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3 authors:

Akhilendra Pratap Singh
Indian Institute of Technology Kanpur

Vikram Kumar
Indian Institute of Technology Kanpur

Avinash Kumar Agarwal
Indian Institute of Technology Kanpur

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Evaluation of comparative engine combustion, performance and emission characteristics of low temperature combustion (PCCI and RCCI) modes

Akhilendra Pratap Singh, Vikram Kumar, Avinash Kumar Agarwal*

Engine Research Laboratory, Department of Mechanical Engineering Indian, Institute of Technology Kanpur, Kanpur, 208016, India

HIGHLIGHTS

- Low temperature combustion modes (PCCI & RCCI) compared with CI mode.
- CI and PCCI modes used diesel and RCCI mode used diesel-methanol fuel-pair.
- RCCI mode combustion was relatively more stable than CI and PCCI modes.
- RCCI mode combustion showed higher BTE than CI and PCCI modes.
- RCCI mode combustion emitted lesser NOx, and higher HC than CI and PCCI modes.
- RCCI mode can be used in modern production grade diesel engines.

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ABSTRACT

In this study, a comparative investigation of engine combustion, performance and emission characteristics of low temperature combustion modes namely premixed charge compression ignition (PCCI) and reactivity controlled compression ignition (RCCI) with conventional compression ignition (CI) combustion mode was performed. Experiments were performed in a single cylinder research engine at constant engine speed (1500 rpm) and at four different engine loads (1, 2, 3 and 4 bar brake mean effective pressure (BMEP)). Baseline CI and PCCI mode combustion experiments were performed using mineral diesel as test fuel; while mineral diesel-methanol fuel pair was used as high-reactivity fuel (HRF) and low-reactivity fuel (LRF) respectively in RCCI mode combustion. Results showed that RCCI mode combustion was relatively more stable compared to baseline CI and PCCI combustion modes. At higher engine loads, RCCI mode combustion exhibited relatively lower knocking and combustion noise than other combustion modes. Performance characteristics showed that brake thermal efficiency (BTE) of RCCI mode combustion was comparable to baseline CI mode combustion, however, at higher engine loads, RCCI mode combustion resulted in relatively higher BTE compared to both baseline CI and PCCI combustion modes. Significantly lower EGT of RCCI mode combustion compared to baseline CI as well as PCCI combustion modes was another important finding of this study. Emission results showed that RCCI mode combustion emitted relatively lower oxides of nitrogen (NOx), but significantly higher hydrocarbons (HC) compared to baseline CI and PCCI combustion modes. A NOx-BTE trade-off analysis was also carried out, which demonstrated the suitability of RCCI mode combustion at all engine loads. Finally, a parametric analysis was carried out to compare the critical parameters of baseline CI, PCCI, and RCCI combustion modes at low and high engine loads, which exhibited improved engine performance and emission characteristics of low temperature combustion (LTC) modes, especially the RCCI mode combustion.

1. Introduction

Growing energy demand and strict emission norms have motivated researchers to develop a more efficient and cleaner engine technology, which is compatible with alternative fuels. Among different engine technologies, diesel-fuelled compression ignition (CI) engines and gasoline-fuelled spark ignition (SI) engines are the two most common. In comparison to SI engines, CI engines are more popular among different

* Corresponding author.
E-mail address: akag@iitk.ac.in (A.K. Agarwal).

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sectors of economy including transport, agriculture, construction etc., due to their higher brake thermal efficiency (BTE), higher power/ torque output, durability and reliability. However, diesel engines using conventional CI mode combustion are facing serious challenges such as higher emissions of oxides of nitrogen (NOx) and particulate matter (PM) compared to their SI engine counterparts [1]. In many studies, it has been proven that these pollutants are extremely harmful to the human health as well as to the environment [2–3]. NOx and PM emitted by diesel engines are a serious challenge to tackle because of NOx-PM trade-off, in which simultaneous reduction of these two pollutants is extremely challenging [4]. To resolve this issue, a number of solutions have been developed and implemented by the researchers, among which, the utilization of alternative fuels [5–6], use of after-treatment systems [7–8], and adaptation of advanced combustion strategies [9–11] are the important ones. In last two decades, several after-treatment systems such as diesel particulate filters (DPF), diesel oxidation catalysts (DOC), selective catalysts reduction (SCR) technique, lean NOx trap technique, etc. have been extensively explored for both light-duty vehicles (LDVs) as well as heavy-duty vehicles (HDVs) using diesel engines [10–11]. These systems have shown significant potential to reduce NOx or PM individually, however, several difficulties such as cost, system complexity, reliability, operational constraints, etc. have limited their application in a wide range of vehicles used in the road transport sector [12]. In some fundamental studies, it has been reported that formation of NOx and PM in the combustion chamber of diesel engines can be controlled using combustion optimization, which is significantly affected by the in-cylinder air-flow and fuel spray characteristics [13–14]. Results of these studies directed the research efforts towards the active control techniques for limiting emissions of NOx and PM. Among different techniques, low temperature combustion (LTC) technology has attracted significant attention of researchers due to its capability of simultaneous reduction of NOx and PM, without the need of using any exhaust gas after-treatment system. In last two decades, different LTC strategies such as homogeneous charge compression ignition (HCCI) [9,15], premixed charge compression ignition (PCCI) [16–17], reactivity controlled compression ignition (RCCI) [18–19], etc. have been introduced as substitute to the conventional CI mode combustion. In HCCI mode combustion, homogeneous fuel–air mixture is supplied to the engine combustion chamber, which auto-ignites at the end of the compression stroke [9]. This results in complete absence of fuel-rich zones, leading to lower soot formation and a dominant premixed phase combustion of lean fuel–air mixture, leading to significantly lower bulk in-cylinder temperature, resulting in lower NOx formation [4]. Gan et al. [20] reviewed different aspects of mineral diesel-fuelled HCCI combustion technology, including its control and performance parameters. They emphasized on fuel–air mixing, flexible fuel injection strategies, and exhaust gas recirculation (EGR) as important control parameters for HCCI mode combustion. Singh and Agarwal [21–22] carried out HCCI mode combustion investigations using mineral diesel, biodiesel blends and blends of volatile additives with mineral diesel. They used an external mixture preparation equipment ‘fuel vaporizer’ for homogeneous fuel–air mixing. They reported that HCCI mode combustion resulted in significantly lower NOx and PM emissions, however, lack of combustion control, especially at higher engine load was the most challenging aspect of HCCI mode combustion [4]. A lot of research studies have already been carried out to resolve this issue, however, in most studies, HCCI mode combustion was not found to be adequate for practical implementation in production grade internal combustion (IC) engines [4].

Therefore, researchers developed PCCI mode combustion, which is based on early-direct injection of fuel in presence of EGR to achieve a premixed homogeneous fuel–air mixture. Ignition of this premixed fuel–air mixture can be controlled by parameters such as pilot injection, pressure–temperature history of in-cylinder charge, etc. Compared to HCCI mode combustion, PCCI mode combustion exhibited better combustion control along with superior engine performance, however, NOx and PM emissions were relatively higher compared to HCCI mode combustion [10]. PCCI mode combustion offered superior emission characteristics up to medium engine loads, however, at higher engine loads, severe knocking due to excessive pressure rise rate (PRR) limited its applicability in production grade engines. Few researchers suggested that the operating load range of PCCI mode combustion could be increased by lowering the compression ratio (CR), which reduced the NOx and soot emissions compared to conventional CI mode combustion. However, this resulted in relatively lower BTE, and higher HC and CO emissions compared to PCCI mode combustion at higher CR [23–25]. PCCI mode combustion operating range was also enhanced by using a split injection strategy, in which a main injection along with a pilot injection was used. PCCI mode combustion using split injection strategies resulted in relatively lower NOx and PM emissions without any significant change in the BTE [26]. Therefore, many researchers explored split injection strategies using different fuel injection parameters such as fuel injection pressure (FIP), fuel injection timings, etc. and reported that fuel injection parameters provided superior combustion control and resulted in slightly higher BTE and in-cylinder pressure [24–27]. Parks et al. [28] performed the conventional CI mode and PCCI mode combustion experiments and reported that PCCI mode combustion emitted relatively lower NOx and PM compared to baseline CI mode combustion. In another study, effect of fuel properties was investigated in the PCCI mode combustion, which exhibited that NOx emissions reduced upon using dimethyl ether (DME) in the PCCI mode combustion [29]. Benajes et al. [30] also investigated the performance, emissions, and combustion noise of a diesel/gasoline blend-fuelled high-speed direct injection (HSDI) diesel engine operated in PCCI mode combustion. They reported that increasing fraction of gasoline in the test fuel enhanced the ignition delay, which improved the combustion due to longer time available for fuel–air mixing. Although PCCI mode combustion emitted relatively lower NOx and PM compared to baseline CI mode combustion, however, it has several limitations such as uncontrolled combustion and knocking at high engine loads.

Due to these limitations of HCCI and PCCI combustion modes, another LTC technique ‘RCCI mode combustion’ was developed, in which, different alternative fuels such as alcohols, biodiesel, etc. can be utilized more efficiently. In RCCI mode combustion, different combinations of low reactivity fuels (LRF) and high reactivity fuels (HRF) such as gasoline-diesel, gasoline-gasoline (with cetane number improver), E85 (85% ethanol + 15% gasoline)-diesel, and alcohol-diesel can be used to achieve a reactivity stratification in the engine combustion chamber [31–33]. Splitter et al. [34] and Curran et al. [35] studied the effect of fuel reactivities on RCCI mode combustion. They used ethanol, gasoline, and E85 as LRF, and diesel as HRF and reported superior RCCI mode combustion for fuel-pair having higher reactivity gradient. Few researchers also studied the effect of different control parameters such as swirl of the intake charge, EGR, start of injection (SoI) timing, FIP, etc. for both port fuel injection (PFI) as well as direct injection (DI). Hanson et al. [36] investigated the effect of SoI timing on RCCI mode combustion and reported that advancing SoI timing of mineral diesel resulted in higher NOx emissions. Walker et al. [37] studied the effect of FIP on RCCI mode combustion and observed that the combustion phasing was significantly affected by the FIP of HRF. Dempsey and Reitz [38] performed RCCI mode combustion experiments using mineral diesel and methanol fuel-pair as HRF and LRF respectively. They reported that RCCI mode combustion using higher premixed ratios of methanol resulted in retarded combustion phasing, due to relatively higher latent heat of vaporization and octane number (ON) of methanol compared to gasoline. Jia and Denbratt [39] studied the combustion characteristics of RCCI mode combustion at higher engine loads (12 bar brake mean effective pressure (BMEP)). They carried out experiments using diesel-methanol fuel-pair and reported ultra-low soot and NOx emissions compared to baseline CI mode combustion. Han et al. [40] compared the PCCI, HCCI and RCCI combustion modes using n-butanol and mineral diesel as test fuels. They reported that PCCI and HCCI combustion modes emitted significantly lower NOx and soot emissions compared to baseline CI mode combustion, however, RCCI mode combustion exhibited relatively higher efficiency along with superior combustion control compared to other LTC techniques. Most results presented by Han et al. [40] included a comparison of two test fuels namely mineral diesel and butanol but they didn't show a comparative analysis of different combustion modes, which was the main drawback of this study.

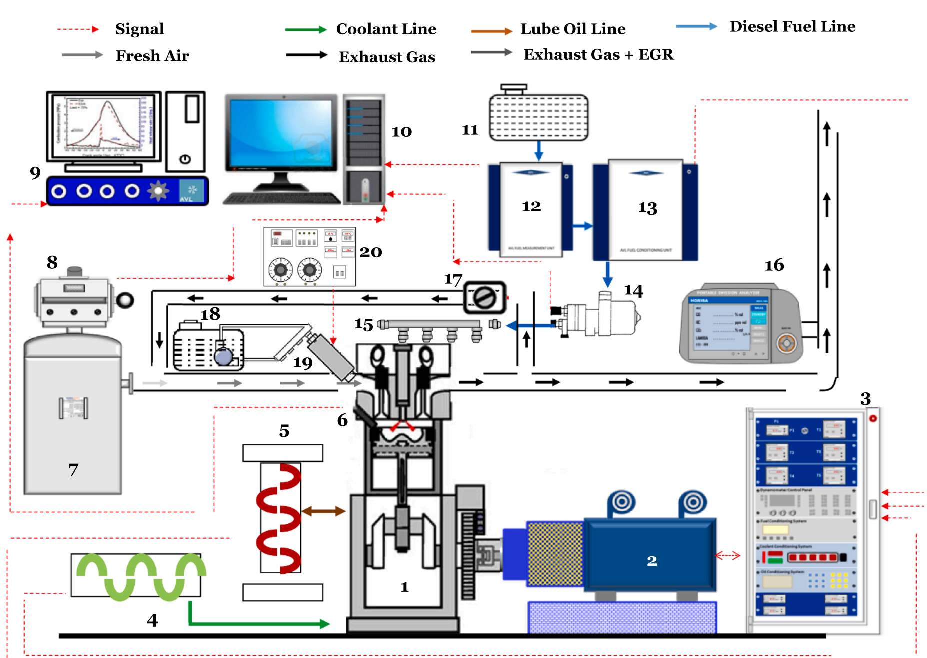
In most of these studies, combustion, performance and emissions characteristics of baseline CI, PCCI, and RCCI combustion modes were investigated separately using different test fuels and engine operating parameters. Very few studies are available in the open literature, in which combined investigations of different LTC modes were carried out to compare their combustion, performance and emissions characteristics at varying engine loads. In these studies, variety of combustion modes were explained separately without any emphasis on the comparison among different combustion modes. Therefore, this experimental study is focused on comparison of different combustion, performance and emissions characteristics of conventional CI, PCCI, and RCCI combustion modes. Baseline CI and PCCI combustion mode experiments were performed using mineral diesel, whereas RCCI mode combustion experiments were performed using methanol as LRF and mineral diesel as HRF at a fixed premixed ratio ($r_p = 0.50$). For all three modes of combustion, experiments were performed in a single-cylinder research engine at a fixed engine speed (1500 rpm) and at four different engine loads (1, 2, 3, and 4 bar BMEP). For all three combustion modes, FIP was kept constant (500 bar) and SoI timings were varied for each mode of combustion as 4°, 12° and 17° CA before top dead center (bTDC) for baseline CI, PCCI and RCCI mode combustion, respectively. These SoI timings were selected based on optimum engine performance for each combustion mode. An analysis of trade-off between NOx-BTE at different engine loads was also done to compare advantages of individual modes of combustion at different engine loads, which makes this study different from previous studies. Detailed combustion analysis including knocking and combustion noise was another novel aspect of LTC. The qualitative correlations between combustion, performance and emissions characteristics of three combustion modes at low and high engine loads was another novel aspect of this study, which demonstrated a clear comparison of different combustion modes.

2. Experimental setup and methodology

The experimental investigations of conventional CI, PCCI and RCCI combustion modes was performed in a single-cylinder, four stroke, direct injection compression ignition (DICI) research engine (AVL List GmbH; 5402). This engine is a single-cylinder version of a multi-cylinder engine, equipped with high-pressure common rail direct injection (CRDI) system. For controlling the engine speed and load, an AC dynamometer (Wittur Electric Drives GmbH; 2SB 3) was coupled to the test engine, which controlled the engine speed and load with accuracies of ± 1 rpm and ± 0.1 Nm respectively. The schematic of the experimental setup is shown in Fig. 1.

Technical specifications of the test engine are given in Table 1.

The test engine was also attached to three conditioning systems, namely fuel condition system (AVL, 553), lubricating oil conditioning system (Yantrashilpa; YS4312), and coolant conditioning system (Yantrashilpa; YS4027) for performing the experiments under controlled conditions. During all combustion modes, temperatures of lubricating oil, fuel and coolant were maintained at 90°C, 25°C, and 60°C respectively.



1	Test Engine	2	Transient Dynamometer	3	Control Panel
4	Coolant Conditioning System	5	Lubricating Oil Conditioning System	6	Pressure Transducer
7	Intake Air Surge Tank	8	Air-Flow Measurement System	9	Data Acquisition System
10	ECU Interface System	11	Primary Fuel Tank	12	Fuel Measurement System
13	Fuel Conditioning System	14	High Pressure Fuel Pump	15	High-Pressure Common Rail
16	Raw Exhaust Gas Analyzer	17	EGR Regulator	18	Secondary Fuel Tank
19	Port Fuel Injector	20	Injection Driver		

Fig. 1. Schematic of the experimental setup.

Table 1
Technical specifications of the test engine.

Engine make/ model	AVL/ 5402
Number of cylinders	1
Cylinder bore/ stroke	85/ 90 mm
Displacement volume	510.7 cc
Compression ratio	17.0
Inlet ports	Tangential and swirl inlet port
Nominal swirl ratio	1.78
Maximum power output	6 kW
Rated speed	4200 rpm
Fuel injection pressure	200–1400 bar
Fuel injection system	Common rail direct injection
High-pressure system	BOSCH Common Rail CP-4.1
Engine management system	AVL-RPEMS + BOSCH ETK7
Valves per cylinder	4 (2 inlet, 2 exhaust)

For measuring the fuel flow-rate of HRF, a fuel metering unit (AVL, 733S) was installed, which worked on the gravimetric measurement principle and provided the fuel flow rate in kg/h with an accuracy of ± 0.001 kg/h. For measuring the intake air flow rate, an air measurement system (ABB Automation Products; Sensy-flow P) was used in the experimental setup, which provided intake air flow rate in kg/h with an accuracy of ± 0.1 kg/h. For baseline CI mode combustion and PCCI mode combustion experiments, DI fuel system's parameters namely fuel injection quantity, SoI timing, FIP, number of injections, etc. were controlled by a complex system. This system included an electronic control unit (ECU), a communication interface (ETAS, ETK 7.1 Emulator probe) and a software control program (ETAS; INCA). For RCCI mode combustion, a secondary fuel injection system was also required, which injected LRF in the intake port of the engine. This fuel injection equipment (FIE) was a typical PFI system, which included an electric fuel pump, a fuel tank, a fuel accumulator, a fuel injector (Denso; 1500M844M1) and a fuel injector control circuit. In the secondary fuel injection system, test fuel was injected at low FIP of 3 bar only. Other details of the secondary fuel injection system and fuel injection driver circuit can be found in our previous publication [41]. For controlling the combustion, EGR system was also used in the PCCI and RCCI combustion modes, in which a fraction of exhaust gas was recirculated back in to the intake manifold, where it mixed with the fresh inlet air and then the mixture was supplied to the engine combustion chamber. For controlling the EGR rate, an EGR control valve was installed in the EGR line.

For combustion analysis, a high-speed data acquisition (DAQ) system (AVL; IndiMicro) was used, which processed the raw signals of a water-cooled pressure transducer (AVL; QC34C) and an optical angle encoder (AVL; 365C). Pressure transducer was flush-mounted in the cylinder head and measured the in-cylinder pressure up to 250 bar. Other important details of in-cylinder pressure analysis can be found in our previous publication [21]. Gaseous emission analyzer was capable of measuring different exhaust gas species such as CO, HC, NOx, and carbon dioxide (CO_2). Technical details of the gaseous emission analyser are given in Table 2.

For the measurement of fuel properties, a portable density meter (Kyoto Electronics; DA130N), a viscometer (Stanhope-Seta; 83541–3), and a bomb calorimeter (Parr; 6200) were used to measure density, kinematic viscosity and calorific value of both test fuels respectively. Test fuel properties are given in Table 3.

In all three modes of combustion, experiments were performed at constant engine speed (1500 rpm), constant FIP (500 bar) but varying engine loads (1, 2, 3, and 4 bar BMEP). In conventional CI mode combustion, SoI timing was kept constant at 4° bTDC at all engine loads. In PCCI mode combustion, split injection strategy was used, in which, pilot injection was done at 35° CA bTDC and main injection was done at 12° CA bTDC. Selection of fuel injection parameters for baseline CI and PCCI combustion modes were based on preliminary investigations carried out using a wide range of these parameters. In RCCI mode combustion, methanol was injected in the inlet port and mineral diesel was directly injected in the combustion chamber at 35° CA bTDC. The premixed ratios (r_p) of methanol was decided based on energy replacement and kept constant ($r_p = 0.50$) for all engine loads. Other important details of RCCI mode combustion can be seen in our previous publication [41]. Experimental methodology is shown in Fig. 2 pictorially.

All experimental measurements were made after thermal stabilization of the test engine in order to reduce the experimental errors. To reduce the measurement errors, experiments were performed thrice and an average of these measurements was reported as the experimental data point. In this study, root-of-the-sum-of-the-squares (RSS) technique was used for the uncertainty analysis, in which all uncertainties such as precision, calibration and measurement were considered. Uncertainties data provided by the emission measurement systems was also included in the uncertainty analysis [41].

3. Results and discussion

Results of the experiments were divided into three sub-sections namely: combustion, performance, and emissions characteristics. In each sub-section, a comparison between different combustion modes namely baseline CI, PCCI and RCCI has been presented at different engine loads at constant engine speed.

3.1. Combustion characteristics

Experiments were performed to assess the combustion parameters [in-cylinder pressure, heat release rate (HRR), start of combustion (SoC), combustion phasing (CP), and combustion duration (CD)] of different combustion modes at four engine loads. In order to avoid cyclic variations and to account for measurement errors, average in-cylinder pressure data of 250 consecutive engine cycles was used for the combustion analysis. Fig. 3 shows the in-cylinder pressure and HRR variations w.r.t. crank angle positions for the conventional CI, PCCI, and RCCI combustion modes at different engine loads.

Fig. 3 shows that the in-cylinder pressure of baseline CI, PCCI and RCCI combustion modes followed different trends. Effect of significantly retarded SoI timing was clearly visible in the in-cylinder pressure curves of baseline CI mode combustion, where two separate peaks were present, corresponding to motoring and combustion respectively. The in-cylinder pressure curves showed similar trend for varying engine loads, however, the height of the combustion peak of the in-cylinder pressure curves in baseline CI mode combustion increased with increasing engine load. This was mainly due to increased fuel quantity injected in the combustion chamber, which exhibited dominant diffusion phase combustion. At 1 bar BMEP, RCCI mode combustion exhibited relatively inferior combustion compared to PCCI mode combustion. Combined effect of lower in-cylinder temperature, relatively lower global reactivity and charge cooling effect of methanol were the

Table 2
Technical specifications of exhaust gas emission analyser.

Species	Measurement Principle	Range	Repeatability
CO	Non-dispersive infrared (NDIR)	0% to 10%	0.01%
HC		0 ppm to 20000 ppm	3.3 ppm
CO_2		0% to 20%	0.17%
NOx	NO sensor	0 ppm to 5000 ppm	5 ppm

Table 3
Important measured test fuel properties.

Test fuel	Calorific Value (MJ/kg)	Kinematic Viscosity (mm^2/s) @ 40 °C	Density (g/cm^3) @ 30 °C
Mineral Diesel	44.26	2.96	0.837
Methanol	21.90	0.57	0.787

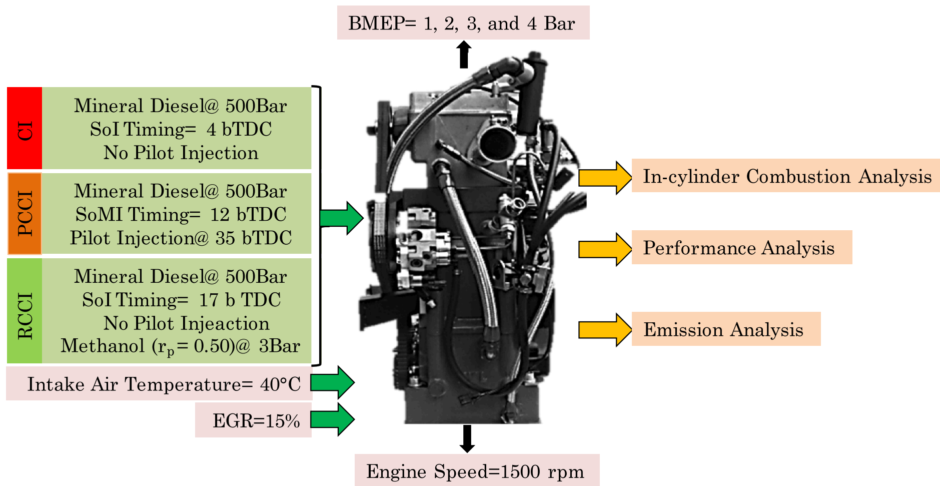


Fig. 2. Experimental methodology.

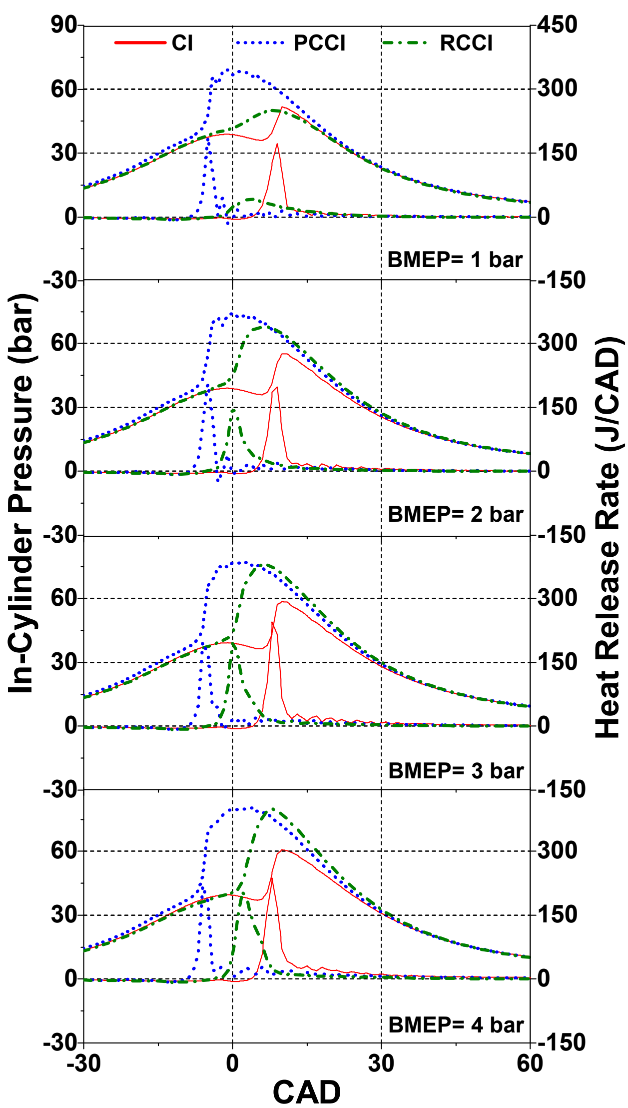


Fig. 3. In-cylinder pressure and heat release rate variations for baseline CI, PCCI and RCCI combustion modes at varying engine loads.

main factors responsible for relatively inferior RCCI mode combustion. At lower engine loads, only PCCI mode combustion exhibited knocking characteristics, and baseline CI and RCCI combustion modes did not show knocking. At 2 bar BMEP, in-cylinder pressure characteristics of PCCI and RCCI combustion modes were quite similar, wherein premixed phase combustion was dominant, however, dominance of diffusion phase combustion was clearly visible in baseline CI mode combustion. Relatively more time availability for the fuel–air mixing and presence of premixed methanol-air charge were the two main reasons for dominant premixed combustion phase in PCCI and RCCI combustion modes. Compared to 1 bar BMEP, RCCI mode combustion exhibited relatively superior combustion characteristics at 2 bar BMEP. This was mainly due to improved in-cylinder conditions (temperature), which enhanced global reactivity of the in-cylinder charge. At 2 bar BMEP, PCCI mode combustion exhibited relatively higher knocking compared to that at 1 bar BMEP. At 3 bar BMEP, in-cylinder pressure curves of all three combustion modes exhibited greater similarity with the in-cylinder pressure curves at 2 bar BMEP. At higher engine loads (3 and 4 bar BMEP), relatively more stable RCCI mode combustion was observed, which exhibited P_{max} similar to PCCI mode combustion, without knocking. In-cylinder pressure curves of RCCI mode combustion clearly exhibited dominant effect of methanol, which retarded the SoC and encouraged relatively faster combustion compared to PCCI mode combustion. Fig. 3 also shows the HRR trends of baseline CI, PCCI and RCCI combustion modes at varying engine loads. HRR trends also showed the dominant premixed phase combustion in PCCI and RCCI combustion modes, however, baseline CI mode combustion exhibited dominant diffusion phase combustion. For all three combustion modes, increasing engine load exhibited increased peak of HRR (Q_{max}). With increasing engine load, shifting of Q_{max} towards the bTDC was an important observation, which exhibited faster fuel–air combustion kinetics at higher engine loads. This trend was relatively more dominant in PCCI and baseline CI combustion modes, and RCCI mode combustion didn't show this trend.

Fig. 4 shows the variations of maximum rate of pressure rise (R_{max}), P_{max}, and Q_{max} of baseline CI, PCCI and RCCI combustion modes w.r.t. engine load. These parameters were related to the combustion stability of different combustion modes.

Fig. 4 showed that R_{max} of all three combustion modes increased with increasing engine load. Relatively higher fuel quantity injected in the combustion chamber and increased in-cylinder temperature resulted in faster fuel–air chemical kinetics, leading to higher R_{max}. R_{max} of baseline CI and RCCI combustion modes didn't follow increasing trend at 4 bar BMEP. Among different combustion modes, PCCI mode combustion exhibited significantly higher R_{max} compared to the other two

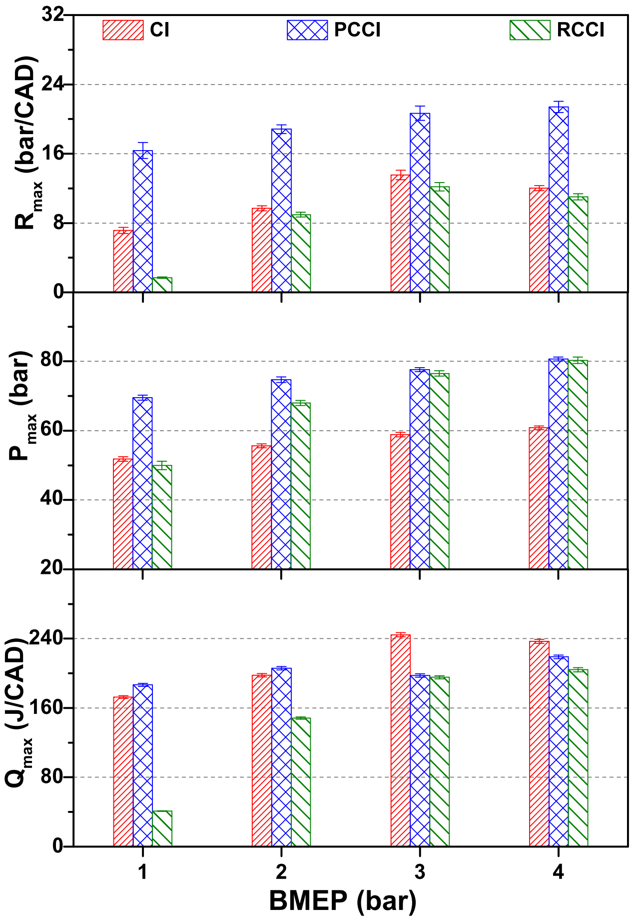


Fig. 4. R_{max}, P_{max}, and Q_{max} of baseline CI, PCCI and RCCI combustion modes at varying engine loads.

combustion modes. Dominant premixed phase combustion due to advanced SoI timing was the main reason for this behavior. Relatively more stable combustion characteristics of baseline CI and RCCI combustion modes were also seen in R_{max} trends. Retarded SoI timing and dominant contribution of methanol were the main factors responsible for relatively lower R_{max} of baseline CI and RCCI combustion modes respectively. Fig. 4 showed that the P_{max} of all three combustion modes increased with increasing engine load and this increase was dominant in RCCI mode combustion. Presence of relatively higher fuel quantity in the combustion chamber and more intense in-cylinder conditions were the main reasons responsible for higher P_{max} at higher engine loads. At all engine loads, PCCI mode combustion exhibited the highest P_{max}, however, at higher engine loads, RCCI mode combustion exhibited P_{max} similar to PCCI mode combustion. Fig. 4 also showed the trends of Q_{max} of different combustion modes at varying engine loads. Increasing engine load resulted in a random pattern of Q_{max} variation. Q_{max} of all three combustion modes first increased with increasing engine load and then slightly decreased. At lower engine loads, PCCI mode combustion exhibited relatively higher Q_{max} compared to other combustion modes, however, at higher engine loads, baseline CI mode combustion exhibited the highest Q_{max}. At all engine loads, RCCI mode combustion exhibited the lowest Q_{max}, which also exhibited relatively more stable combustion characteristics of RCCI mode combustion.

Fig. 5 showed the variations of ignition delay (ID) of baseline CI, PCCI and RCCI combustion modes at different engine loads. ID was calculated as the difference between the SoI timing and the SoC timing. SoC was measured as the crank angle position corresponding to 10% cumulative heat release (CHR). ID was controlled by chemical kinetics of the fuel–air mixture, which was affected by the fuel properties, in-cylinder pressure and temperature history, fuel injection parameters, etc. [42].

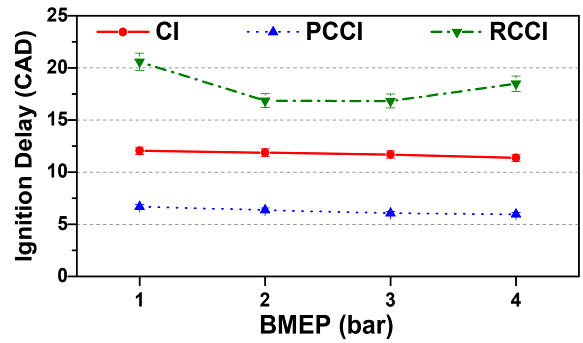


Fig. 5. Ignition delay of baseline CI, PCCI and RCCI combustion modes at varying engine loads.

Fig. 5 shows an interesting trend of ID variations of baseline CI, PCCI and RCCI combustion modes at varying engine loads. ID for baseline CI and PCCI combustion modes slightly reduced with increasing engine load. Relatively higher in-cylinder temperature might be a possible reason for slight reduction of ID at higher engine loads, however, this reduction was not very significant. ID of RCCI mode combustion first reduced (up to 3 bar BMEP) and then increased with increasing engine load. Dominant contribution on in-cylinder temperature and low reactivity of methanol were the two main parameters responsible for this trend. Up to 3 bar BMEP, increased in-cylinder temperature resulted in lower ID, however, at 4 bar BMEP, presence of larger fraction of methanol in the engine combustion chamber reduced global reactivity of fuel–air mixture, leading to longer ID. Results showed that ID of RCCI mode combustion was significantly higher than baseline CI and PCCI combustion modes. Relatively lower reactivity of methanol, lower in-cylinder temperature, and EGR were the main factors responsible for longer ID of RCCI mode combustion. Relatively longer ID of baseline CI mode combustion compared to PCCI mode combustion was an important observation. This was mainly due to presence of pilot injection in PCCI mode combustion, which improved in-cylinder conditions for the main injection, leading to shorter ID compared to baseline CI mode combustion.

Fig. 6 shows the CP and CD variations of baseline CI, PCCI and RCCI combustion modes at different engine loads.

CP was measured as the crank angle position corresponding to 50% cumulative heat release (CHR), denoted as CA_{50}. CP was a critical parameter for both LTC modes (PCCI and RCCI combustion modes) since too advanced CP resulted in rapid combustion/ heat release, leading to knocking, and on the other hand, too retarded CP leads to higher HC and CO emissions due to incomplete combustion [42]. Fig. 6 exhibited an interesting trend of CP variations of different combustion modes. CP of PCCI mode combustion was significantly advanced compared to baseline CI mode as well as RCCI mode combustion. Significantly advanced SoI timing was the main reason for this trend, which resulted in dominant premixed phase combustion. CP of baseline CI mode combustion didn't show any variation at different engine loads, however, CP of PCCI mode combustion retarded with increasing engine load. This was mainly due to presence of fuel quantity, which took more time to complete the combustion. In contrast to PCCI mode combustion, CP of RCCI mode combustion first advanced (up to 3 bar BMEP) and then slightly retarded with increasing engine load. Slightly different SoC and CP of RCCI mode combustion at 1 bar compared to SoC and CP at higher engine loads was another important observation. This was due to combined effect of higher latent heat of vaporization of methanol present in the combustion chamber and relatively lower in-cylinder temperature, which led to un-optimized CP of RCCI mode combustion at 1 bar BMEP. Effect of un-optimized CP was also visible in performance (Fig. 8) and emission

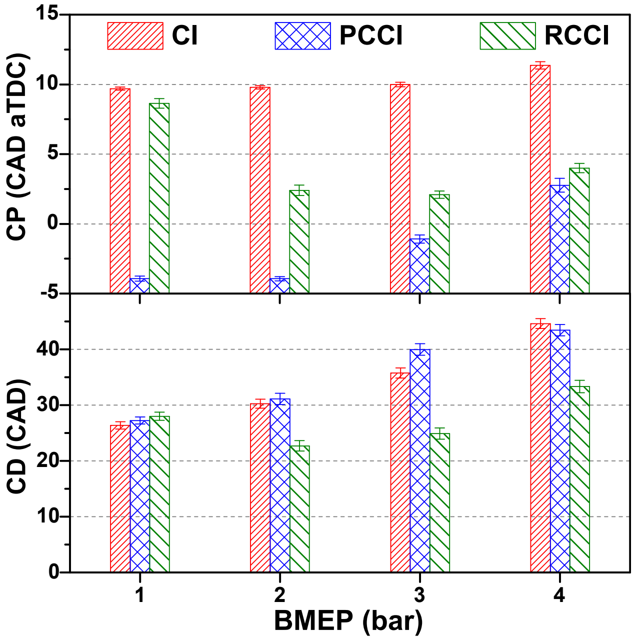


Fig. 6. Combustion phasing and combustion duration of baseline CI, PCCI and RCCI combustion modes at varying engine loads.

(Fig. 9) characteristics of RCCI mode combustion at 1 bar BMEP. CD was another combustion parameter, which was measured as the crank angle degree difference between the end of combustion (crank angle position corresponding to 90% CHR) and the SoC. Results showed that CD of baseline CI and PCCI combustion modes increased with increasing engine load, however, CD of RCCI mode combustion first decreased (up to 2 bar BMEP) and then increased with increasing engine load. Increased fuel quantity injected in the combustion chamber was the main reason for longer CD of baseline CI and PCCI combustion modes. CD of RCCI mode combustion was affected by both, increased amount of methanol as well as mineral diesel inducted. Increasing engine load up to 2 bar BMEP resulted in relatively lower CD, mainly due to dominant effect of mineral diesel and more intense in-cylinder conditions, leading to faster-fuel–air combustion kinetics. However, at higher engine loads, effect of methanol became dominant, which reduced the global reactivity, leading to slightly longer CD. Among different combustion modes, RCCI mode combustion exhibited relatively shorter CD compared to other combustion modes. Presence of reactivity stratification and relatively higher flame speed of methanol might be possible reasons for this behavior, which became more dominant at higher engine loads.

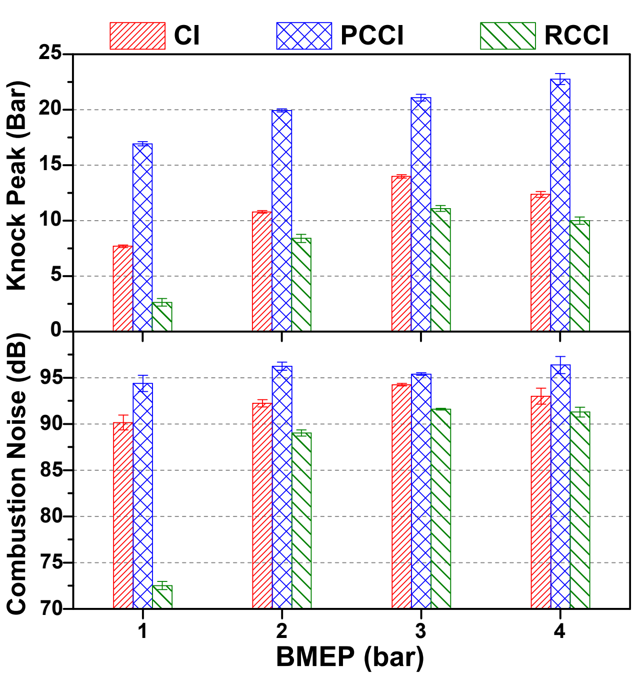


Fig. 7. Knock peak and combustion noise of baseline CI, PCCI and RCCI combustion modes at varying engine loads.

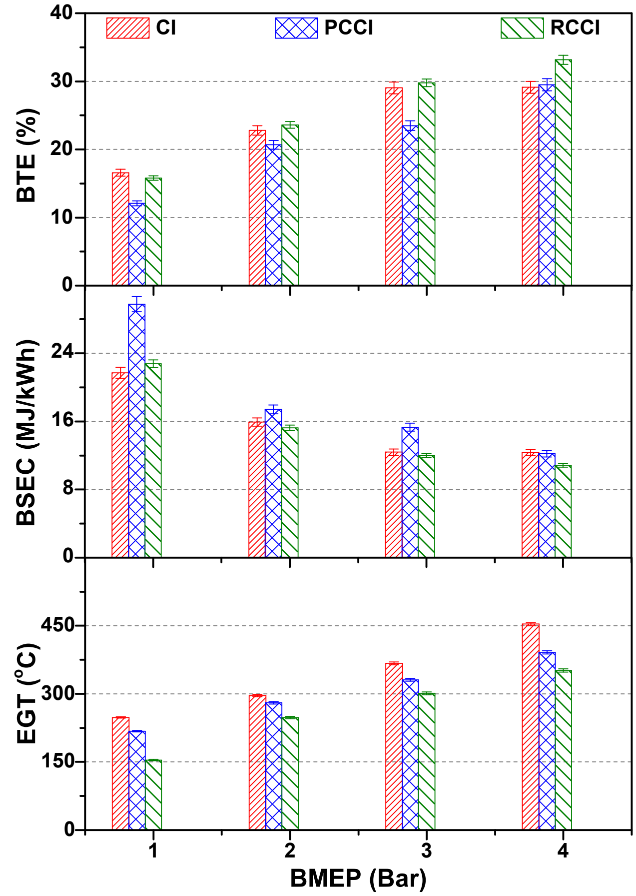


Fig. 8. BTE, BSEC and EGT of baseline CI, PCCI and RCCI combustion modes at varying engine loads.

Fig. 7 shows the variations of knock peak (KP) and combustion noise of baseline CI, PCCI, and RCCI combustion modes w.r.t. engine load. KP is defined as the maximum pressure obtained by the superimposing rectified oscillations on the cylinder pressure curve. The combustion noise could be determined from filtered measured pressure signals using a standard methodology [15]. The shockwave generated in the combustion chamber was the main source of combustion noise [42].

For all three combustion modes, KP increased with increasing engine load, however, baseline CI and RCCI combustion modes exhibited slightly lower KP at maximum engine load (4 bar BMEP). KP trends showed that KP in RCCI mode combustion was lower than both baseline CI and PCCI combustion modes at all engine loads. KP results of RCCI mode combustion were in agreement with other combustion modes. Reactivity stratification due to presence of methanol in the combustion chamber and relatively lower in-cylinder temperature were the main reasons for the lowest KP in RCCI mode combustion. KP in PCCI mode combustion was the maximum at all engine loads. Dominant premixed phase combustion due to advanced SoI timing was the main reason for relatively higher KP in PCCI mode combustion. KP of baseline CI mode combustion was in between PCCI and RCCI combustion modes. Dominant diffusion phase combustion (slower combustion) due to retarded

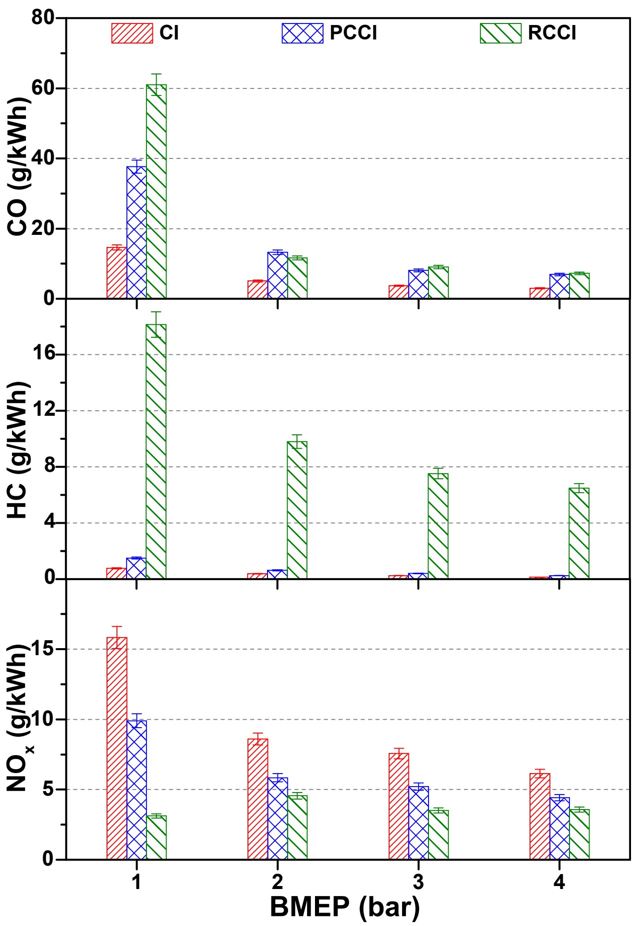


Fig. 9. CO, HC and NOx emitted from baseline CI, PCCI and RCCI combustion modes at varying engine loads.

SoI timing (4° CA bTDC) was the main factor responsible for lower KP of baseline CI mode combustion. For all three combustion modes, combustion noise increased with increasing engine load (up to 3 bar BMEP), however, increase in combustion noise at maximum engine load was not significant. Combustion noise trends exhibited great similarity with KP and R_{max} trends. Similar to KP, combustion noise was the highest for PCCI mode combustion, and RCCI mode combustion exhibited the lowest combustion noise at all engine loads. Due to lower in-cylinder temperature and dominant contribution of methanol, RCCI mode combustion exhibited significantly lower combustion noise at 1 bar BMEP. Baseline CI mode combustion exhibited intermediate combustion noise between PCCI and RCCI combustion modes. Relatively more stable combustion due to retarded SoI timing was the main reason for this trend.

3.2. Performance characteristics

In this study, performance parameters namely brake thermal efficiency (BTE), brake specific energy consumption (BSEC), and exhaust gas temperature (EGT) of the three combustion modes namely baseline CI, PCCI, and RCCI were compared at varying engine loads.

Fig. 8 shows that the BTE of all three combustion modes increased with increasing engine load, however, this increase was more dominant in PCCI and RCCI combustion modes. Relatively higher in-cylinder temperature was the main reason for higher BTE at higher engine loads, which led to more efficient fuel-burning, hence higher power output. Among different combustion modes, RCCI mode combustion exhibited the maximum BTE (~34%) at 4 bar BMEP, and the lowest BTE (~13%) was exhibited by PCCI mode combustion at 1 bar BMEP. At lower engine loads (up to 2 bar BMEP), baseline CI mode combustion exhibited relatively higher BTE compared to both PCCI and RCCI combustion modes, however, at higher engine loads, increase in BTE was higher in PCCI and RCCI combustion modes. At the maximum engine load, BTE of both baseline CI and PCCI combustion modes was almost similar. There were many factors responsible for relatively higher BTE of RCCI mode combustion, among which, improved combustion due to retarded CP, lower heat transfer through cylinder walls due to lower in-cylinder temperature, relatively faster combustion/ HRR due to presence of methanol, etc. were the important ones [41–42]. At lower engine loads, PCCI mode combustion exhibited significantly lower BTE, which makes this less suitable for part-load applications. Relatively more advanced SoI timing was the main reason for this trends, leading to incomplete combustion. Lack of combustion control and knocking might be the other factors responsible for lower BTE of PCCI mode combustion. Unlike PCCI and RCCI combustion modes, baseline CI mode combustion exhibited slight reduction in BTE at 4 bar BMEP. Pyrolysis of lubricating oil due to significantly higher in-cylinder temperature might be a possible reason for this trend, which increases the frictional losses, leading to lower power being available at the engine shaft. BSEC variations of baseline CI, PCCI and RCCI combustion modes followed a trend, which was reverse of BTE. In this study, fuel consumption is presented as BSEC due to involvement of two different fuels (mineral diesel and methanol) having different calorific values, especially in the RCCI mode combustion. Results showed that BSEC reduced with increasing engine load. Among different combustion modes, PCCI mode combustion exhibited significantly higher BSEC. BSEC trends were in general agreement with combustion results (Fig. 3). EGT was another important performance parameter of this study, which was used as qualitative measure of the in-cylinder temperature. Results showed that EGT of all three combustion modes increased with increasing engine load. Presence of relatively higher fuel quantity and contribution of diffusion phase combustion might be the possible reasons for higher EGT at higher engine loads. Among different combustion modes, baseline CI mode combustion exhibited the maximum EGT at all engine loads. Dominant diffusion phase combustion was the main reason for relatively higher EGT of baseline CI mode combustion. Similarly, RCCI mode combustion exhibited the lowest EGT at all engine loads. Relatively higher latent heat of vaporization of methanol, advanced SoI timing of mineral diesel, presence of EGR, and absence of diffusion phase combustion were the factors responsible for lower EGT in RCCI mode combustion. At all engine loads, EGT in PCCI mode combustion were in-between baseline CI and RCCI combustion modes. This was mainly due to advanced SoI timing and contribution of EGR, which resulted in relatively lower EGT of PCCI mode combustion, compared to baseline CI mode combustion. However, absence of contribution of methanol in PCCI mode combustion was the main reason for higher EGT of PCCI mode combustion, compared to RCCI mode combustion.

3.3. Emission characteristics

Fig. 9 shows the variations in emissions of exhaust gases namely HC, CO and NOx in baseline CI, PCCI and RCCI combustion modes at varying engine loads. These emission species were measured in their raw concentrations (ppm/ %) and then converted to the brake-specific mass emission values (g/kWh) using standard set of equations [43].

Fig. 9 shows that CO emission from all three combustion modes reduced with increasing engine load. This was mainly due to increase in the in-cylinder temperature, which directly affected the oxidation of CO-to-CO_2. CO trends showed that PCCI and RCCI combustion modes emitted relatively higher CO compared to baseline CI mode combustion. Relatively lower in-cylinder temperature due to advanced SoI timing and presence of EGR were the main reasons for this trend. Among the two LTC modes, RCCI mode combustion resulted in relatively higher CO emission compared to PCCI mode combustion. Additional reduction in the in-cylinder temperature due to dominant contribution of methanol was the main factor responsible for higher CO emission from the RCCI mode combustion. At higher engine loads, significant increase in the in-cylinder temperature reduced the effects of advanced SoI timing and in-cylinder cooling of methanol in the PCCI and RCCI combustion modes respectively, leading to almost similar CO emission from all three combustion modes. In CI engines, incomplete combustion, fuel trapped in the crevices, and wall quenching were the main factors responsible for HC emissions. Results showed that increasing engine load resulted in lower HC emissions from all three combustion modes. This was due to higher in-cylinder temperature, leading to more complete combustion. Effect of engine load was clearly visible in the trends of HC emissions for RCCI mode combustion, wherein increased in-cylinder temperature drastically reduced the HC emissions from ~ 18 g/kWh to ~ 6 g/kWh. RCCI mode combustion emitted significantly higher HC compared to baseline CI and PCCI combustion modes. Dominant contribution of methanol trapped in the crevices might be a major reason for higher HC emissions from RCCI mode combustion. In-cylinder cooling due to relatively higher latent heat of vaporization of methanol also promoted incomplete combustion of fuel, leading to higher HC emissions compared to other combustion modes. In diesel engines, peak in-cylinder temperature, availability of oxygen locally, and time for reactions are the most important parameters, which affect NOx formation [42]. Fig. 9 showed that NOx emissions decreased with increasing engine load and this trend was common for baseline CI and PCCI combustion modes. This was mainly due to improved engine performance, which reduced the brake specific NOx emissions. RCCI mode combustion didn't show any significant variation in the NOx emissions at different engine loads. Among different combustion modes, baseline CI mode combustion emitted significantly higher NOx compared to the LTC modes. Relatively higher in-cylinder temperature and dominant diffusion phase combustion were the main reasons for higher NOx emissions from baseline CI mode combustion. This trend was in agreement with EGT variations (Fig. 8). Among the two LTC modes, RCCI mode combustion was more effective in NOx reduction. Combined effect of methanol and EGR resulted in significantly lower in-cylinder temperature, leading to relatively lower NOx emissions compared to PCCI mode combustion.

Fig. 10 shows the NOx-BTE trade-off w.r.t. BMEP for conventional CI, PCCI and RCCI combustion modes. For each combustion mode, engine loads were divided into two regions based on NOx and BTE magnitudes: (i) low efficiency-high NOx region (red pattern), and (ii) high efficiency-low NOx region (blue pattern). The inter-section point of NOx and BTE lines was termed as the saddle point, at which low efficiency-high NOx changed to high efficiency-low NOx region. This analysis has two qualitative parameters such as (i) area of high efficiency-low NOx region, and (ii) location of the saddle point. Movement of saddle point towards the lower engine loads represents superior engine combustion. Similarly, higher area of high efficiency-low NOx region exhibits suitability of that combustion mode for wider load range.

Fig. 10 shows that the saddle points of baseline CI mode combustion was at ~ 1.7 bar BMEP, however, the location of saddle point in PCCI mode combustion was at ~ 1.4 bar BMEP. This showed that PCCI mode combustion was relatively superior compared to baseline CI mode combustion. Relatively higher area of low efficiency-high NOx regions of baseline CI mode combustion compared to PCCI mode combustion also exhibited superior performance of PCCI mode combustion. However, the areas of high efficiency-low NOx regions were almost similar for these two combustion modes. RCCI mode combustion showed that there was no saddle point in NOx-BTE trade-off and the area of high efficiency-low NOx region was significantly more compared to baseline CI and PCCI combustion modes. This suggested that RCCI mode combustion exhibited relatively superior performance and emissions compared to baseline CI and PCCI combustion modes.

Fig. 11 showed the parametric analysis of combustion, performance and emission characteristics of baseline CI, PCCI and RCCI combustion modes at low engine load (1 bar BMEP) and high engine load (4 bar BMEP). In this analysis, NOx and smoke opacity were used as emission parameters, R_{max} was used as combustion parameter and BSEC was used as the performance parameter. This radar was divided into four quadrants for (i) NOx-R_{max}, (ii) BSEC-NOX, (iii) BSEC-smoke, and (iv) smoke-R_{max}. The area of quadrilateral formed using these parameters presented the effectiveness of each combustion mode and smaller area covered in each quadrant represented the effectiveness of each combustion mode in that particular aspect. Shape of quadrilateral also presented important information about each combustion mode e.g. elongation of quadrilateral in any specific direction exhibited relative dominance of that particular parameter. Fig. 11(a) showed that RCCI mode combustion was effective in combustion and emission characteristics, however, performance of RCCI mode combustion was slightly inferior to the baseline CI mode combustion. PCCI mode combustion exhibited superior emission characteristics (NOx and smoke opacity), however, combustion and performance of PCCI mode combustion were relatively inferior compared to both baseline CI and RCCI combustion modes. Baseline CI mode combustion was found to be effective only in terms of engine performance, which exhibited relatively lower BSEC compared to both PCCI as well as RCCI combustion modes. Dominant NOx emissions from CI combustion mode was also clearly visible in the parametric analysis, which exhibited an elongated quadrilateral towards the NOx-axis. Significantly lower area of quadrilaterals formed by the parameters of RCCI mode combustion compared to baseline CI and PCCI combustion modes presented its overall effectiveness in terms of combustion, performance and emission characteristics.

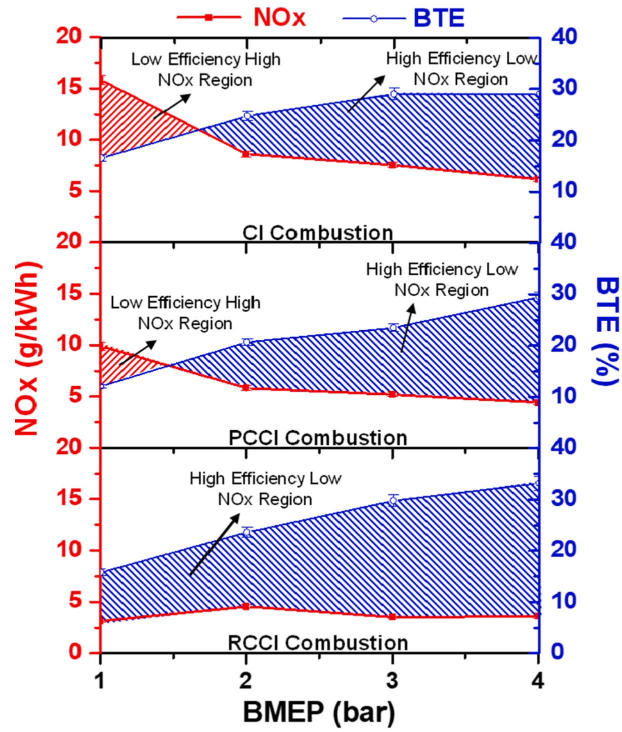


Fig. 10. NOx-BTE trade-off of baseline CI, PCCI and RCCI combustion modes at varying engine loads.

Fig. 11(b) shows the parametric analysis of different combustion modes at high engine load (4 bar BMEP). At higher engine load, combustion and smoke opacity showed a significant difference in all three combustion modes, however, difference between BSEC and NOx emissions were relatively lower. Among different combustion modes, RCCI emitted relatively lower NOx and smoke compared to baseline CI and PCCI combustion modes, however, BSEC and R_{max} of RCCI mode combustion were comparable to baseline CI mode combustion. At higher engine load, NOx and BSEC of PCCI mode combustion were comparable to RCCI mode combustion, but smoke opacity was slightly higher.

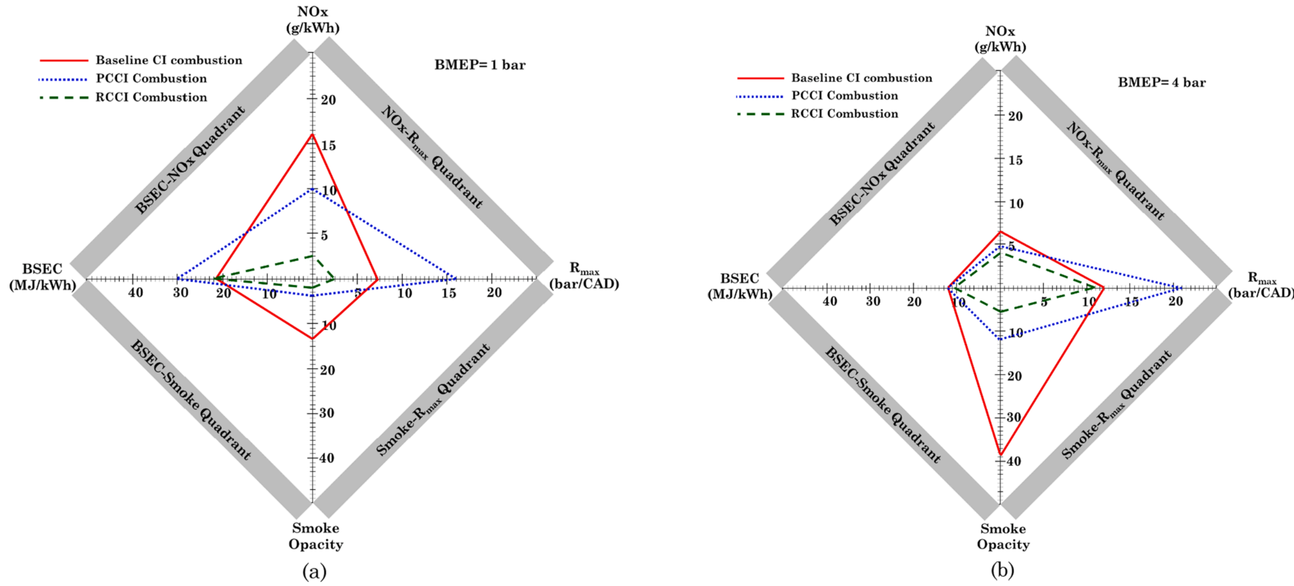


Fig. 11. Comparison of baseline CI, PCCI and RCCI combustion modes at (a) low engine load (1 bar BMEP) and (b) high engine load (4 bar BMEP).

Among different combustion modes, significantly higher R_{max} (~24 bar/CAD) of PCCI mode combustion was an important observation, which indicates that PCCI mode combustion was less suitable for higher engine load applications. Elongated quadrilateral corresponding to baseline CI mode combustion towards the smoke opacity exhibited the dominance of smoke opacity at higher engine loads. Comparison of quadrilateral areas corresponding to each combustion mode indicated that RCCI mode combustion was superior compared to baseline CI and PCCI combustion modes. A similarity in the shape of quadrilaterals corresponding to PCCI and RCCI combustion modes was an important observation. This exhibited that both LTC strategies have similar advantages, however, RCCI mode combustion was more effective in terms of combustion, performance and emissions compared to PCCI mode combustion.

4. Conclusions

In this experimental study, baseline CI, PCCI and RCCI combustion modes were investigated using a single-cylinder research engine. For conventional CI and PCCI combustion modes, experiments were performed using mineral diesel as test fuel and for RCCI mode combustion, mineral diesel was used as HRF and methanol was used as LRF. For each combustion mode, other parameters such as FIP, SoI timing, etc. were optimized. Results showed that RCCI mode combustion was relatively more stable than baseline CI and PCCI combustion modes. Among different combustion modes, PCCI mode combustion resulted in relatively earlier SoC, which exhibited knocking. At lower engine loads, PCCI mode combustion exhibited improved combustion characteristics, however, at higher engine loads, RCCI mode combustion became similar to PCCI mode combustion. Knocking analyses exhibited that PCCI mode combustion resulted in relatively higher knocking and combustion noise compared to other two combustion modes. Relatively advanced SoC and CP of PCCI mode combustion compared to baseline CI and RCCI combustion modes resulted in relatively lower BTE. Performance analysis showed that BTE of baseline CI mode combustion was slightly higher at lower engine loads, however, BTE of LTC modes, especially RCCI mode combustion were relatively higher at higher engine loads. LTC characteristics were clearly visible in the EGT trends where both PCCI and RCCI combustion modes exhibited significantly lower EGT compared to baseline CI mode combustion. Emission characteristics exhibited that HC and CO emissions from LTC modes were higher than baseline CI mode combustion, however, both PCCI as well as RCCI combustion modes emitted significantly lower NOx. Absence of NOx-BTE trade-off in RCCI mode combustion was an important outcome of this study, which exhibited the applicability of RCCI mode combustion at all engine loads. Parametric analysis of important combustion, performance and emissions characteristics of baseline CI, PCCI and RCCI combustion modes exhibited the effectiveness of RCCI mode combustion compared to baseline CI and PCCI combustion modes. Overall, this study concluded that RCCI mode combustion has significant potential for utilization of alternative fuels with improved engine performance and emissions advantage therefore it can be implemented in modern production grade diesel engines as a sustainable transport technology solution.

CRediT authorship contribution statement

Akhilendra Pratap Singh: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing - original draft. **Vikram Kumar:** Investigation, Writing - original draft. **Avinash Kumar Agarwal:** Conceptualization, Methodology, Project administration, Resources, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors 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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