conditions and the integration of novel engine management systems into existing platforms. These factors underline the need for continued innovation and robust experimental validation to realise clean and

efficient marine propulsion [5,11–12].

Boosting is no longer merely a means of increasing engine power but is rather an integral element of the overall combustion control strategy, particularly for next-generation engines realising low-temperature combustion like RCCI. Optimal combustion phasing and efficiency in RCCI operation are typically achieved under ultra-lean conditions, where the optimum global excess air ratio ( $\lambda$ ) lies well beyond stoichiometric values, as widely reported in the literature [5–7]. Intake pressure under such conditions directly governs mixture reactivity, combustion stability and load capability, making charge air boosting a key control input for combustion behaviour. Consequently, understanding and managing boost pressure within an integrated control framework is essential for enabling stable and efficient RCCI operation. The following section reviews the state of the art in RCCI combustion control and boosting strategies. Fig. 1 illustrates the classification of previous studies on charge air boosting methods in RCCI engines, categorised into six major technological approaches and application scopes. Several previous studies have employed compressed building air systems as a method to precisely control intake conditions for RCCI engine research. Splitter et al. [13–14] used compressed building air to explore intake and charge effects on a single-cylinder RCCI engine. They demonstrated how varying intake pressures and temperatures could significantly affect RCCI combustion phasing, thermal efficiency and emission profiles, identifying optimal combinations for enhancing engine efficiency. DelVescovo et al. [15] employed a compressed building air system in their experiments to investigate the effects of charge preparation and fuel stratification on RCCI combustion in a single-cylinder engine. They demonstrated that varying the start of injection timing and global equivalence ratios significantly influenced combustion phasing, with peak gross efficiency observed at intermediate injection timings. Additionally, late injection timings were shown to reduce combustion efficiency and significantly increase NO<sub>x</sub> emissions, highlighting the critical role of precisely controlled intake conditions in optimising RCCI combustion performance and minimising emissions. Similarly, Merts et al. [16] conducted optical investigations using a medium-speed engine configured for dual-fuel RCCI combustion, using compressed building air to mimic realistic turbocharged intake

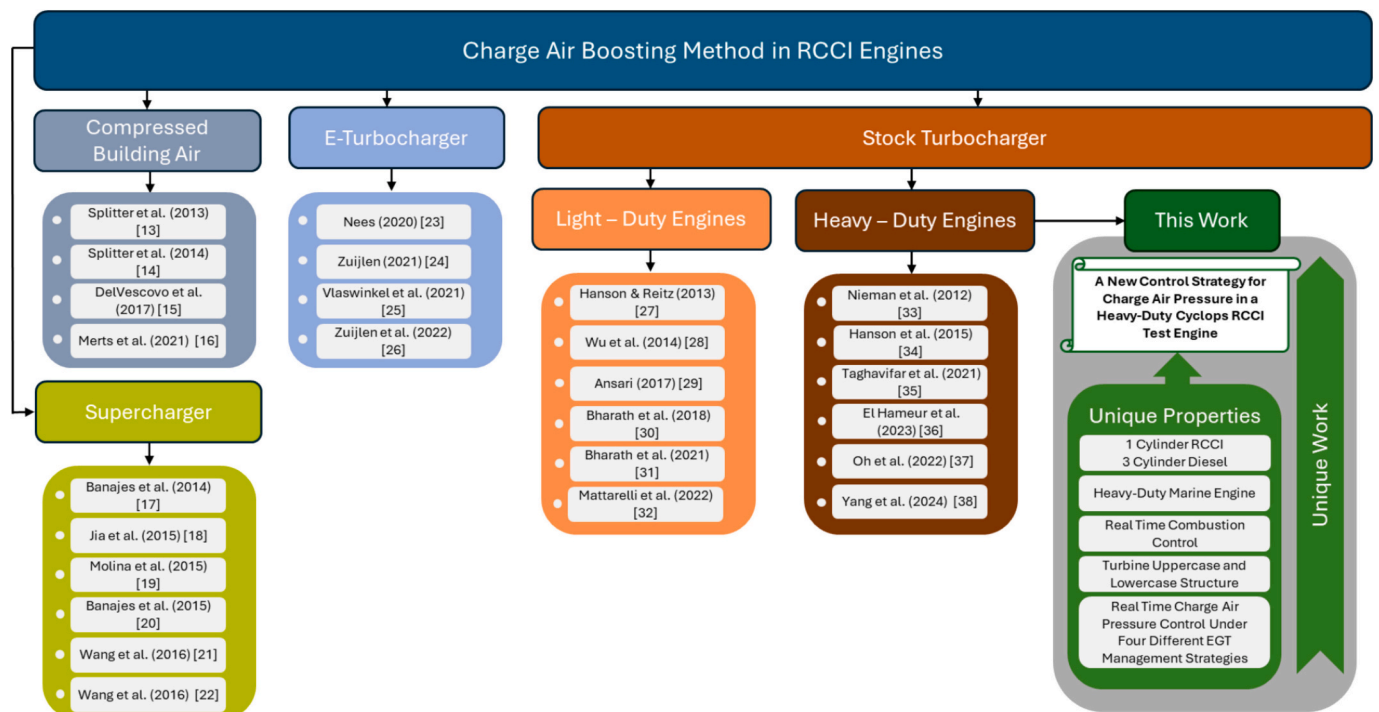


Fig. 1. An overview of prior studies on charge air pressure boosting in RCCI engines.

conditions. Although a six-cylinder test engine used, only one cylinder was operated in RCCI mode and the remaining cylinders were inactive. This setup allowed detailed optical diagnostics of combustion, highlighting differences in ignition characteristics and heat release relationship between RCCI and conventional dual-fuel operation. The present RCCI study used compressed building air to ensure stable and consistent intake conditions, independent of variations in exhaust gas temperature or mass flow, thus eliminating potential cross-dependencies among critical engine parameters during the experimental campaigns.

Supercharging to enhance air mass flow rates has also been extensively investigated, particularly at lower engine-speeds, where natural aspiration becomes limiting. Benajes et al. [17] used mechanically driven superchargers in a diesel-RCCI configuration using a single-cylinder, heavy-duty engine to assess their impact on cyclic variability and low-load operability. Their results showed that supercharging reduced cycle-to-cycle variability, while enabling stable RCCI combustion under previously unattainable conditions. Jia et al. [18] focused on the thermal and volumetric efficiency implications of boost-on-demand configurations during transient load shifts. They used a single-cylinder, heavy-duty research engine fuelled with natural gas and diesel under RCCI combustion conditions. An electrically assisted mechanical supercharger regulated intake manifold pressure across different load transitions. The experimental results revealed that increased intake boost led to higher charge density, enabling more stable ignition and faster combustion phasing, even under high EGR-dilution conditions. This approach significantly enhanced transient responsiveness and reduced combustion delays by improving mixing and reactivity control. Moreover, the study emphasised that proper boost scheduling was crucial for optimising fuel reactivity stratification and mitigating the trade-off between combustion efficiency and NO<sub>x</sub> emissions during dynamic engine operation. Molina et al. [19] extended the analysis by combining experimental testing with computational fluid dynamics (CFD) simulations to evaluate RCCI performance from low- to full-load operation. The study concluded that appropriate intake pressurisation was essential for managing in-cylinder reactivity and mitigating pressure rise rates, particularly at high loads. In another study, Benajes et al. [20] examined the effect of different compression ratios in the same engine and confirmed that the use of moderate boost levels facilitated full-load RCCI operation, while simultaneously meeting stringent NO<sub>x</sub> and soot emission targets, especially with optimised combustion phasing and direct-injection timing. Wang et al. [21,22] advanced this concept through numerical optimisation of supercharger performance maps, tailored for RCCI combustion. Their models showed that moderate boost pressures promoted earlier combustion phasing while reducing ringing intensity, thereby balancing combustion stability and thermal efficiency. Intake pressure in all these studies was precisely regulated using electrically driven mechanical superchargers to ensure stable air delivery, independent of exhaust gas temperature, mass flow rate or turbocharger lag - factors which typically vary with engine speed and load conditions.

Recent studies [23–26] have explored electrically assisted turbochargers (*E*-turbos) as a solution to the transient response limitations inherent in conventional turbine systems. Nees et al. [23] investigated an *E*-turbo on a four-cylinder RCCI engine, where all cylinders operated in RCCI mode and the electric motor was coupled directly to the turbocharger shaft. Their findings showed that the *E*-turbo enabled real-time boost modulation, which significantly improved control of the intake charge and facilitated earlier combustion phasing, without increasing knock intensity under load variation. Building upon this, Zuljen et al. [24] and Viswanikel et al. [25] introduced hybrid boosting strategies which integrated *E*-turbo operation with dynamic EGR and lambda control. These studies, conducted on multi-cylinder heavy-duty platforms operating fully in RCCI mode, revealed that hybrid boosting could refine charge preparation and reduce combustion instability at part-load by enhancing fuel–air mixture uniformity and suppressing cylinder-to-cylinder variability. Furthermore, Zuljen et al. [26]

demonstrated that the *E*-turbo provided rapid torque response and improved the operating range, without sacrificing combustion efficiency. Unlike conventional mechanical or pneumatic boosting systems, the *E*-turbo offers decoupled and flexible control over intake pressure dynamics, independent of exhaust gas enthalpy. This makes it particularly suitable for RCCI engines where precise control of combustion phasing is essential.

Recent research on light-duty RCCI engines has explored various strategies for managing combustion phasing and emissions under realistic driving conditions, with a particular focus on maximising the effectiveness of stock turbocharging systems. Hanson and Reitz [27] conducted one of the earliest investigations into transient RCCI operation, using a multi-cylinder engine equipped with a stock variable geometry turbocharger (VGT). Their work emphasised the feasibility of RCCI during load transitions, demonstrating improved control via closed-loop phasing without requiring hardware beyond production-level components. Wu et al. [28] expanded on this by employing detailed CFD modelling to refine combustion control strategies during transient load changes. Their simulations, validated against experiments on a multi-cylinder test engine, accounted for intake pressure lag associated with turbocharger response delays and informed adaptive fuel-blending techniques. Ansari [29] approached the problem through model-based calibration, using experimental data from a four-cylinder, light-duty diesel engine. With emphasis on optimising injection and airpath parameters, the study retained the stock boosting system to examine emissions compliance and operational cost. Bharath et al. [30] introduced a novel divided exhaust strategy on a simulated multi-cylinder RCCI engine, retaining conventional boosting while using valve control to improve gas exchange efficiency. In a complementary simulation study, Bharath et al. [31] explored active control of VGT actuation in a light-duty RCCI engine, showing that dynamic modulation of the stock turbocharger could enhance fuel economy and torque performance without structural modifications. Mattarelli et al. [32] applied 1D-CFD to examine the feasibility of two-stroke RCCI operation, using a virtual engine derived from a modified four-cylinder platform. Their findings suggested that adapting standard four-stroke engine hardware for two-stroke RCCI could mitigate load limitations while preserving combustion uniformity.

Despite growing interest in RCCI combustion, studies on heavy-duty engine platforms remain relatively limited, with most efforts focused on system-level analysis and boosting strategy integration. Nieman et al. [33] investigated RCCI operation using a high-displacement, single-cylinder engine derived from a heavy-duty, multi-cylinder platform. Their work centred on dual-fuel natural gas/diesel combustion and evaluated the interaction between combustion phasing and turbocharger dynamics under low- temperature combustion regimes. The study revealed that turbo lag and limited exhaust enthalpy posed significant constraints on stable RCCI operation, especially under rapid load transients. Hanson et al. [34] used a multi-cylinder, heavy-duty platform with natural gas/diesel fuelling and a production-based turbocharger setup, proposing an adaptive injection methodology to extend RCCI operation across a wider load range. In a complementary modelling effort, Taghavifar et al. [35] employed 1D thermodynamic simulations of a multi-cylinder, marine-scale RCCI engine to assess system-level energy and exergy flows. Their model included a conventional turbocharging system and highlighted how turbocharger inertia and heat loss in the intake and exhaust paths could restrict overall efficiency under dual-fuel combustion. El Hamouz et al. [36] explored the broader decision-making framework for turbocharging heavy-duty engines under advanced combustion modes, focusing on intake tuning and system flexibility as key parameters. While not exclusively focused on RCCI, their insights informed the importance of airpath adaptation for viable implementation of reactivity-controlled combustion. Oh et al. [37] conducted experimental work using a six-cylinder turbocharged diesel engine, operated in dual-fuel RCCI mode with diesel and natural gas. The engine retained a stock turbocharger configuration, and the

study focused on quantifying how boost pressure variations affected emissions and thermal efficiency under different combustion regimes. They found that adjusting lambda through turbocharger control was essential, not only for NO<sub>x</sub> suppression, but also for maintaining combustion stability. Most recently, Yang et al. [38] examined a marine-type, dual-fuel RCCI engine operating with diesel and natural gas. Their experiments were carried out on a multi-cylinder test platform, equipped with a conventional boosting system. The study introduced a new method for identifying and quantifying multi-stage heat release events caused by diesel split injection, and demonstrated how optimised injection phasing could improve combustion efficiency while reducing incomplete combustion products. In all the aforementioned studies on both light-duty and heavy-duty RCCI engines, stock turbochargers were applied either to single-cylinder research engines or to multi-cylinder configurations in which all cylinders operated in RCCI mode.

The limitations of stock turbocharging outlined in the preceding review present a pivotal barrier to the further development of RCCI combustion. Beyond issues of boost stability and exhaust energy imbalance, turbine thermal durability is a critical operational constraint, since turbine inlet temperatures must generally be kept below 600–650 °C to prevent material degradation and ensure long-term reliability [39–41]. This constraint becomes particularly restrictive in mixed combustion modes, where cylinder-to-cylinder variability in exhaust temperature and energy release is inherently amplified. Although previous RCCI studies have demonstrated the importance of intake pressure control for combustion phasing, load extension and emission reduction, the current state of the art still presents several important limitations. Compressed building air and supercharging systems provide accurate control of intake conditions, but they introduce additional hardware complexity and do not represent a directly scalable solution for large-bore marine engines. Electrically assisted turbochargers offer enhanced air-path flexibility, but they require dedicated electromechanical hardware and additional integration effort. Studies using stock turbochargers have mainly focused either on single-cylinder research engines or on multi-cylinder configurations in which all cylinders operate in RCCI mode. Therefore, to the authors' knowledge, the specific challenge of operating a heavy-duty cyclops configuration, where one cylinder operates in RCCI mode while the remaining cylinders operate in conventional diesel mode and share the same stock twin-scroll turbocharger, has not been sufficiently addressed. In such a mixed-mode configuration, the low exhaust temperature of the RCCI cylinder and the unequal exhaust energy contribution of the diesel cylinders create scroll-wise thermal asymmetry, which directly affects turbine loading, compressor operation and charge-air pressure control.

To address this gap, the present study experimentally demonstrates a novel software-driven charge-air control strategy for a heavy-duty cyclops RCCI-diesel research engine using a stock single-stage twin-scroll turbocharger. The main scientific contribution of this work is the coordinated use of four control actions—diesel start-of-injection advancement, diesel rail-pressure increase, selective activation of the RCCI cylinder and cylinder-individual diesel injection rebalancing—to regulate turbine thermal loading and charge-air pressure without external supercharging hardware or major airpath modification. This approach enables simultaneous management of exhaust energy distribution, turbine thermal constraints, compressor surge/choke boundaries and RCCI cylinder pressure-ratio demand. By combining the experimental fidelity of single-cylinder research setups with the realism and scalability of a multi-cylinder turbocharged platform, the proposed cyclops architecture provides a practical and experimentally validated pathway for extending RCCI operability in large-bore marine engine research platforms while preserving the original turbocharging architecture.

This control-centric architecture also offers a cost-effective research and development solution, particularly for large-scale marine engines, by reducing the need for hardware-intensive prototyping and external compressor systems. While the primary goal is to facilitate combustion

development under flexible research conditions, the proposed control concept is also relevant for future large-bore engine applications operating with low- and zero-carbon fuels under ultra-lean combustion conditions.

## 2. Methods

### 2.1. Hybrid single-/multi-cylinder research engine setup

The object of this study is a multipurpose, large-bore engine test bench designed to facilitate efficient development of advanced combustion concepts in various technology readiness levels (TRLs). It features single-cylinder research engine (SCRE) functionality implemented on a multi-cylinder version of the Wärtsilä 20 engine product family. Fig. 2 depicts a schematic of the mechanical test setup: Table 1 summarises the test engine's key technical specifications.

The baseline Wärtsilä 4 L20 engine features a four-cylinder, in-line configuration and is designed as a modular, common-rail based, development platform for Wärtsilä's medium-speed, 200 mm-bore engine family. This range of engines typically is used in genset or main propulsion applications. The baseline engine configuration is a four-cylinder, heavy-duty CI engine with a stock compression ratio of 15.8:1, equipped with a factory-installed common-rail direct injection (CRDI) system and a single-stage turbocharger. In the baseline configuration, all four cylinders operate under conventional diesel combustion, with camshaft-driven valve actuation and an unmodified intake and exhaust airpath architecture. The turbocharger features a divided turbine housing with upper and lower scrolls, where cylinders 2 and 3 are connected to the upper scroll, and cylinders 1 and 4 to the lower scroll.

A dedicated test functionality for RCCI investigations was implemented on the fourth cylinder, while the remaining cylinders kept their standard configuration. The compression ratio of the fourth cylinder was reduced from the original diesel value of 15.8:1 to 13.44:1 using a dedicated flat-piston RCCI retrofit. This reduction was required to moderate the end-of-compression temperature and pressure under natural gas/diesel RCCI operation, thereby avoiding excessively advanced auto-ignition and high pressure rise rates. The selected value represents a compromise between preventing premature combustion and maintaining sufficient charge reactivity for stable pilot-assisted RCCI operation under boosted conditions. Cylinders 1, 2 and 3 remained unaltered and continued operating in conventional diesel combustion mode using the CRDI system. The RCCI-enabled cylinder was configured with dual-fuel injection, employing port fuel injection (PFI) for natural gas and high-pressure direct injection for diesel pilot fuel. In addition, the RCCI cylinder's valve actuation system was substantially re-engineered, with an electro-hydraulic valve actuation (EHVA) system instead of the camshaft-driven mechanism. The EHVA unit operates independently via a dedicated hydraulic pump, capable of supplying pressures up to 250 bar for flexible and precise valve timing essential for RCCI combustion control.

To preserve the engine's original airpath configuration and maintain mechanical simplicity, the stock single-stage turbocharging system was retained during RCCI operation. Consequently, the turbine is exposed to exhaust gases originating from both conventional diesel combustion and RCCI modes. Due to the distinct combustion characteristics of RCCI, particularly its lower exhaust gas temperatures and mass flow compared with diesel combustion, significant exhaust energy imbalance may arise at the turbine inlet under this mixed-mode operation. This non-uniform energy distribution can influence turbine loading and charging behaviour, forming a key aspect of the experimental challenge addressed in this study.

Intake airflow was measured using an orifice-plate-based flow meter placed upstream of the compressor. The compressed air was cooled using a water-cooled, charge air cooler, integrated into a two-circuit cooling system consisting of high-temperature (engine block) and low-

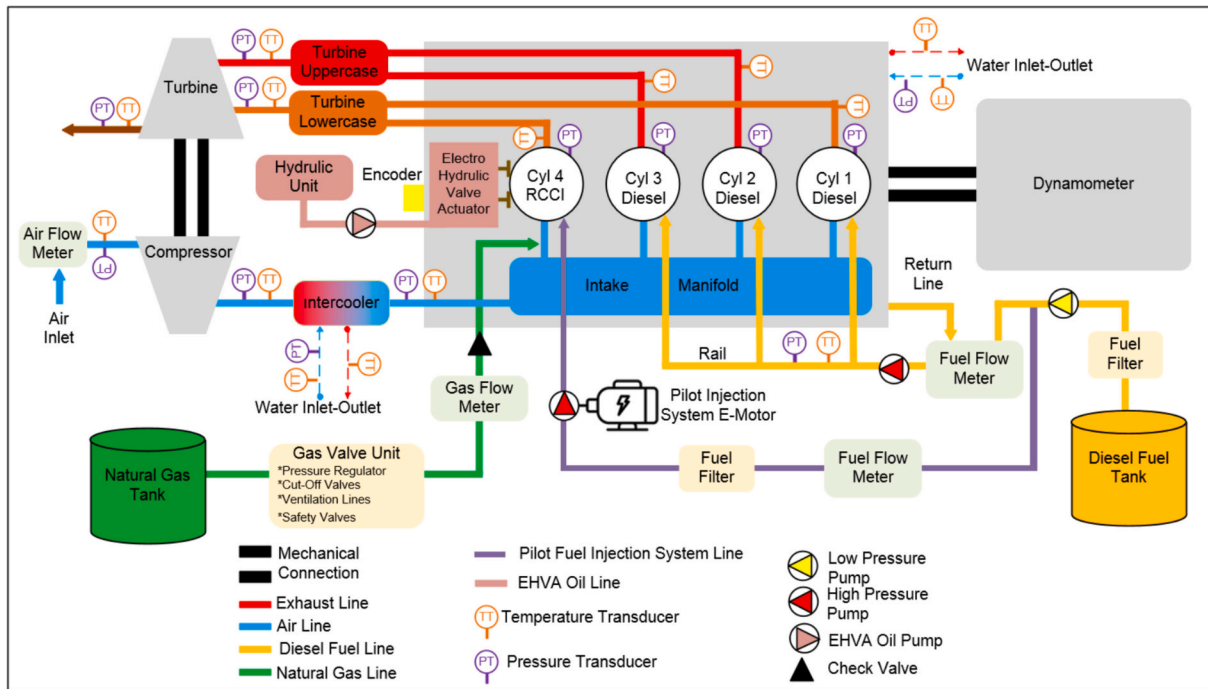


Fig. 2. Schematic view of experimental engine test setup.

Table 1  
Specification of the Wärtsilä 4 L20 research engine with RCCI retrofit.

Engine	Wärtsilä 4 L20 Diesel	RCCI retrofit
Cylinder configuration	four-cylinder, inline	Semi-decoupled 1-cylinder with common airpath and individual fuel paths
Bore [mm]/ Stroke [mm]	200 / 280	200 / 280
Cylinder displacement [dm <sup>3</sup> ]	8.8	8.8
Compression ratio	15.8:1	13.44:1
Diesel fuel system	CRDI – Wärtsilä, engine-driven HP pump; solenoid common-rail injector	CRDI – independent electrically driven HP pump; solenoid common-rail injector
Gas fuel system	–	PFI 20 bar
Valve system	Cam-based four valves/cylinder	EHVA four valves/cylinder
Airpath	Single-stage turbocharger; up to 8 bar boost pressure, charge air cooler	
Rated RPM	1000	

temperature (intercooler) loops. The engine was loaded using a 1050 kW AC dynamometer, connected to the power grid via a frequency converter. Separate fuel supply lines and flow meters were installed for diesel (for both conventional and pilot injection), as well as for natural gas injection.

## 2.2. Electronic management and data acquisition system

The control architecture of the experimental test setup was designed to ensure precise, real-time management of various subsystems, especially those for RCCI combustion. It used a multi-module control scheme, distributed across five dedicated computers located in the control room. These computers handled load control, combustion actuation, data acquisition and safety monitoring. Fig. 3 is a schematic representation of the electronic control structure.

The engine load is controlled via a programmable logic controller (PLC)-based interface connected to the dynamometer. The electrical

power generated by the engine is fed into the public grid through a frequency converter and transformer system. PLC modules are also responsible for controlling auxiliary systems such as the low-pressure diesel transfer pumps, pilot fuel electric motors and natural gas solenoid valves. SpeedGoat real-time target machines were used extensively for real-time control and signal processing. The primary SpeedGoat module manages key engine functions, including sensor data acquisition and actuator control. A separate, dedicated SpeedGoat unit was allocated solely to the electro-hydraulic valve actuation (EHVA) system, due to its stringent real-time requirements. This separation ensures both system stability and operational safety. The technical configuration of the Speedgoat real-time target machines used in the test setup is presented in Table 2. The camshaft for the RCCI cylinder was deactivated, so valve operation relied entirely on synchronisation with the crankshaft. Any loss of synchronisation could result in valve-piston interference, necessitating robust fail-safe algorithms and high-frequency control loop execution.

Cylinder pressure and crank-angle data were recorded using a data acquisition module connected to the crankshaft encoder and in-cylinder pressure transducers. All analogue and digital data were monitored and stored using DeweSoft software, enabling high-resolution logging of pressure, temperature, flow rate and system status signals throughout the tests. The gas temperatures at the turbine inlet were measured separately at the upper and lower casing locations, while the turbine outlet gas temperature was measured at a single point. All temperature measurements were performed using K-type thermocouples with a measurement range of  $-200\text{ }^{\circ}\text{C}$  to  $+1350\text{ }^{\circ}\text{C}$ . Emissions from the RCCI cylinder were analysed through a separate exhaust sampling line, ensuring that gas measurements were not contaminated by the exhaust from diesel-operating cylinders. This isolated measurement approach provides an accurate assessment of combustion behaviour and emission characteristics specific to RCCI operation. All control and data acquisition modules communicate via standardised industrial protocols, including Modbus, Ethernet and CAN bus. This interconnected architecture ensures high-speed data sharing between modules, real-time system response and robust coordination across all the subsystems.

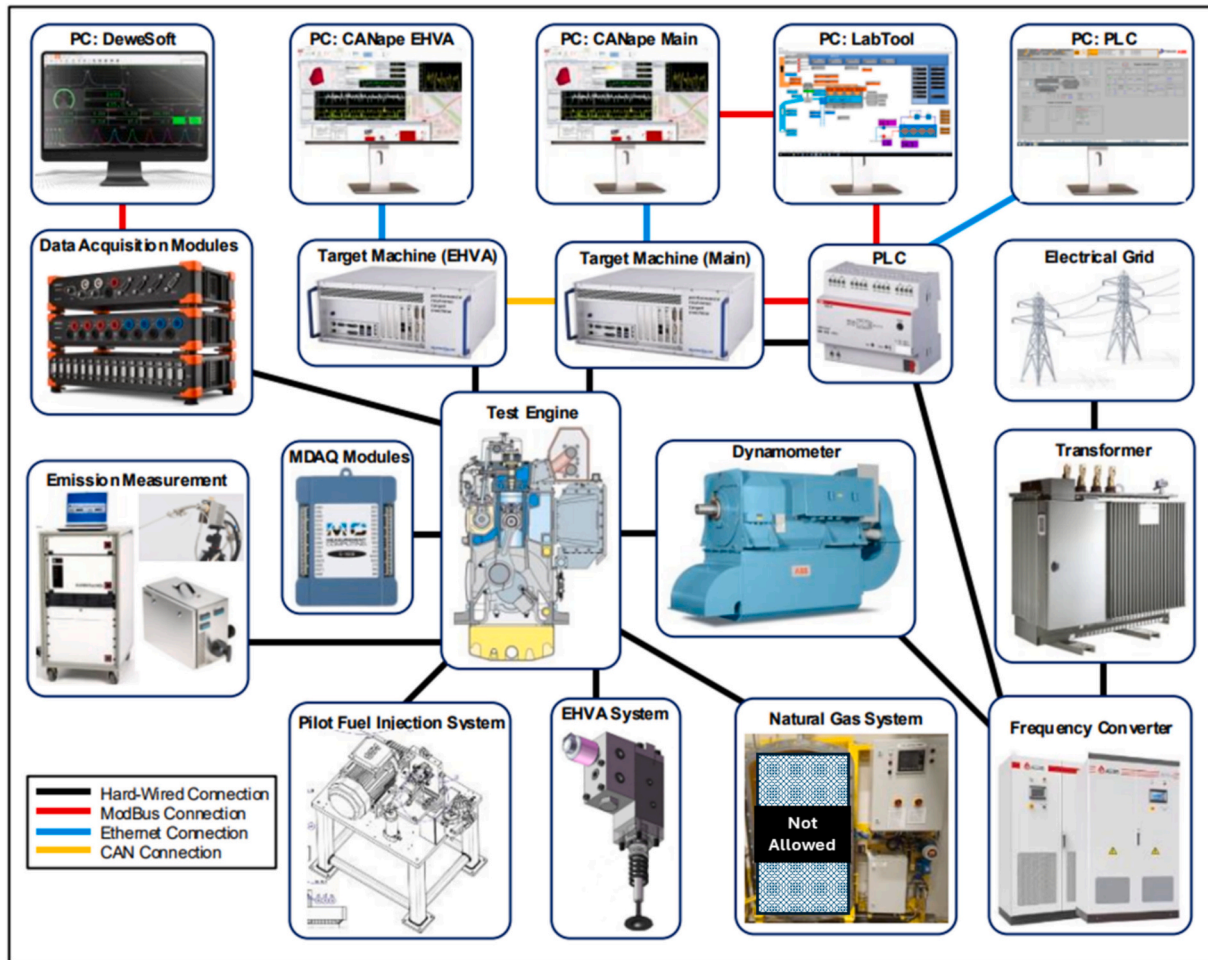


Fig. 3. Schematic view of electronic management of engine test setup.

Table. 2  
Technical configuration of the Speedgoat real-time target machines used in the test setup.

Unit	Module	Technical function	Role in the experimental setup
Main Speedgoat	IO106–64/ 32	64 single-ended or 32 differential analog inputs; 16-bit A/D resolution; 200 kSPS per channel; $\pm 10$ V, $\pm 5$ V, $\pm 2.5$ V, 0–5 V and 0–10 V input ranges	Runs the main engine management algorithm developed in MATLAB/Simulink
	IO143	8 single-ended analog outputs; 16-bit D/A resolution; 24 $\mu$ s settling time; max. 38 kSPS simultaneous D/A conversion; $\pm 5$ V, $\pm 10$ V, $\pm 12$ V, 0–5 V and 0–10 V output ranges; 20 digital I/O lines	Reads analog sensor signals and provides analog outputs for actuator control
	IO205	32 galvanically isolated digital outputs; 6–48 V DC external supply range; 0.5 A typical output current per channel; 1.1 V typical voltage drop at 0.5 A	Provides digital output signals for control and switching operations
	IO206	32 galvanically isolated digital inputs; 8 V, 12 V or 24 V input variants; 24 V DC +20% maximum input voltage; configurable debounce time from 7 $\mu$ s to 440 ms	Acquires digital input signals from the test setup
	IO333–6	16 analog inputs; 16-bit A/D resolution; 500 kSPS per channel; 8 analog outputs with 10 $\mu$ s settling time; 16 TTL digital I/O lines	Receives real-time FPGA-based combustion parameters such as maximum in-cylinder pressure and maximum pressure rise rate
	IO601	2 galvanically isolated CAN interfaces; CAN HS: 10 kBAud–1 Mbaud; CAN LS: 10 kBAud–125 kBAud; 1000 VDC CAN-bus isolation; LIN voltage range: 8–18 V	Enables CAN communication between the Main Speedgoat and the EHVA Speedgoat
	IO753	Modbus TCP client module; 2 RJ45 Ethernet ports; up to 16 linkable servers; 5760 bytes maximum RX/TX data length; 10/100 Mbit/s communication rate	Communicates with PLC modules over the Modbus TCP line
EHVA Speedgoat	IO754	Modbus TCP server module; 2 RJ45 Ethernet ports; TCP port 502; 5760 bytes maximum I/O-mode data length; 65,536 bytes maximum message-mode data length; 10/100 Mbit/s communication rate	Supports Modbus TCP communication with PLC-based subsystems
	IO333–6	16 analog inputs; 16-bit A/D resolution; 500 kSPS per channel; 8 analog outputs with 10 $\mu$ s settling time; 16 TTL digital I/O lines	Runs the high-precision real-time control algorithm for EHVA valve timing and lift
	IO601	2 galvanically isolated CAN interfaces; CAN HS: 10 kBAud–1 Mbaud; CAN LS: 10 kBAud–125 kBAud; 1000 VDC CAN-bus isolation; LIN voltage range: 8–18 V	Provides CAN communication with the main Speedgoat while keeping the EHVA control algorithm independent

2.3. RCCI boost control strategy via cylinder-individual load control

managing charge air pressure under mixed-mode RCCI–diesel operation. Unlike conventional setups, where charge air pressure is governed by hardware modifications such as variable geometry turbines or

Fig. 4 illustrates this study's proposed novel control strategy for

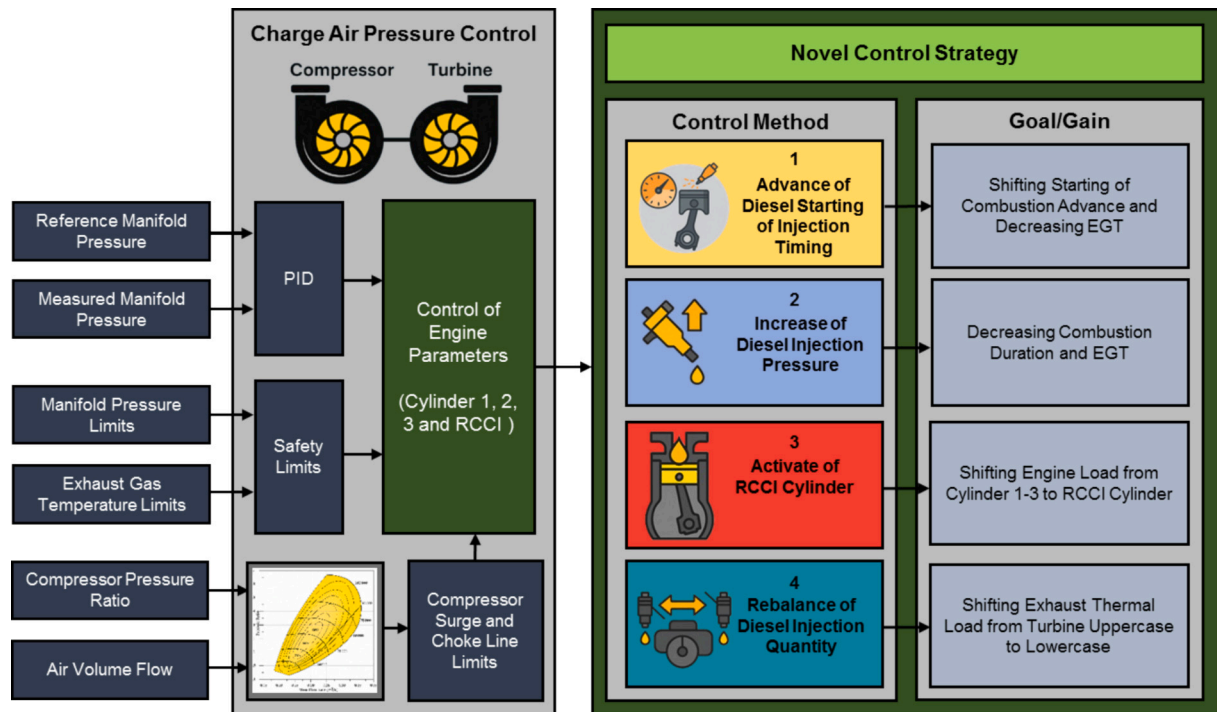


Fig. 4. Control strategy of charge air pressure.

electrically assisted superchargers, the proposed strategy leverages fully software-driven manipulation of combustion-related parameters across all four cylinders, including the RCCI cylinder. At the core of the system lies a closed-loop control architecture, using a proportional-integral-derivative (PID) controller to maintain the manifold pressure at a reference value, while continuously monitoring exhaust gas temperatures (EGT), compressor pressure ratio and airflow. Safety thresholds are enforced to prevent operation outside turbocharger surge and choke limits. The controller dynamically adjusts injection timing, pressure and cylinder load distribution to modulate the thermal energy delivered to the turbine, thereby influencing the turbocharger's operating point in real time.

The methodology involves four sequential control actions:

**Advancement of diesel injection timing (Strategy 1):** Advancing the start of diesel injection shifts the combustion event closer to the top dead centre (TDC), enabling earlier completion of the main heat release phase. This reduces the likelihood of combustion continuing into the exhaust stroke, thereby lowering exhaust gas temperature (EGT) and minimising residual heat transfer to the turbine. By controlling post-combustion heat release, this strategy allows thermal energy moderation in the upper and lower case of the turbine, contributing to improved charge air pressure balance and preventing excessive turbocharger loading.

**Increase of diesel injection pressure (Strategy 2):** Increasing diesel injection pressure improves fuel atomisation, promoting finer droplet formation and enhanced fuel-air mixing at the molecular level. This improved mixture quality reduces ignition delay, effectively advancing the combustion phasing. Consequently, the heat release process becomes faster, shortening the overall combustion duration. Thus, combustion completes earlier in the expansion stroke, reducing residual burning during the exhaust phase. This leads to lower exhaust gas temperatures and helps maintain turbocharger operation within safe thermal and flow limits, especially under dynamic engine conditions.

**Activation of the RCCI cylinder (Strategy 3):** When the fourth cylinder is activated to operate in RCCI mode, and the total engine load is held constant, the load demand on cylinders 1, 2 and 3 is proportionally reduced. This lowers the exhaust gas temperatures from these diesel-

operated cylinders. In contrast, the RCCI-enabled fourth cylinder, which was previously inactive and only supplied fresh air to the exhaust system, begins contributing combustion gases, increasing the exhaust gas temperature on the lower-case side of the turbine. This causes a thermal energy shift from the upper-case (fed by cylinders 2 and 3) toward the lower-case (fed by cylinders 1 and 4), effectively redistributing the turbine's thermal input. Consequently, the upper-case scroll moves further away from the turbocharger's thermal threshold limits, operating under reduced exhaust enthalpy. In the case where the RCCI cylinder remains deactivated, the lower-case scroll receives exhaust gas only from cylinder 1, while cylinder 4 supplies only fresh air, resulting in inherently low exhaust gas temperature and minimal thermal loading. This configuration means the lower-case scroll operates well below its thermal limit. However, even when the RCCI cylinder is activated and its load increased, the resulting exhaust gas remains relatively cool due to the low-temperature combustion characteristics of RCCI. Therefore, under a constant total engine-load, a perfectly symmetrical exhaust energy distribution between the upper-case and lower-case scrolls cannot be achieved. This persistent asymmetry presents a challenge in achieving uniform turbine inlet conditions and requires precise control strategies to maintain turbocharger stability.

**Rebalancing of diesel injection quantity (Strategy 4):** Fine-tuning the injected fuel quantities across individual cylinders provides an effective mechanism for managing exhaust gas temperature (EGT) asymmetry, which is critical for maintaining turbine inlet balance in a split-scroll turbocharger system. The proposed architecture controls each injector independently, allowing cylinder-specific adjustment of injection duration and quantity in real time. This enables precise thermal management on a per-cylinder basis. Specifically, reducing the fuel quantity in cylinders 2 and 3, which are connected to the turbine's upper-case, while increasing the load on cylinder 1, which shares the lower-case scroll with the RCCI-enabled cylinder 4, facilitates targeted redistribution of exhaust energy. RCCI combustion inherently limits exhaust gas temperature, so cylinder 1's thermal contribution becomes particularly important for balancing the lower-case input. This strategy allows dynamic modulation of scroll-specific exhaust flow, without altering the combustion phasing or load of the RCCI cylinder itself. As a result,

turbine inlet energy asymmetry is minimised, helping to keep the turbocharger operating within stable performance limits and away from surge or choke conditions.

Together, these four strategies allow the system to regulate charge air pressure without mechanical intervention, ensuring stable operation even in the presence of large combustion variability. The control algorithm is capable of adaptively compensating for cylinder-to-cylinder differences in exhaust energy contribution, a common challenge in semi-decoupled RCCI configurations. This approach is especially effective in preventing turbocharger operation from drifting into unstable regions such as the surge line, while also maintaining combustion stability and emission performance.

#### 2.4. Design of experiments and testing conditions

The Wärtsilä W20L engine underwent a gradual warm-up procedure before testing, to avoid thermal shock and potential mechanical damage to the engine block. This involved progressively increasing the coolant temperature, allowing the engine structure to reach thermal equilibrium in a controlled manner. Following this initial phase, cylinders 1, 2 and 3 were operated in conventional diesel combustion mode at idle speed, without applying an external dynamometer load, allowing the engine to reach its nominal steady-state operating temperatures. Experimental testing started when both the coolant and lubricant temperatures stabilised. Commercial diesel fuel was used as the primary fuel throughout the testing, which was conducted under standard atmospheric conditions representative of sea-level pressure and temperature. Before activating the RCCI cylinder, the external pilot injection fuel system, including its dedicated electric motor and pump, was operated to ensure the pilot fuel return temperature reached a stable condition. This is essential because fuel viscosity is highly sensitive to temperature variations, which could affect injection characteristics and repeatability.

Table 3 summarises the parameter range used during the experimental campaign. The engine load was increased incrementally during the tests. Start of injection (SOI) and rail pressure (Strategies 1 and 2 respectively) were adjusted gradually in synchronisation with load increments, to avoid exceeding the predefined turbine inlet temperature threshold. Once the turbine inlet temperature approached the limit, the maximum brake power attainable without RCCI activation was determined. Then, the RCCI cylinder was gradually brought into operation (Strategy 3), and total engine output power was further increased. Upon reaching the maximum exhaust gas temperature again, Strategy 4 was employed to redistribute thermal load between the turbine's upper and lower casings. This entailed reducing the injection quantity in cylinders 2 and 3 - connected to the upper case - through the implementation of a control coefficient, thereby shifting the exhaust thermal load toward the lower case, associated with the RCCI-enabled cylinder.

The cylinder-based power values were derived from the measured total brake power by using the relative contribution of each cylinder's real-time IMEP value. The IMEP value of each cylinder was compared with the sum of the IMEP values of all active cylinders, and this ratio was used to determine the corresponding share of the measured total brake power. In this way, the power contribution of each cylinder, including the RCCI cylinder, was continuously monitored and recorded during the

**Table 3**  
Parameter ranges used in the engine test campaign.

Parameters	Minimum	Maximum	Related cylinders
Engine total brake power (kW)	0	686	All cylinders
Start of injection (degrees bTDC)	13	18	Diesel cylinder 1, 2 and 3
Rail pressure (bar)	1000	1500	Diesel cylinder 1, 2 and 3
RCCI cylinder power (kW)	0	111	RCCI cylinder 4
Cylinder 2 and 3 injector coefficient (-)	0.8	1	Diesel cylinder 2 and 3

experiments. The test setup also allowed the injected fuel quantity of each cylinder to be controlled semi-independently. Therefore, in Strategy 4, reducing the injector coefficients of cylinders 2 and 3 decreased their fuel input and IMEP contribution, while the dynamometer/load-control loop maintained the required total brake power.

#### 2.5. Sensitivity analysis

A regression-based sensitivity analysis was performed to evaluate the relative influence of selected input parameters on the turbine input exhaust gas temperature (EGT). The analysis employs a linear model where each input is first normalised to ensure dimensional consistency and facilitate direct comparison across variables. The formula used in this study is presented in Eq. (1) [42]:

$$EGT = \beta_0 + \sum_{i=0}^n \beta_i \cdot x_i^{(norm)} \quad (1)$$

In this formula,  $\beta_0$  represents the intercept of the regression model, while  $\beta_i$  denotes the sensitivity coefficient associated with the  $i^{th}$  input parameter, and  $x_i^{(norm)}$  refers to the normalised form of the corresponding independent variable. This linear structure allows each  $\beta_i$  to be interpreted as a quantitative measure of influence, where a greater absolute value of  $\beta_i$  indicates a stronger impact of the associated input on EGT. All input parameters were normalised within the range of 0 to 1 before analysis, thereby eliminating potential scale effects and ensuring consistency and comparability among variables. The regression model was constructed using least-squares estimation across the full experimental dataset, providing statistical robustness and mitigating the influence of multicollinearity.

### 3. Results and discussion

#### 3.1. Control strategy implementation and operating envelope

In LTC engines, as in conventional internal combustion engines, increasing the intake air pressure extends the operating range, enhances the engine's power output, and thereby improves the specific power per unit mass. External compressors or supercharging devices are commonly employed to increase the intake pressure in LTC engine research and development. However, such solutions are technically complex and economically challenging to implement, particularly in large-bore applications such as marine engines. When all cylinders operate in LTC mode with a stock turbocharger, the inherently low exhaust gas temperature - one of the typical characteristics of LTC combustion - adversely affects turbocharger performance. In contrast, in a research engine where one cylinder can be operated in RCCI mode while the others remain in conventional diesel mode, using the stock turbocharger offers significant advantages in terms of cost, implementation simplicity and experimental flexibility. Turbocharger matching typically is based on the combined exhaust flow rate and temperature of all cylinders, so converting only one cylinder to RCCI combustion alters this balance. The turbocharger must be controlled across different engine-loads to ensure reliable operation, without exceeding the surge or choke boundaries and while remaining within the turbine's maximum allowable temperature limit. As outlined in the previous section, an adaptive control algorithm was developed to coordinate four key strategies: advancement of diesel injection timing; increase of diesel injection pressure; activation of the RCCI cylinder; and rebalancing of diesel injection quantity. These strategies enabled stable engine operation across varying load conditions, while maintaining the turbocharger within its safety margins. The following results were obtained.

Fig. 5 illustrates the variation of start of injection, injection pressure, RCCI cylinder load and the injector coefficient of cylinders 2–3 as a function of total engine load. At idle condition, SOI was set to 13° bTDC, injection pressure to 1000 bar, the RCCI cylinder was deactivated and

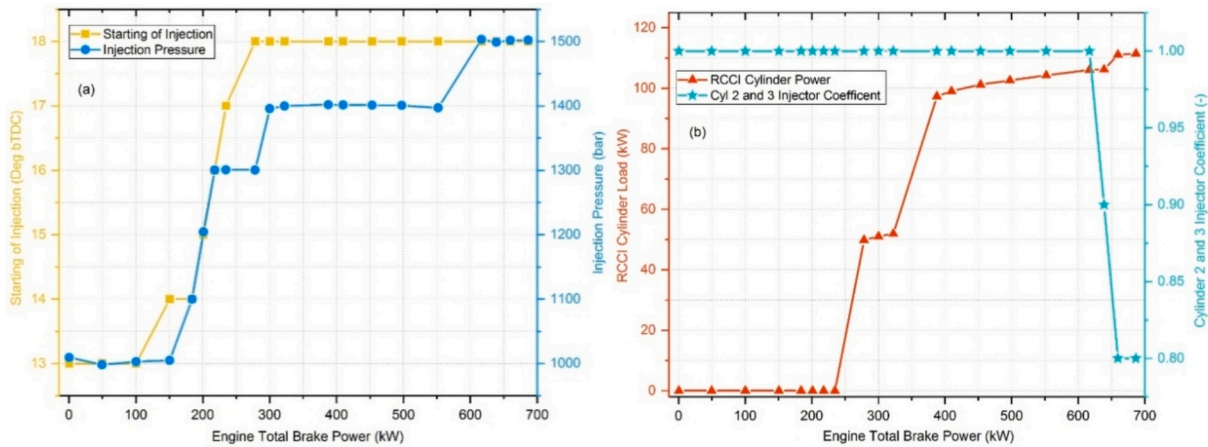


Fig. 5. Variation of SOI, injection pressure, RCCI cylinder load and cylinder 2–3 injector coefficient, based on total engine load.

the injector coefficient for cylinders 2 and 3 was fixed at 1.0, ensuring that the fuel balance across the cylinders remained unaltered. The SOI angle was kept constant up to a total engine load of 100 kW, then progressively advanced to 14° at 150–183 kW; 15° at 201 kW; 16° at 217 kW; 17° at 234 kW; and finally 18° for the 278–686 kW range. Injection pressure was maintained at 1000 bar up to 150 kW. Then it was increased to 1100 bar at 183 kW; 1200 bar at 201 kW; 1300 bar at 217–278 kW; 1400 bar at 300–551 kW; and finally 1500 bar at 616–686 kW. The RCCI cylinder remained inactive up to 234 kW, and was then operated with a 50 kW load in the 278–322 kW range, and with a 100–110 kW load between 453 and 686 kW total engine load. Cylinders 2 and 3 were connected to the turbine upper case while cylinders 1 and 4 (cylinder 4 is the RCCI one) were connected to the turbine lower case, so the injection balance between groups was adjusted by applying injector coefficients to cylinders 2 and 3. The coefficient remained at 1.0 up to 638 kW, but the coefficient was reduced to 0.9 at 638 kW, and further to 0.8 at 659–686 kW in order to reach higher loads within safe turbo-charger operating limits. These parameter selections were determined through more than 200 experimental tests, where instantaneous exhaust gas temperature constraints as well as surge and choke line boundaries

were carefully considered. Subsequently, the selected operating parameters were calibrated within a real-time control algorithm, enabling the experimental engine to be operated under algorithm-based control.

### 3.2. Turbine Inlet exhaust gas temperature control under mixed-mode operation

Fig. 6 presents the variation of exhaust gas temperatures at the turbine upper- and lower-case inlets under different control strategies. The maximum allowable turbine inlet temperature is 600 °C, beyond which material degradation and component failure may occur. Fig. 6 shows that the exhaust gas temperatures at both turbine inlets remain low at idle operation condition. With increasing total engine load, the higher fuel energy delivered into the cylinders leads to a progressive rise in exhaust gas temperatures. Cylinders 1, 2, and 3 operate in diesel mode, with their fuel injection quantities controlled through a PID controller, using feedback from engine load and speed. The RCCI cylinder, however, is managed independently by a separate control algorithm. Consequently, when the RCCI cylinder is deactivated, the load is equally distributed among cylinders 1–3. The loads of cylinders 2 and 3, which

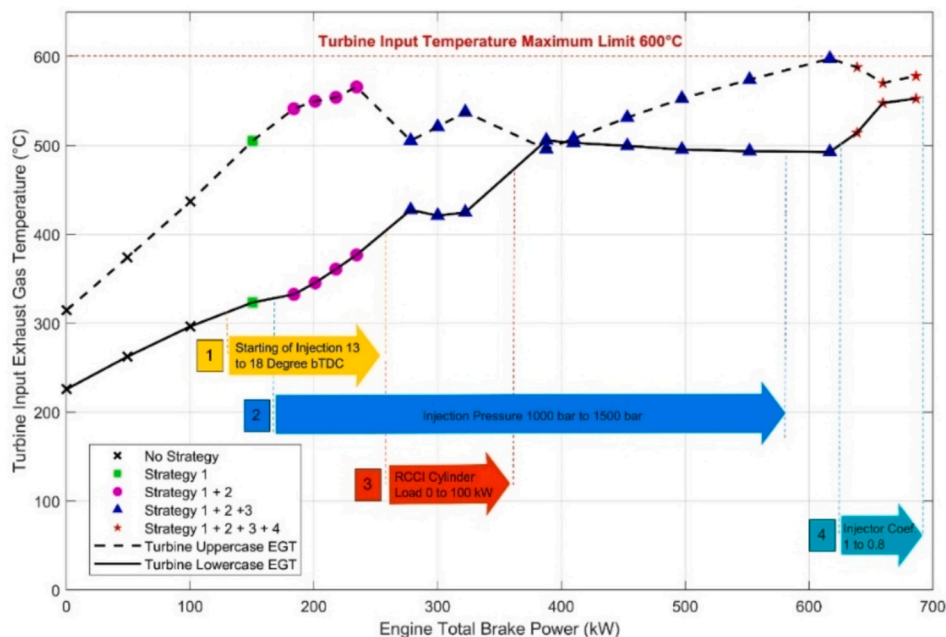


Fig. 6. Variation of exhaust gas temperatures in the inputs of turbine upper and lower cases under different control strategies.

are connected to the turbine upper case, increase simultaneously, so the upper-case exhaust temperature becomes higher than that of the lower case. This occurs because the lower case receives hot exhaust gases from only cylinder 1, while the RCCI cylinder (cylinder 4) delivers only fresh air when inactive.

Beyond 100 kW total engine load, the first set of control parameters was introduced by advancing the SOI angle from 13° to 18° bTDC across the 100–278 kW load range. This shifts the overall heat release to earlier crank angles, ensuring that late-cycle burning occurs within the cylinder before the exhaust stroke [43–44]. This moderates the rate of exhaust temperature rise with load, as observed in Fig. 6. Further SOI advance beyond 18° bTDC was not possible at the fixed engine speed of 1000 rpm, since the combustion phasing (CA50) would occur too far before TDC, adversely affecting power output and risking engine durability. In addition, injection pressure was gradually increased from 1000 bar at 150 kW to 1500 bar at 616 kW. Higher injection pressure improves atomisation, accelerates evaporation and enhances mixing, thus shortening both ignition delay and total combustion duration, thereby advancing combustion phasing and reducing exhaust temperatures [45–46]. Fig. 6 shows this effect is particularly pronounced in the turbine upper-case temperature when Strategies 1 and 2 (SOI and pressure adjustments) were applied simultaneously. The upper-case exhaust temperature reached 565 °C at 234 kW, approaching the 600 °C threshold, marking the maximum sustainable load achievable without activating the RCCI cylinder.

Implementation of Strategy 3 (RCCI activation) saw the exhaust temperature at the turbine upper case drop rapidly from 565 °C to 505 °C, while the lower-case temperature increased from 376 °C to 427 °C. This redistribution of thermal load occurs because part of the total engine load is now carried by the RCCI cylinder, reducing the load on cylinders 2 and 3, while cylinder 4 begins contributing hot exhaust gas. Consequently, the upper-case thermal burden is relieved and partially shifted to the lower case, maintaining turbocharger operation safely below the critical temperature. Both upper- and lower-case temperatures resumed their rising trends as the engine load was further increased. When the total load exceeded 322 kW, the RCCI cylinder load was raised to 100 kW, which further alleviated the load on cylinders 2 and 3. This resulted in nearly balanced exhaust gas temperatures of ~500 °C at both turbine inlets with the load at 387–409 kW. However, maintaining the RCCI load at 100–110 kW while further increasing total

engine load caused the upper-case temperature to rise again, due to the relatively higher share of load carried by cylinders 2 and 3 compared with cylinder 4. The upper-case exhaust temperature reached 597 °C at 616 kW, defining the maximum safe load achievable with Strategies 1–3. The turbine upper case would exceed the 600 °C threshold beyond this load point.

To extend the load range further, Strategy 4 was applied by reducing the injection quantities of cylinders 2 and 3 relative to cylinder 1, using coefficients of 0.9 and 0.8, respectively. This lowered the exhaust gas temperature of cylinders 2 and 3, thereby reducing the upper-case thermal load, while increasing the lower-case temperature. This allowed the total engine load to be increased to 686 kW. Any further load would cause the lower-case temperature to exceed the 600 °C safety limit, so 686 kW represents the maximum sustainable engine load attainable with the combined application of all four strategies, while maintaining turbocharger operation within thermal safety boundaries. The developed real-time control algorithm dynamically adjusted SOI, injection pressure, RCCI cylinder activation and injector balancing in response to instantaneous exhaust conditions, ensuring safe and stable turbocharger operation across the full load range.

### 3.3. Cylinder-resolved exhaust gas temperature analysis

Fig. 7 illustrates the variation of exhaust gas temperatures measured individually at the outlets of each cylinder under different control strategies. The measurements were taken immediately downstream of the exhaust valves, before the gases were mixed, to capture cylinder-resolved exhaust conditions. Cylinders 1–3 exhibited exhaust gas temperatures in the range of 242–291 °C at idle condition, while cylinder 4 showed only 72 °C. Cylinder 4's markedly lower temperature reflects the absence of combustion: the compressed charge was expelled as fresh air, which was nevertheless preheated by the cylinder walls and coolant, raising its temperature above ambient. Increasing total engine load up to 234 kW raised the exhaust temperatures of cylinders 1–3 in a similar trend. The application of Strategies 1 and 2 (SOI advancement and higher injection pressure) moderated the rate of temperature increase. The RCCI cylinder (cylinder 4) remained inactive during this phase, so its exhaust temperature stayed substantially lower than those of the diesel cylinders. However, the growing load also raised turbine speed, increasing intake air pressure. As a result, the outlet temperature of

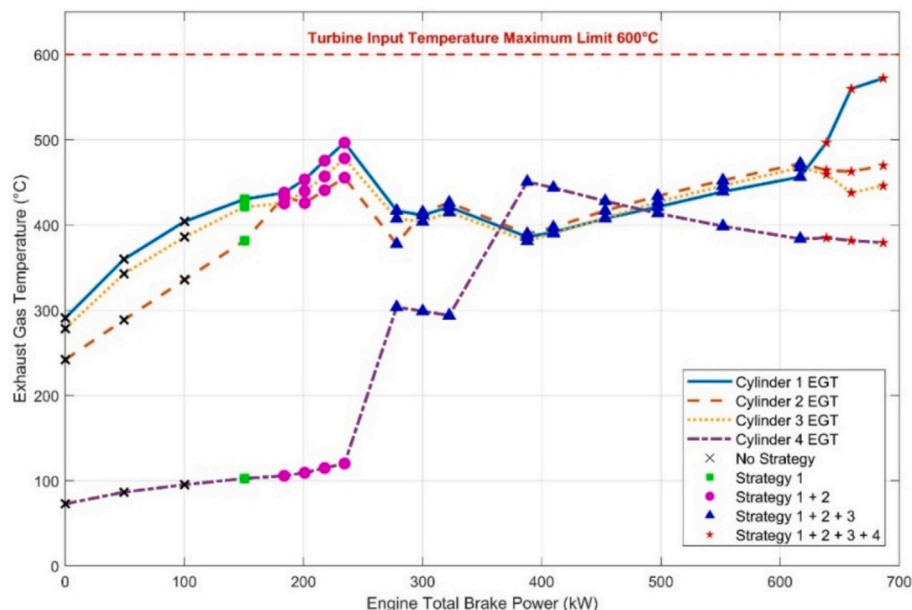


Fig. 7. Variation of exhaust gas temperatures of cylinder outputs under different control strategies.

cylinder 4 increased from 72 °C at idle to nearly 120 °C, despite the absence of combustion. When the RCCI cylinder was activated at 234 kW with a partial load of 50 kW, its exhaust temperature quickly rose to ~300 °C, while the exhaust temperatures of cylinders 1–3 decreased. This reflected a redistribution of load, as part of the total engine output was shifted to the RCCI cylinder, relieving cylinders 1–3. Further increases in total load subsequently caused the exhaust temperatures of cylinders 1–3 to rise again. Beyond 322 kW, the RCCI cylinder load was increased to 100 kW. The higher injected fuel energy elevated its exhaust temperature from ~300 °C to 450 °C, while the diesel cylinders' exhaust temperatures fell to ~385 °C. As the total engine load continued to increase above 387 kW, the exhaust temperatures of cylinders 1–3 again rose in parallel with the load. However, as shown in Fig. 7, although the load of the RCCI cylinder (cylinder 4) was unchanged, its exhaust gas temperature exhibited a decreasing trend, despite the total engine load continuing to increase. This occurred because, despite the fixed fuel quantity supplied to cylinder 4, the rising intake pressure with increasing load progressively leaned-out the mixture, thereby suppressing further increases in exhaust temperature.

As previously discussed with reference to Fig. 6, at 616 kW the upper-case turbine inlet temperature approached 597 °C, near the material limit of 600 °C, even under Strategies 1–3. Strategy 4 was applied to redistribute thermal load away from the upper case. Reducing the injection quantities of cylinders 2 and 3 meant cylinder 1 carried more of the total load, so its exhaust temperature rose sharply, while those of cylinders 2 and 3 decreased slightly or remained stable. This successfully shifted thermal stress from the turbine upper case to the lower case, ensuring safe turbocharger operation. Finally, at a total engine load of 686 kW, the combined application of Strategies 1–4 defined the maximum achievable operating condition. Exhaust temperatures of individual cylinders at this point remained within acceptable ranges, and the overall thermal load was effectively redistributed to maintain turbine inlet temperatures below the critical limit.

### 3.4. Turbocharger performance: turbine speed and compressor pressure ratio

Fig. 8 presents the variation of turbine mean EGT, turbine speed and pressure ratio under increasing engine load. As total engine load rises, the additional fuel energy supplied to the cylinders increases the combustion temperature, prolongs combustion duration and shifts part of the heat release toward the exhaust stroke [47]. Consequently, the average turbine inlet EGT increases with load. Fig. 8 (a) shows the mean turbine inlet temperature was approximately 270 °C at idle condition and increased to 565 °C when engine load reached 686 kW. The rise in exhaust temperature with load enhances the expansion work across the turbine, thereby accelerating turbine speed. Fig. 8 (b) shows turbine speed increased from 300 revolutions per second (rps) at 270 °C inlet temperature to 860 rps when the turbine inlet temperature reached 565 °C. The turbine and compressor are mounted on the same shaft, so their rotational speeds are identical. Fig. 8 (c) shows the increase in turbine (and thus compressor) speed increased the mass flow of air delivered to the cylinders, raising the intake pressure. The intake pressure ratio was 1.15:1 at a turbine speed of 300 rps, increasing to 3.48:1 at 860 rps, demonstrating the strong coupling between turbine thermal loading and compressor performance. The turbine inlet exhaust gas temperature rises with increasing total engine load, which accelerates turbine speed and elevates the compressor pressure ratio. The test engine can be operated at higher pressure ratios within this cycle, while keeping the turbocharger safely within its operational limits, avoiding mechanical or thermal damage. The real-time control algorithm managing charge air pressure, combined with the stock turbocharger, could successfully meet the pressure ratio demands of the RCCI cylinder, ranging from 1.0:1 to 3.48:1.

### 3.5. Compressor operating limits and stability assessment

Fig. 9 illustrates the variation of compressor volume flow and pressure ratio across the tested engine operating points. The turbocharger manufacturer's confidentiality policy does not allow disclosure of the detailed compressor map, turbine speed and efficiency data.

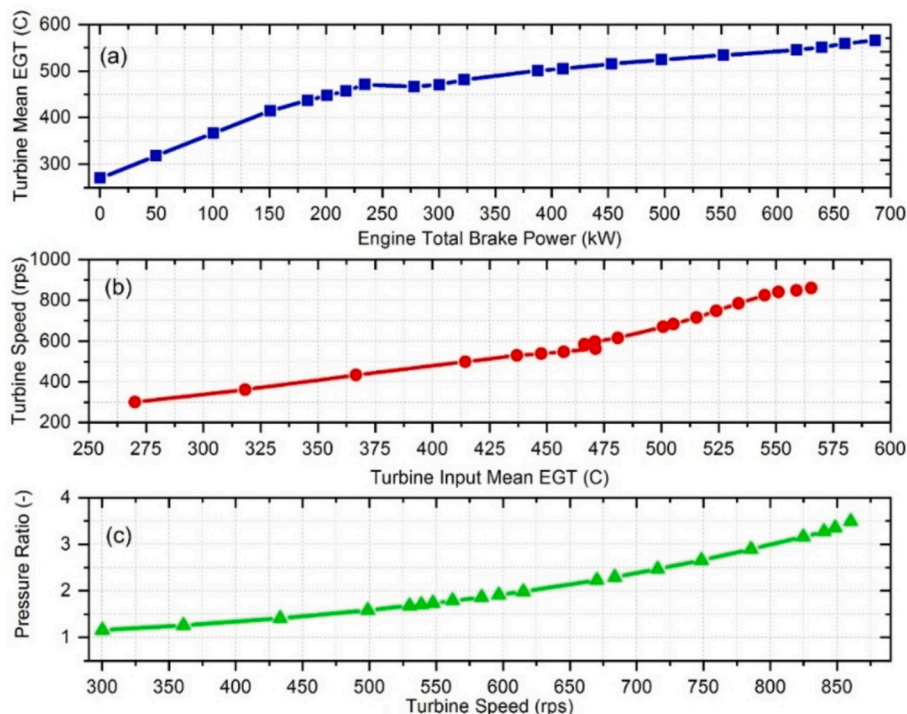


Fig. 8. Variation of turbine mean EGT, turbine speed and pressure ratio.

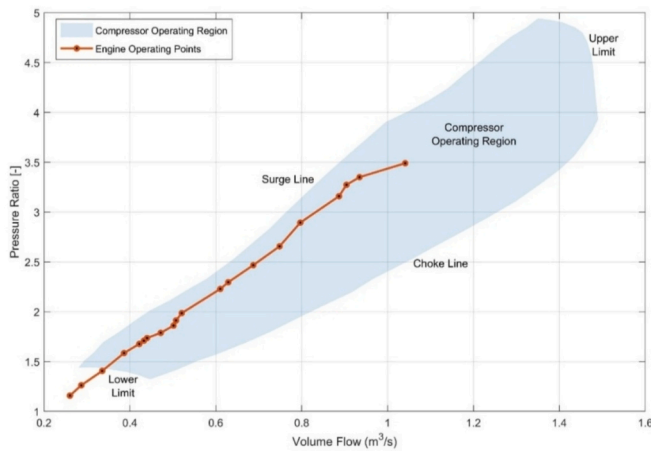


Fig. 9. Variation of volume flow and pressure ratio of compressor based on engine operating points.

Nevertheless, Fig. 9 shows the increase in total engine load and corresponding rise in compressor speed resulted in simultaneous increases in both volume flow and pressure ratio. The engine operating line must remain within the surge and choke boundaries of compressor operation region for safe operation. Flow instabilities can occur if the operating point crosses these limits, imposing excessive aerodynamic and mechanical stresses on the compressor blades, potentially leading to hardware damage. Test results from the developed real-time control algorithm confirmed that the compressor consistently operated within its safe boundaries across all tested loads and operating conditions. The results indicate that some margin remains before reaching the compressor's upper operating limit. However, further load increases were not attempted because the turbine inlet exhaust gas temperature would exceed its maximum allowable threshold at even higher loads. As explained in Fig. 4, the developed real-time control algorithm incorporates the compressor map boundaries and continuously monitors the relationship between the engine operating point and the compressor operating region. The test engine ensures turbocharger safety by automatically shutting down if a parameter causes the engine operating point to approach either the surge or choke line.

### 3.6. Sensitivity analysis of control parameters on turbine thermal loading

As detailed in previous sections, variations in control parameters such as total engine load, start of injection, rail pressure, RCCI activation in cylinder 4 and injection balance of cylinders 2 and 3 significantly influence exhaust gas temperatures, thereby affecting the turbocharger's operating window. A sensitivity analysis quantified the relative importance of these effects. Fig. 10 presents the sensitivity of turbine upper- and lower-case EGTs to the selected control parameters. The results show that increases in total engine load have the greatest impact, with sensitivities of 42.9% for the turbine upper case and 27.4% for the lower case. Engine load is directly proportional to the injected fuel quantity, so more fuel generates more in-cylinder heat release, making EGT highly sensitive to load variations. Moreover, because most of the additional load is carried by cylinders 2 and 3, which are connected to the turbine upper case, the upper-case EGT demonstrates greater sensitivity than the lower case. Both turbine inlets show positive sensitivity to increasing engine load. The SOI strategy, on the other hand, exhibits negative sensitivity, indicating that advancing injection reduces EGT. SOI adjustments yielded sensitivities of 12.1% for the upper case and 36.2% for the lower case. Similarly, higher rail pressure reduced EGT, with sensitivities of 7.3% and 14.1% for the upper and lower cases, respectively. The stronger influence on the lower case can be explained by the fact that, up to a certain point in the tests, it was affected only by cylinder 1. Consequently, changes in injection timing and rail pressure were proportionally more significant in this configuration.

Activation of the RCCI cylinder (Strategy 3) produced contrasting sensitivities: a negative 31% effect on the upper-case EGT and a positive 17.5% effect on the lower case. This reflects the redistribution of thermal load, as activating the RCCI cylinder at 50 kW and subsequently at 100 kW output reduced the exhaust thermal contribution of cylinders 2 and 3, while shifting more heat to the lower case. The substantial reduction in EGT of cylinders 2 and 3 highlights the pronounced sensitivity of upper-case temperature to RCCI load distribution. Finally, Strategy 4, which applied scaling factors to the injection duration of cylinders 2 and 3, resulted in a negative sensitivity of 6.7% for the upper case and a positive sensitivity of 4.8% for the lower case. The relatively small magnitudes of these effects are due to the moderate injection reductions (coefficients of 0.9 and 0.8, corresponding to 10% and 20% fuel reductions). Nevertheless, this strategy rapidly lowered the EGT of cylinders 2 and 3, thereby relieving the turbine upper case from approaching

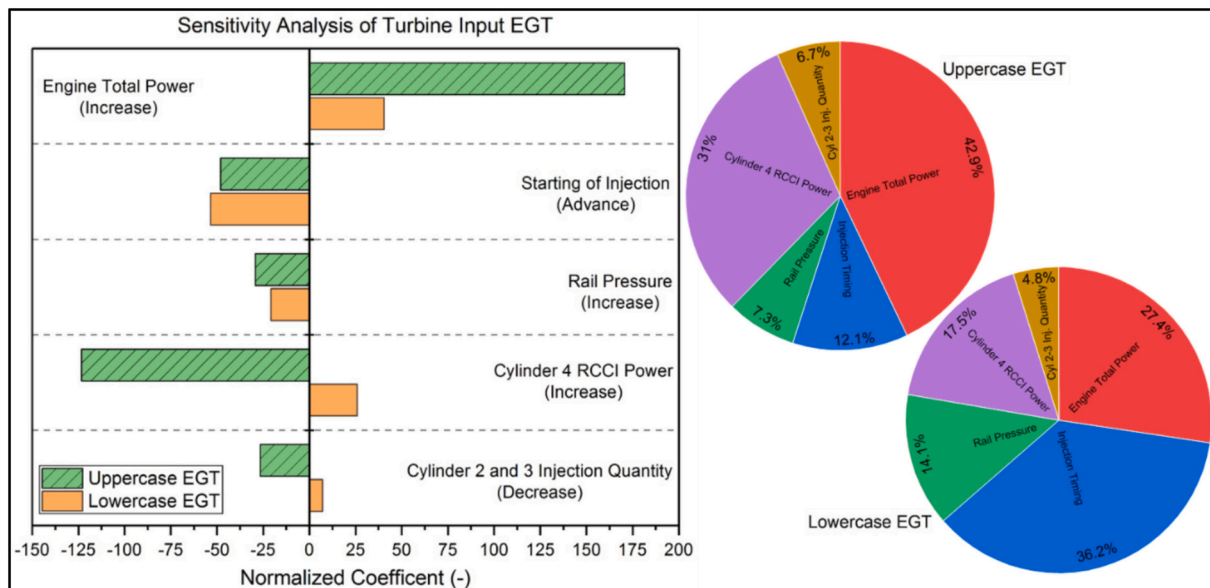


Fig. 10. Sensitivity analysis of exhaust gas temperatures of turbine upper and lowercase input based on control parameters.

its maximum thermal limit.

#### 4. Conclusion

This work demonstrated that a stock, single-stage turbocharger can be retained and operated safely in a mixed-mode heavy-duty RCCI research engine by modulating only software-accessible combustion levers, without recourse to external supercharging hardware. A four-action, closed-loop strategy (SOI advancement; rail-pressure increase; selective activation of the RCCI cylinder; and per-cylinder diesel rebalancing) steered exhaust thermal load delivered to the twin-scroll turbine, thereby controlling charge air pressure in real time, while respecting turbocharger surge/choke and temperature limits. The controller secured stable operation up 686 kW while keeping turbine-inlet temperatures below the 600 °C material threshold (upper-case peak  $\approx$ 597 °C before Strategy 4) and it satisfied the RCCI cylinder's pressure-ratio demand over 1.0:1–3.48:1. Testing was across >200 steady operating points at 1000 rpm.

The main originality of this study is the experimental demonstration that charge-air pressure and turbine thermal loading can be controlled in a heavy-duty cyclops RCCI–diesel configuration by coordinating cylinder-individual combustion parameters, rather than by introducing external boosting hardware or modifying the original airpath architecture. This provides a distinct contribution to RCCI engine research by showing that scroll-wise exhaust energy imbalance, turbine thermal constraints and compressor surge/choke boundaries can be managed simultaneously on a stock twin-scroll turbocharged platform.

Mechanistically, the strategy leverages two complementary effects. First, advancing SOI and raising rail pressure shorten ignition delay and total burn duration, pulling heat release away from the exhaust stroke and curbing EGT rise with load. Second, activating the RCCI cylinder and rebalancing diesel injection redistribute exhaust thermal load between turbine scrolls, relieving the upper-case (fed by cylinders 2–3) and shifting burden to the lower-case (cylinders 1 + RCCI). This scroll-wise thermal shaping prevented incursion toward surge/choke while preserving the charge air supply required for stable RCCI combustion.

A regression-based sensitivity analysis quantified the relative influence of the control parameters on turbine-inlet EGTs. Engine load dominated the response (upper/lower-case sensitivities 42.9%/27.4%), whereas SOI and rail pressure exhibited negative sensitivities (upper: 12.1% and 7.3%; lower: 36.2% and 14.1%), confirming their efficacy as thermal-mitigation levers. Strategy 3 (RCCI activation) produced a –31% sensitivity on the upper case and +17.5% on the lower case, consistent with the intended thermal redistribution. Strategy 4 (diesel rebalancing, coefficients 0.9–0.8 for cylinders 2–3) yielded additional fine control (–6.7%/+4.8%). Together, these results establish a clear actuation hierarchy for safe boosting with production hardware.

From a systems perspective, the proposed approach offers three practical advantages for marine-scale engines: (i) hardware parsimony: control is achieved with stock turbo/air-path components; (ii) operability extension: the usable load/boost window is expanded without exceeding thermal limits; and (iii) scroll-aware robustness: cylinder-resolved exhaust measurements and balancing specifically manage twin-scroll asymmetry inherent to mixed-mode operation. These traits close a gap in the RCCI literature, where external compressors, superchargers or e-turbos are commonly required to guarantee intake conditions.

Areas for future research include: (1) extension from steady 1000 rpm operation to fast transients, where turbo inertia and RCCI phasing control interact more strongly; (2) integration with model-predictive, constraint-handling supervisors which natively enforce surge/choke and temperature limits while optimising emissions and efficiency; (3) exploration of alternative fuel pairs and higher EGR levels to probe generality; and (4) broader compressor-map utilisation (subject to OEM confidentiality) to formalise stability margins across ambient conditions. Addressing these topics would further mature the software-centric

boosting paradigm and accelerate deployment on marine and stationary engines seeking high efficiency with low emissions under real-world duty cycles.

#### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Maciej Mikulski reports financial support was provided by Bussines Finland. Xiaoguo Storm reports financial support was provided by Bussines Finland. Seyfi Polat reports financial support was provided by TUBITAK. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Data availability

No data was used for the research described in the article.

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