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Researchers have investigated reactivity-controlled compression ignition (RCCI) combustion in the past several years because of its excellent combustion, performance, and emission features. In this experimental study, the RCCI combustion strategy was investigated using mineral diesel/butanol fuel-pair at various premixed ratios (r_p) on an energy basis (r_p = 0.25, 0.50, and 0.75) at varying engine loads (BMEP = 1, 2, 3, and 4 bars) vis-à-vis baseline compression ignition (CI) combustion (r_p = 0.0) strategy. Experiments were performed at constant engine speed (1500 rpm) in a single-cylinder research engine equipped with state-of-the-art features. The outcome of the investigation showed that port injection of Butanol as low reactivity fuel (LRF) improved the combustion and yielded superior engine performance than baseline CI combustion strategy. Engine exhaust emissions exhibited significantly lower nitrogen (NO_x) oxides with butanol RCCI combustion strategy than baseline CI combustion strategy. Increasing r_p of butanol showed improved combustion and emission characteristics; however, performance characteristics were not affected significantly. Particulate characteristics of the RCCI combustion strategy also showed a significant reduction in particle number concentration than baseline CI combustion. Slightly different combustion, performance, and emission characteristics of mineral diesel/ butanol-fueled RCCI combustion strategy compared to other test fuels such as mineral diesel/methanol, and mineral diesel/ethanol-fueled RCCI combustion strategy was an interesting observation of this study. Overall, this study indicated that butanol could be used as LRF in RCCI combustion engines to achieve superior combustion and emission characteristics.

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Keywords: alternative energy sources, fuel combustion, renewable energy, unconventional petroleum

1 Introduction

Internal combustion (IC) engines play a crucial role in developing/developed nations' economies since the agriculture, industrial, and transport sectors are heavily dependent on IC engines. IC engines are powered by diesel or gasoline, which results in the formation of pollutants such as nitrogen oxides (NO_x), particulate matter (PM), etc. These species are harmful to human health and the environment; therefore, the concentration of these species emitted from IC engines is monitored by emission regulatory bodies by implementing strict emission norms. These emission norms have become increasingly stringent in the last few years, especially for mineral diesel-fueled compression ignition (CI) engines. Although CI engines are far more efficient than spark ignition (SI) engines, CI engines face resistance in the transport sector due to relatively higher NO_x and PM emissions. Many studies have shown that PM emitted by CI engines causes severe health effects such as cancer and respiratory diseases [1–5]. A few recent studies suggested that compressed natural gas (CNG) can replace mineral diesel to reduce diesel engines' harmful emissions. Researchers suggested using alternative fuels and after-treatment systems to control exhaust emissions; however, these solutions have several drawbacks, including engine performance issues [6–10]. In such a scenario, it becomes necessary to introduce advanced combustion techniques, reducing these emissions without affecting the engine performance adversely. Low-temperature combustion (LTC) is one such technology, which has drawn researchers' attention due to its excellent NO_x and PM reduction capabilities [11,12]. Initially, LTC was introduced in the form of homogeneous charge compression ignition (HCCI) and premixed charge compression ignition (PCCI) modes of combustion. However, lack of control over combustion and difficulty in catering to high engine loads were the two main obstacles for implementing these strategies in a production-grade engine [13–15]. A new LTC technique has been developed to resolve these issues, which is referred to as "reactivity-controlled compression ignition" (RCCI) combustion. RCCI combustion strategy has relatively better control of combustion than other LTC strategies.

In the RCCI combustion strategy, two fuels of different reactivities are used, resulting in a reactivity gradient inside the combustion chamber for controlling the combustion. The fuel-pair consists of a high reactivity fuel (HRF) like mineral diesel, biodiesel, etc., which are directly inducted into the combustion chamber. The other is a low reactivity fuel (LRF), such as gasoline, alcohol, etc., which is inducted in the engine's intake manifold. Relative proportions of these two fuels control the reactivity gradient as well as global reactivity in the combustion chamber. Start of combustion (SoC) mainly controls the reactivity gradient; however, overall combustion parameters such as combustion duration (CD), maximum in-cylinder temperature, etc., control the global

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reactivity. Like other LTC strategies, the RCCI combustion strategy also uses exhaust gas recirculation (EGR) for combustion control. Singh et al. [16] performed a RCCI combustion strategy experiment using methanol as LRF and mineral diesel as HRF. They reported that the combustion stability of the RCCI combustion strategy was more stable than the baseline CI combustion strategy, and it exhibited relatively lower knocking. The effects of mineral diesel fuel injection parameters were investigated by Singh et al. [17]. They reported that the fuel injection parameters of HRF should be optimized to improve the engine performance and reduce the exhaust emissions. Mobasheri and Seddiq [18] investigated the effects of fuel injection timings on RCCI combustion strategy. They observed reduced peak in-cylinder temperature and pressure due to advancing the start of injection (SoI) timing of the HRF. However, too advanced SoI timing led to inferior engine performance and higher exhaust emissions.

In a few studies, EGR and intake charge temperature have been suggested as essential parameters for achieving an efficient RCCI combustion strategy [19,20]. Zou et al. [21] numerically investigated the RCCI combustion strategy using mineral diesel and primary alcohols (methanol, ethanol, and butanol) as HRF and LRF, respectively. They observed relatively longer CD for methanol/mineral diesel and ethanol/ mineral diesel-fueled RCCI combustion strategy compared to butanol/ mineral diesel-fueled RCCI combustion strategy. They also reported that the RCCI combustion strategy for all fuel pairs exhibited significant effects of premixed ratio (r_p) of LRF, intake charge temperature, and injection strategies of HRF. Premixed ratio (r_p) is defined as the energy fraction contributed by the premixed LRF fuel to the total energy inducted in every engine cycle. Zheng et al. [22] investigated the RCCI combustion strategy using n-butanol/biodiesel fuel-pair. They reported that the RCCI combustion strategy was susceptible to the EGR rate and r_p of butanol. They reported that a 30% EGR rate was the optimum for the RCCI combustion strategy, where the engine efficiency was the maximum, and soot, HC, and CO emissions were the minimum. Superior characteristics of RCCI combustion strategy compared to fuel blending strategy was another critical observation of their study. Soloiu et al. [23] studied a new version of RCCI combustion strategy as intelligent charge compression ignition (ICCI) combustion using methyl oleate as HRF and n-butanol as LRF. They reported a significant reduction of pollutants emitted from the engine of the ICCI combustion strategy compared with conventional diesel combustion. Pan et al. [24] compared the effect of LRFs (gasoline and iso-butanol) on the combustion and emissions characteristics of the RCCI combustion strategy. They observed that butanol/mineral diesel-fueled RCCI combustion strategy exhibited relatively higher indicated mean effective pressure (IMEP) than gasoline/mineral diesel-fueled RCCI combustion strategy. They suggested that relatively more retarded combustion phasing (CP) with higher ignition delay was the principal cause for this finding, resulting in reduced HC, CO, and PM emissions vis-a-vis gasoline-diesel RCCI combustion.

The studies mentioned above showed that the RCCI combustion strategy is not a very new technology. Much research on RCCI combustion strategy has already been carried out using different fuel pairs, engine operating conditions, and control parameters. However, most studies focused on combustion, performance, and emission characteristics of the RCCI combustion strategy. Detailed particulate characteristics and their relationship with RCCI combustion strategy have not been covered in most studies. Therefore, this study was undertaken, in which combustion characteristics, performance, gaseous, and particulate emissions of a mineral diesel/butanol-fueled RCCI combustion strategy was investigated. In this study, RCCI combustion experiments were performed at four engine loads (BMEP = 1, 2, 3, and 4 bars) and varying r_p of butanol ($r_p = 0.25$, 0.50, and 0.75) vis-à-vis conventional CI combustion ($r_p = 0.0$). Particulate characteristics are an important aspect of this study, which provided detailed information about the potential of butanol utilization in the RCCI combustion strategy.

2 Test Setup and Experimental Methodology

In this investigation, a single-cylinder, four-stroke CI engine [16] was used for the experiments. This research engine consisted of a common rail direct injection (CRDI) system for injecting mineral diesel at high fuel injection pressure (FIP) up to 1400 bars. This test engine was connected to a transient dynamometer [16] for varying the engine speed and load. This engine test setup consisted of three conditioning units namely fuel conditioning unit, oil conditioning unit, and coolant conditioning unit to avoid adverse effects of variations in lubricating oil temperature, coolant temperature, and fuel temperature respectively on the engine-out emissions and performance [16]. These systems maintained the lubricating oil temperature and fuel temperature at 90 °C and 25 °C, respectively. The fuel conditioning unit was connected to the HRF circuit only. The test setup schematic is shown in Fig. 1.

The fuel injection timing and injection pressure were controlled by an electronic control unit (ECU) attached to the engine. This unit had a control program (INCA) and an interface for data transmission (ETAS, ETK 7.1) for executing the user input parameters. This fuel injection system was used to inject the fuel four times (two pilot injections, one main, and one post-injection) in an engine cycle. A gravimetric fuel metering system (AVL, 733S) was used to measure the fuel-flow rate (kg/h) of mineral diesel, and its measuring accuracy was ±0.001 kg/h. The intake air flow rate (in kg/h) was measured using air flow measuring equipment [16], and its accuracy was ±0.1 kg/h. This air flow measuring unit was connected to the engine's air intake line. Technical specifications of the test engine are given in Table 1.

Another fuel injection system was used for the low reactivity fuel (butanol) injection into the inlet manifold in the RCCI combustion strategy. This fuel injection system consisted of an electrically driven fuel pump (Denso; 1500M844M1), an accumulator, a solenoid injector, and a dedicated injection driver. All fuel injection parameters such as fuel injection timing, injection delay, and fuel injection quantity of butanol were controlled by the fuel injection driver, which took inputs of the top dead center (TDC) position of the piston and generated a transistor-transistor-logic (TTL) pulse for controlling the injector. For both CI and RCCI combustion strategies, an EGR system was used to control the combustion. This EGR system used an EGR control valve to vary the volume flowrate of EGR, maintained at 15% for both combustion modes. Other details of the RCCI combustion strategy experimental setup are given in our previous publication [16]. A piezoelectric pressure transducer (AVL, QC34C) was flush-mounted in the cylinder head for combustion analysis, which provided an in-cylinder pressure signal of the low magnitude of charge (pC). An angle encoder was mounted on the engine crankshaft, which provided crank angle (AVL, 365C) position with a resolution of 0.1 computer-aided design. Signals of the pressure transducer and angle encoder were supplied to a high-speed combustion data acquisition (DAQ) system [16], where the pressure transducer signals were amplified and converted into proportional voltage signals. This DAQ system also analyzed the in-cylinder pressure signals and calculated various combustion parameters. For engine exhaust gas characterization, a portable exhaust gas emission analyzer (Horiba, 584L) was connected to the exhaust line, which was capable of measuring CO (in %, v/v), HC (in ppm, v/v), NO_x (in ppm, v/v), and CO_2 (in %, v/v). Other details of the exhaust gas analyzer can be seen in our previous publications. For particulate characterization, an engine exhaust particle sizer (EEPS) spectrometer (TSI; 3090) was used. This equipment was capable of measuring up to #10^8 particles/cm^3 particle concentration with sizes of 5.6 to 560 nm in the exhaust gas. The working principle and other technical details of EEPS can be seen in our previous publications [25,26].

Experiments were performed at 1, 2, 3, and 4 bars BMEP at varying premixed ratios (r_p) of 0.25, 0.50, and 0.75 in the RCCI combustion strategy vis-à-vis baseline CI combustion strategy ($r_p = 0.0$) in this experimental investigation. During both CI and RCCI combustion strategy experiments, fuel injection timing and

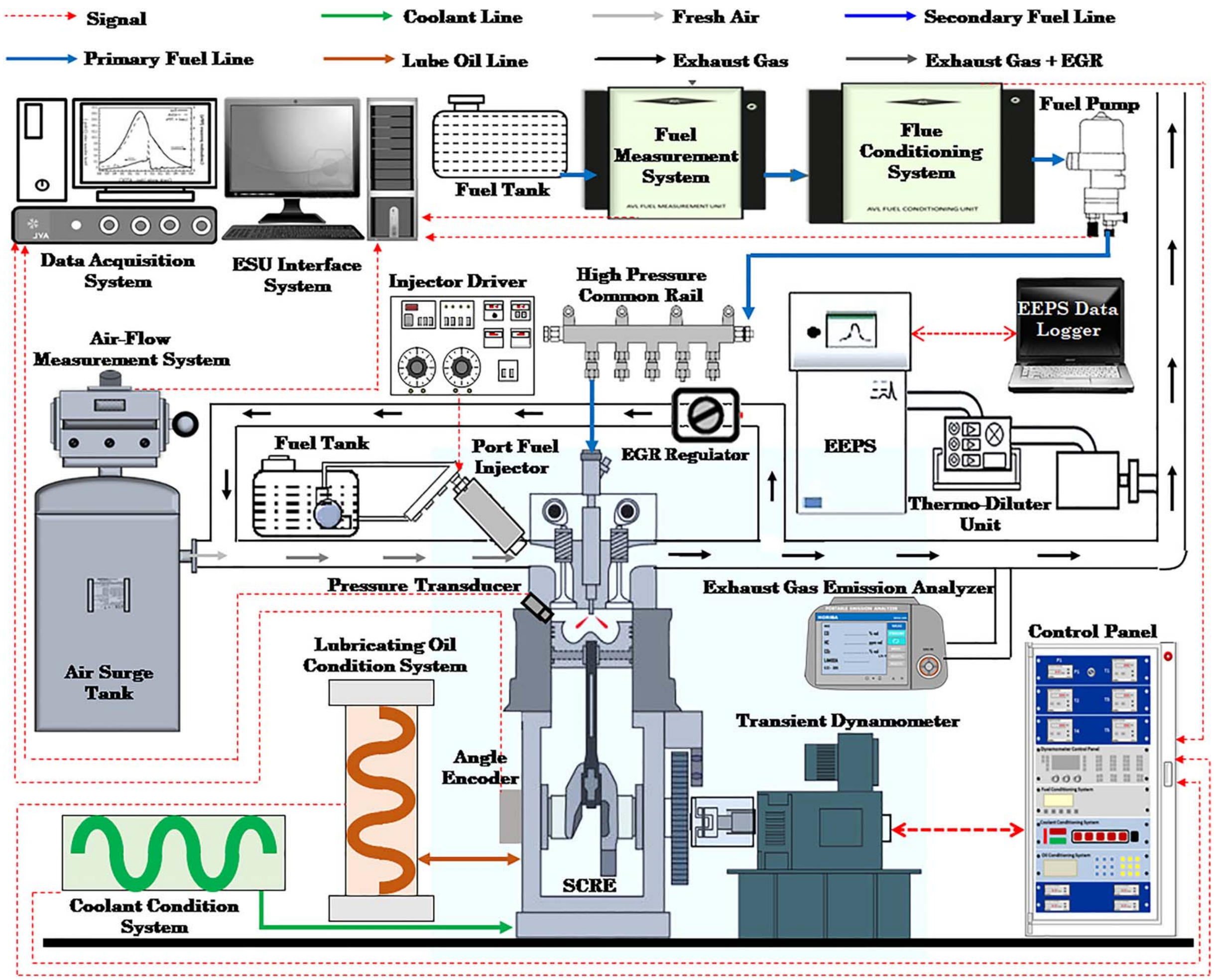

Fig. 1 The experimental setup schematic

pressure of HRF were maintained constant, at 17 deg CA bTDC and 500 bars, respectively. Butanol (butanol) was injected into inlet manifold at 3 bars fuel injection pressure during the suction stroke of the engine in the RCCI combustion strategy. All tests were performed at a fixed engine speed of 1500 rpm. For both combustion modes, intake air temperature and EGR were kept steady at 40 °C and 15%, respectively. All experiments were carried out after the thermal stabilization of the engine to reduce measurement uncertainty. All tests were repeated three times, and the average of three measurements were presented as results with error bars. In this study, the root-sum-of-square technique calculated the total uncertainty, which took care of all uncertainties, such as measurement errors, instrument errors, etc.

Table 1 Technical specifications of the experimental setup

Engine make/model	AVL/5402
Number of cylinders	1
Cylinder bore/stroke	85/ 90 mm
Swept volume	510.7 cc
Compression ratio	17.0
Inlet ports	Two (one tangential port and one swirl port)
Maximum power output	6 kW
Rated speed	4200 rpm
Fuel injection pressure	200–1400 bars
Fuel injection system	Common rail direct injection
Split fuel injection capability	Two pre-injections, one main injection, and one post-injection
High-pressure system	BOSCH Common Rail CP4.1
Engine management system	AVL-RPEMS+ BOSCH ETK7
Valves per cylinder	4 (two inlets, two exhausts)

3 Results and Discussion

Results and discussion are subdivided into four segments: combustion, performance, emissions, and particulate characteristics of butanol/mineral diesel-fueled RCCI combustion strategy at varying engine loads and premixed ratios.

3.1 Combustion Characteristics. The variations of in-cylinder pressure versus crank angle are the most crucial combustion characteristics, analyzed further to derive other combustion variables like SoC, heat release rate (HRR), CP, and CD. In this study, all combustion parameters have been derived from an average data set of 250 consecutive engine combustion cycles, for eliminating the effect of cyclic variations.

Figure 2 shows that the in-cylinder pressure graph followed an identical drift at lower engine load (1 bar BMEP). The crank angle position at which the combustion chamber pressure line disengages from the motoring line represents the SoC. SoC of RCCI combustion strategy at different r_p was not significantly affected by engine load. Rising r_p of butanol resulted in slightly retarded SoC, up to 2 bar BMEP. This was primarily due to the relatively lower reactivity of Butanol than the baseline mineral diesel. With increasing r_p of butanol, relatively decreased peak in-cylinder pressure ($P_{\max}$) showed reduced global reactivity. However, the in-cylinder pressure curve's reduced slope showed the influence

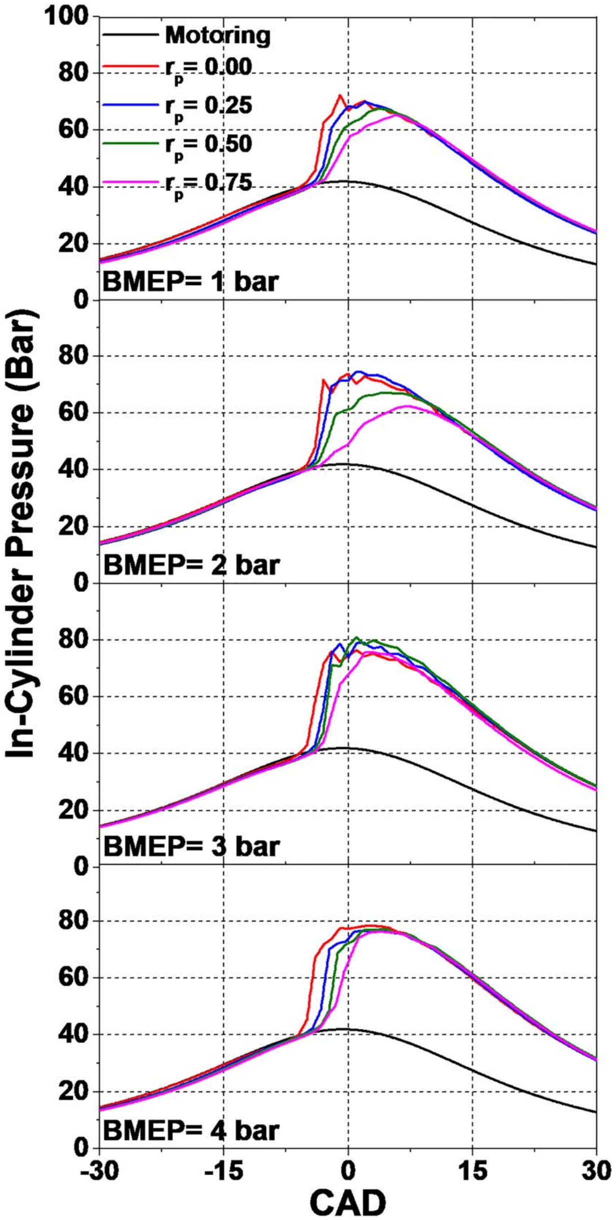

Fig. 2 Variation of in-cylinder pressure with respect to crank angle position at different r_p of butanol and engine loads

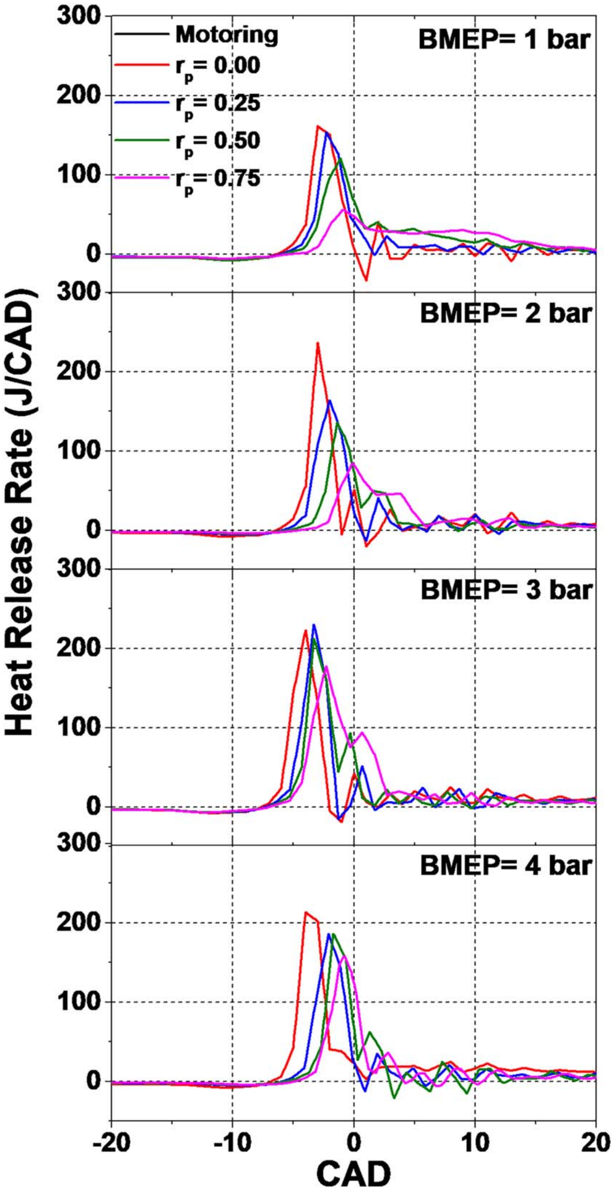

Fig. 3 HRR versus crank angle variations at different r_p of butanol and engine loads

of reactivity stratification, resulting in comparatively smoother combustion than the baseline CI combustion ($r_p = 0.0$). The effect of increasing r_p became less dominant at 3 and 4 bars BMEP engine loads than that at lower engine loads due to the combustion chamber's relatively higher temperature, which reduced the charge-cooling effect of Butanol. The SoC of the RCCI combustion strategy was slightly retarded at higher engine loads than the baseline CI combustion. However, increasing r_p did not show any variation in the SoC. At 3 bars BMEP, increasing r_p of butanol resulted in slightly enhanced $P_{\max}$ because of butanol-bound oxygen, which resulted in relatively superior combustion. However, at 4 bars BMEP, the effect of fuel-bound oxygen was insignificant. In-cylinder pressure curves also exhibited knocking, which escalated with increasing engine load. The impact of Butanol was visible in the knock reduction of RCCI combustion strategy, especially at 2 and 3 bars BMEP, whereas excessive knocking occurred in the baseline CI combustion.

Variations of HRR versus crank angle at various loads and r_p are shown in Fig. 3. HRR was calculated using the "first law of thermodynamics" [27]. HRR trends also support the observations of combustion chamber pressure analysis. HRR trends in RCCI strategy's combustion showed some specific characteristics, which were different from the baseline CI combustion strategy.

Peak HRR of CI combustion increased slightly with rising engine load. HRR advanced because of the increased amount of combustible charge in the combustion chamber and increased the in-cylinder temperature. However, the RCCI combustion strategy did not show any definite pattern due to the relative dominance of combustion characteristics of HRF, LRF, and fuel-bound oxygen contribution during combustion. The dominance of LRF in the RCCI combustion strategy resulted in relatively retarded HRR and lower peak HRR. With increasing r_p of butanol, premixed phase heat release reduced, resulting in lower peak HRR than the baseline CI combustion strategy. Increasing r_p of butanol increased the heat release in the expansion stroke at lower engine load; however, this trend was absent at higher engine loads. At 3 and 4 bars BMEP, premixed phase heat release was dominant in the RCCI combustion strategy. In the RCCI combustion strategy, increasing r_p of butanol did not differ significantly in the premixed phase heat release. The width of the HRR curve also provided important information about the main CD. At all engine loads, the effect of relatively lower fuel reactivity of butanol was visible in the HRR trends, which resulted in retarded SoC compared with baseline CI combustion strategy. Up to medium engine loads, the HRR curve's width slightly decreased with engine load, which exhibited dominance of rapid combustion kinetics of combustible mixture at higher loads than the effect of LRF. However, at higher r_p of butanol, this effect was relatively milder even at higher engine loads due to the dominant characteristics of LRF.

Figure 4 shows the variations of SoC, CP, and CD of RCCI strategy at various r_p of butanol and engine loads. The detailed procedure of obtaining these parameters is given in our previous publication [16]. SoC is considered as the crank angle position, at which 10% cumulative heat release (CHR) is accomplished, as calculated by the mass fraction burned analysis. It was observed that SoC slightly advanced with engine load, which was also clearly seen in Figs. 2 and 3. Increasing r_p of butanol resulted in retarded SoC at each load. This revealed the effect of low butanol reactivity, which resulted in slower kinetics of combustible mixture. However, extreme conditions (in-cylinder temperature and pressure) in the combustion chamber were observed at higher engine loads, resulting in the suppressed effect of butanol on the SoC.

Combustion phasing is another combustion parameter representing that crank angle position at which 50% CHR is accomplished. CP provides comprehensive information of the rate of combustion. Too advanced or retarded CP is undesirable for combustion because they result in inferior engine performance and emission characteristics. Too advanced CP results in unstable combustion due to knocking, and too retarded CP results in higher HC and CO emissions. CP retarded slightly with increasing BMEP in baseline CI combustion strategy (Fig. 4). However, CP variations in the RCCI combustion strategy showed a random pattern at various BMEPs, depending on the r_p of butanol (Fig. 4). At lower r_p of butanol, RCCI combustion strategy exhibited similar CP variations as that of baseline CI combustion strategy; however, for RCCI strategy at higher r_p of butanol ($r_p = 0.50$), CP initially advanced slightly up to medium engine loads, and after that it retarded at higher engine loads. This was primarily because of the combined effect of butanol induction and improved in-cylinder conditions and consequently faster combustion kinetics of combustible mixture. However, at higher r_p of butanol, butanol's superior characteristics suppressed the global reactivity in the combustion chamber, dominated over the extreme conditions of the combustion chamber, leading to the relatively retarded CP. The relatively weaker effect of r_p of Butanol on CP at higher BMEP was another critical observation of this experimental investigation. This might be due to the counter-effects of r_p of butanol and in-cylinder conditions on the CP. CD provides valuable information about the combustion duration, which increases with the engine load. Figure 4 shows a similar pattern for the RCCI combustion strategy, where increasing engine load resulted in extended CD. This was primarily due to relatively higher fuel quantity present in the combustion chamber, which took more time to burn completely. CD of RCCI strategy at various BMEPs varied with r_p of butanol. RCCI combustion strategy at each r_p of butanol followed a general pattern of CD variation at different BMEPs, except $r_p = 0.75$. At lower BMEPs, increasing r_p of butanol resulted in slightly longer CD; however, at higher engine loads, increasing r_p of butanol resulted in shorter CD. This was mainly due to the combined effects of extreme conditions in the combustion chamber, the kinetics of combustible mixture, and the presence of higher fuel quantity in the combustion chamber. At lower engine loads, increasing r_p of butanol retarded the combustion kinetics of fuel-air mixture at inferior in-cylinder conditions, leading to a longer CD. With rising engine load, the effect of Butanol on global reactivity facilitated faster combustion in the presence of higher in-cylinder temperature, which led to slightly shorter CD. The combined impact of the faster flame velocity of butanol and extreme in-cylinder conditions resulted in a relatively shorter CD in case of RCCI strategy at higher r_p of butanol at higher engine load.

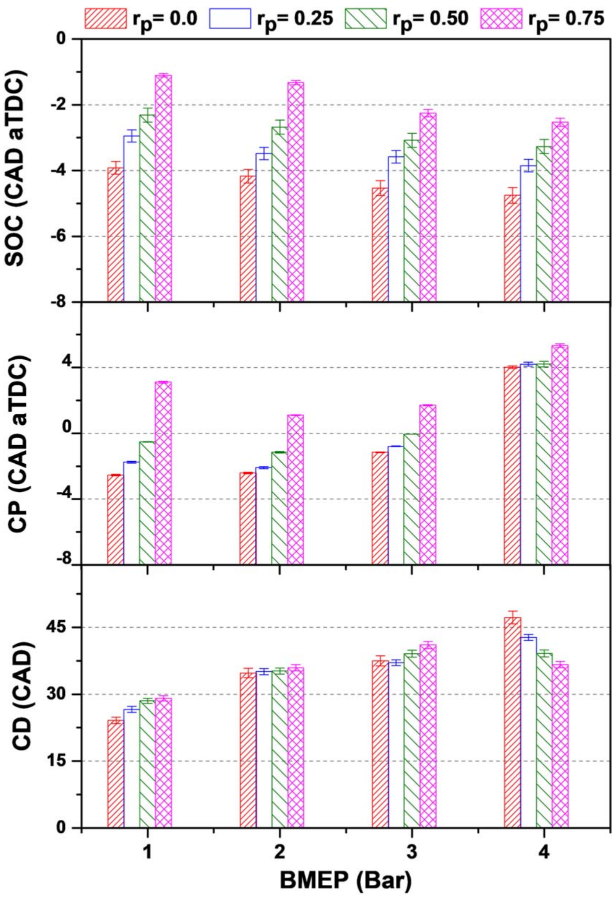

Fig. 4 SoC, CP, and CD of RCCI combustion strategy at different r_p of Butanol and varying engine loads

3.2 Performance and Emissions Characteristics.

In this section, two performance criteria, specifically BTE and EGT, and three regulated exhaust gas species were measured at different engine loads and r_p of butanol. CO, HC, and NO_x were measured in their raw concentrations for exhaust gas characterization and converted into mass emissions in "g/kWh" using standard equations [28].

Figure 5 shows that BTE for both combustion strategies of CI and RCCI enhanced with increasing BMEP. Improved combustion with the existence of superior in-cylinder conditions was the primary cause for this behavior. At all BMEPs, relatively higher BTE of RCCI combustion strategy than baseline CI combustion strategy was the main finding. The contribution of fuel-bound oxygen and relatively faster flame velocity of Butanol were the two principal reasons for the higher BTE of the RCCI combustion strategy. Increasing r_p of Butanol resulted in slightly enhanced BTE of RCCI combustion strategy at all engine loads, which became dominant at 3 bars BMEP. This was mainly because of the combined impact of butanol and extreme in-cylinder conditions. However, at 4 bars BMEP, the impact of increasing r_p of butanol became relatively weaker than 3 bars BMEP. EGT was the second performance parameter, which added qualitative information about the bulk in-cylinder temperature. For both baseline CI combustion strategy and RCCI combustion strategy, rising engine load led to higher EGT. EGT for the combustion of the RCCI strategy was relatively lesser than the baseline CI combustion strategy at all the BMEPs, reported in a previous study [17]. For the RCCI combustion

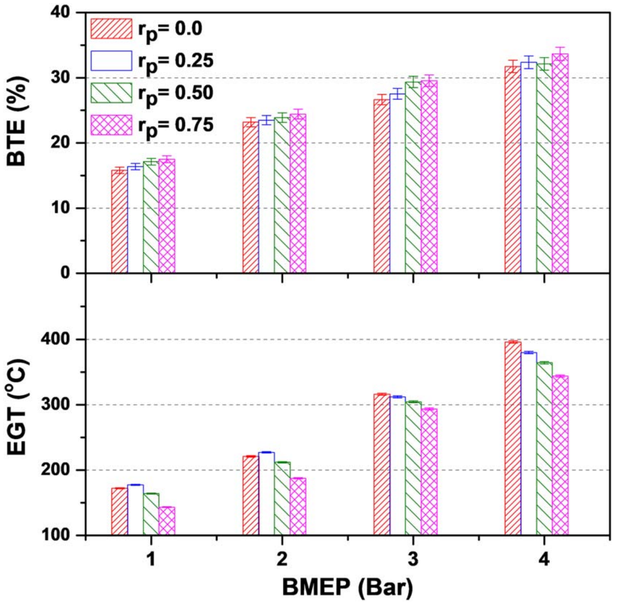

Fig. 5 BTE and EGT variations with BMEP for RCCI combustion strategy at various r_p of butanol

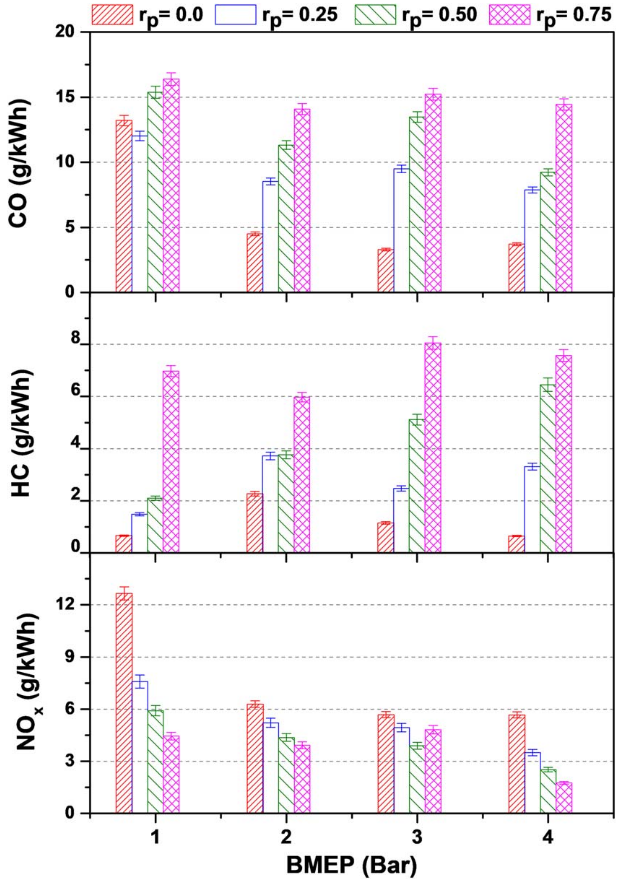

Fig. 6 CO, HC, and NO_x emissions from RCCI combustion strategy at different r_p of butanol and engine loads

strategy, increasing r_p of Butanol resulted in lower EGT. This was primarily due to Butanol's charge-cooling effect, which absorbed a significant fraction of combustion energy, leading to lower peak in-cylinder temperature and lower EGT. EGT for the combustion of RCCI strategy at lower BMEPs and lower r_p of butanol ($r_p = 0.25$) was slightly higher than the baseline CI combustion strategy. This was mainly due to superior combustion because of fuel-bound oxygen and the faster flame speed of butanol. EGT for the combustion of CI and RCCI strategy at 4 bars BMEP was ~400 °C and ~345 °C, respectively, and the difference in EGT for the combustion of CI and RCCI strategies was the maximum.

Figure 6 reveals that CO emission from CI mode combustion decreased with increasing BMEP; however, CO emission from the RCCI strategy's combustion followed a random pattern. Relatively higher CO was emitted from the combustion in RCCI mode than the baseline CI mode at all BMEPs. Increasing r_p of butanol for the combustion in RCCI strategy resulted in a higher CO emission at all engine loads; however, the relative increase in CO emission at various engine loads was different. This was primarily due to the combined effects of less intense in-cylinder conditions, charge-cooling effect, and slower chemical kinetics of butanol-air combustion at lower BMEPs. The combustion chamber temperature increased at higher BMEPs; however, the effects of Butanol increased dominantly, leading to higher CO emission. The emissions of HC followed a pattern different than that of CO emission. HC emissions from the combustion in RCCI strategy were relatively higher than the combustion in baseline CI strategy at all engine loads. The relatively lower in-cylinder temperature in the chamber was the primary reason for this trend, resulting in a greater degree of incomplete combustion.

With increasing r_p of butanol, HC emissions from the combustion of the RCCI strategy also increased. At lower BMEPs, the effect of increasing r_p of butanol was dominant at higher r_p of butanol; however, the impact of increasing r_p of Butanol became dominant at higher BMEPs. Higher fuel quantity in the combustion chamber was the main reason for this trend, which took a longer time to complete the combustion; therefore, a relatively more significant amount of fuel remained unburned, which led to higher HC emissions at higher r_p of butanol.

Figure 6 exhibited that NO_x emissions from both the combustion strategies (CI and RCCI) decreased with BMEP. This was primarily due to enhanced engine power output, which dominated the increase in NO_x emissions (in ppm). RCCI combustion strategy emitted relatively lower NO_x than the baseline CI combustion strategy, which was also observed in previous studies [16–18]. In the RCCI combustion strategy, increasing r_p of butanol resulted in comparatively reduced NO_x emissions. The dominant charge-cooling effect was the primary cause for this behavior, resulting in a reduced bulk in-cylinder temperature, which led to reduced NO_x formation. The impact of increasing r_p of butanol was dominant at BMEP = 1 bar; however, at higher BMEPs, increasing r_p of butanol resulted in a comparatively lower reduction in NO_x emissions than the baseline CI combustion strategy.

3.3 Particulate Characteristics.

Particulate characteristics are a critical aspect of this study. The particle number-size distribution is a primary particulate characteristic parameter, which is further subdivided into the concentration of particle numbers in different size regimes, as given below:

(i) Nanoparticles (NP); $D_p < 10$ nm
(ii) Nucleation mode particles (NMP); $10 \text{ nm} < D_p < 50$ nm
(iii) Accumulation mode particles (AMP); $D_p < 1000$ nm

Particulate characteristics also included several other derived parameters such as total particle number (TPN), and count mean diameter (CMD). Detailed procedure of calculating NP, NMP, AMP, TPN, and CMD of particles is given in our previous publication [26].

For both combustion strategies (CI and RCCI), engine load increase resulted in enhanced particulate emissions (Fig. 7). Presence of higher fuel quantity in the combustion chamber and pyrolysis of lubricating oil due to extreme in-cylinder conditions were the major causes for higher particulate emissions at higher BMEPs.

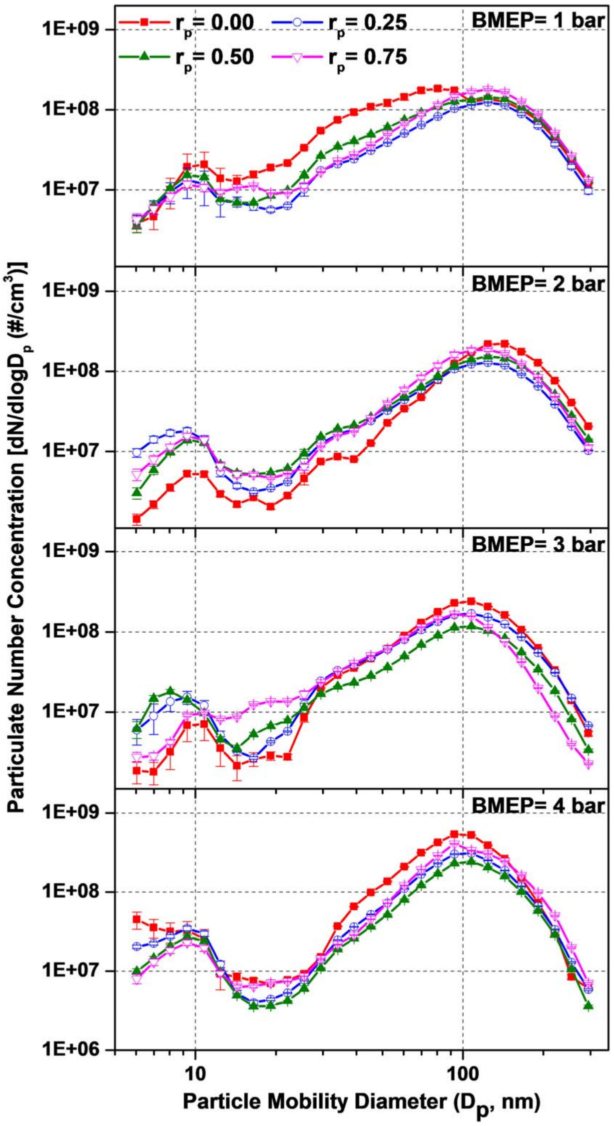

Fig. 7 Number-size distribution of particulates emitted from RCCI combustion strategy at different r_p of butanol and varying BMEPs

The particle number-size distribution exhibited that the RCCI combustion strategy emitted a comparatively lesser number of particles than the baseline CI combustion strategy. The presence of a homogeneous butanol-air mixture was the primary cause for this trend, which suppressed the number of fuel-rich zones in the engine combustion chamber, leading to lower soot nuclei formation. The fuel-bound oxygen was another important reason for lower particle emissions from the RCCI combustion strategy, which promoted soot oxidation during late combustion phases. Increasing r_p of butanol also reduced particle emissions. At higher r_p of butanol, a dominant contribution of homogeneous butanol-air mixture compared to the heterogeneous diesel-air mixture was the principal cause for lower particulate emissions. Increasing r_p of Butanol increased the role of fuel-bound oxygen, which increased the soot oxidation. The number-size distribution of particles exhibited that baseline CI combustion strategy emitted a relatively higher number of particles in the AMP regime; however, the RCCI combustion strategy emitted a slightly higher number concentration of smaller particles (NP and AMP). Figure 8 shows a comparison of NP, NMP, and AMP concentrations emitted from the RCCI strategy's combustion at various BMEPs and r_p of butanol.

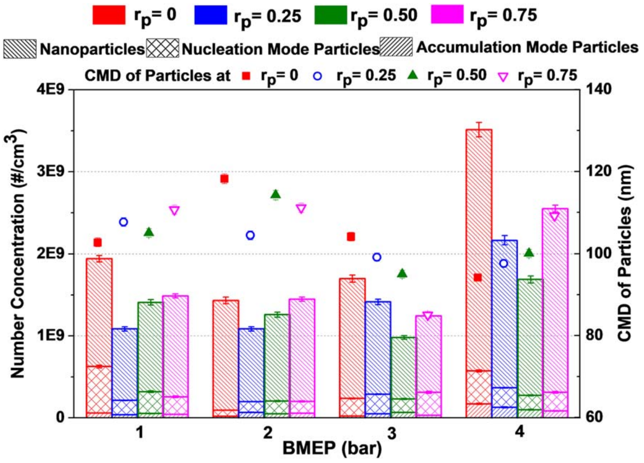

Fig. 8 Number concentration of NP, NMP, and AMP, TPN, and CMD of particles emitted from RCCI combustion strategy at different r_p of butanol and varying engine loads

Figure 8 shows that the concentration of NP and NMP emitted from both combustion strategies (CI and RCCI) was relatively lower than the concentration of AMP. Number concentrations of NP and NMP did not follow any regular pattern of variation at different engine loads. The number concentrations of AMP emitted from baseline CI combustion strategy increased with BMEP; however, the RCCI combustion strategy exhibited a different AMP emission trend at various engine loads and r_p of butanol. For lower r_p of butanol, increasing BMEP resulted in slightly higher AMP numbers; however, at higher r_p of butanol, AMP concentration first decreased to medium r_p of butanol and increased at higher r_p of butanol. This was due to the relative dominance of the fuel quantity in the combustion chamber and the effect of butanol. For the combustion in RCCI strategy at lower r_p of butanol, higher diesel quantity injected resulted in higher AMP concentration at higher engine loads; however, at larger r_p of butanol, the role of homogeneous butanol-air mixture promoted the formation of more number of finer particles (NP and NMP). This reduced the agglomeration tendency of primary particles, leading to a lesser number concentration of AMPs.

Overall height of bar charts analogous to any particular BMEP and r_p of butanol represents the TPN (#/cm^3 of exhaust gas). A comparison of TPN at various engine loads showed that the combustion in the RCCI strategy emitted a comparatively lower particle number concentration compared to the baseline CI combustion strategy. Up to medium engine loads, TPN concentration increased with increasing r_p of butanol; however, TPN trends exhibited a random pattern at higher BMEPs. This was mainly due to the relative dominance of BMEP and r_p of butanol.

TPN reduced with increasing r_p of butanol (up to $r_p = 0.5$) and it increased with further increasing r_p of butanol at higher BMEPs. CMD of particles was an additional crucial parameter, which provided information about the average particle size emitted in the exhaust. Results exhibited that the CMD of particles followed a random pattern of variations. The CMD of particles emitted in the RCCI strategy was slightly higher than the baseline CI combustion strategy at 1 bar BMEP. This was primarily because of the more significant contribution of larger particles emitted because of combustion in RCCI strategy; however, this trend changed at 2 and 3 bars BMEP. At higher engine loads, a slightly higher NP concentration was the primary reason for this trend. The CMD of particles emitted in the engine exhaust in the baseline CI combustion strategy was the lowest at the highest BMEP. This was because of the greater participation of smaller particles. These tiny particles formed primarily because of the partial combustion of lubricating oil.

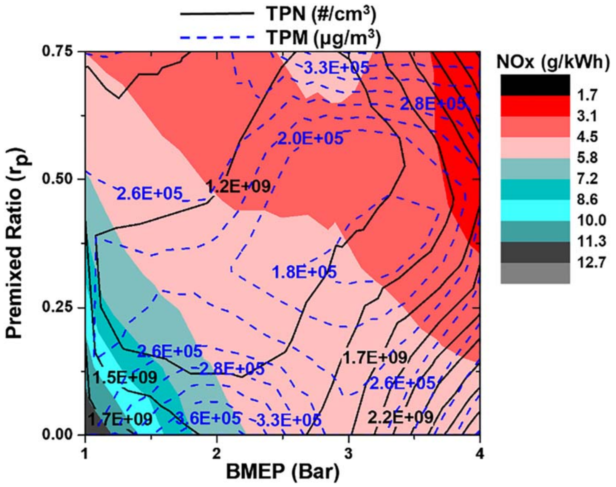

Fig. 9 Qualitative correlation between NO_x (background shade), TPM (dotted contour lines), and TPN (solid contour lines) emitted from mineral diesel/butanol-fueled RCCI combustion strategy at various r_p and varying engine loads

A qualitative interrelationship between the NO_x, total particulate mass (TPM), and TPN at various BMEPs and r_p of butanol is shown in Fig. 9. TPMs were computed from the particulate mass-size distribution emitted at different engine operating points [25]. Figure 9 shows that TPM increased with increasing r_p of butanol; however, TPM first decreased (up to $r_p = 0.50$) and then increased with r_p at higher BMEPs. This trend might be due to the dominance of fuel properties and extreme conditions prevailing in the combustion chamber. Combustion efficiency improved due to the formation of a homogeneous air-fuel mixture in the combustion chamber, resulting in suppression of particulate formation at lower r_p of butanol. However, at higher r_p of butanol, reduction in fuel-air chemical kinetics became more dominant, which led to reduced bulk in-cylinder temperature. This promoted condensation of volatile species on the particulate surface, which led to formations of larger particles.

Increasing r_p of Butanol was suitable up to 3 bars BMEP; however, at 4 bars BMEP, the presence of Butanol did not significantly affect the TPM. NO_x variations at different engine loads and r_p of Butanol were not as sensitive as the TPN variations. For a wide-range of engine loads and r_p of butanol, NO_x emissions remained lower than 3 g/kWh. Increasing r_p of butanol and engine load was found suitable for NO_x reduction.

In contrast to NO_x trends, TPN concentration trends exhibited a significant variations at higher engine loads. TPN concentration was reduced more at higher r_p of butanol in the RCCI combustion strategy compared to the baseline CI combustion strategy. Very low TPN concentration at the center of these contour plots exhibited that the combustion in the RCCI strategy was suitable at moderate premixing at medium engine loads. Combined analysis of NO_x and TPN contours demonstrated that RCCI combustion strategy using 50% premixing of Butanol at medium engine loads resulted in a simultaneous reduction of NO_x and TPN. At higher engine loads, though NO_x emissions reduced; however, TPN concentration increased significantly.

4 Conclusions

In this study, the RCCI combustion strategy was investigated at 1, 2, 3, and 4 bars BMEP at various r_p of Butanol (0.25, 0.50, and 0.75) vis-à-vis baseline CI combustion strategy ($r_p = 0.0$). All the tests were carried out in a CI engine fueled with butanol as LRF and mineral diesel as HRF at constant engine speed (1500 rpm) and constant fuel injection parameters of HRF. Experiments showed that mineral diesel/butanol-fueled RCCI combustion strategy was different compared to other primary alcohols. The effect of relatively higher fuel reactivity of butanol was visible in the typical combustion features, demonstrating a stable RCCI combustion strategy up to intermediate BMEPs. However, the knocking features were observed during the RCCI strategy at higher BMEPs. SoC and CP trends of RCCI combustion strategy at different r_p of butanol clearly showed the effects of reactivity gradient and global reactivity. The relatively superior performance of the RCCI combustion strategy than the baseline CI combustion strategy was amply demonstrated in this study, which improved further with increasing r_p of butanol. The effect of increasing r_p of Butanol was also visible in the EGT variations of the RCCI combustion strategy. RCCI combustion strategy emitted comparatively higher CO and HC emissions, which enhanced with increasing r_p of Butanol. However, the RCCI combustion strategy's NO_x emissions were relatively lower than CI mode combustion and decreased further with increasing r_p of butanol. Particulate characteristics demonstrated that the RCCI combustion strategy resulted in the emission of relatively lower particle numbers; however, the contribution of smaller particles was higher in the RCCI combustion strategy. Qualitative correlations between NO_x, TPM, and TPN at various engine loads and r_p of butanol showed that increasing r_p was suitable to cater to medium engine loads. Overall, this study experimentally demonstrated that Butanol could also be used as LRF in the RCCI combustion strategy; however, r_p of butanol needs to be optimized at different engine loads to achieve a trade-off between the engine performance and the emissions.

Conflict of Interest

There are no conflicts of interest.

Nomenclature

Greek Symbol

λ = relative fuel-air ratio

Superscript/Subscript

r_p = premixed ratio

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