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Original Research Article

Experimental study on reduction of pollutant emissions in reactivity controlled compression ignition (RCCI) engine fueled with diesel/gasoline fuels

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ABSTRACT

Reactivity Controlled Compression-Ignition (RCCI) concept presents a great potential to reduce both NO_x and soot emissions from conventional diesel engines with improved thermal efficiency. Therefore, in this work, a single-cylinder diesel engine with CRDI was operated on RCCI mode. To investigate the effect of RCCI mode on engine performance and emissions, gasoline was injected into the port as LRF, while diesel was injected directly into the cylinder as HRF. Premixed ratio of low reactivity fuel was varied from 0% (conventional diesel mode, CDM) to 60% with 15% intervals as energy ratio given to engine per cycle. Engine load was also studied from 20% to 60% of max. engine torque with 20% intervals to stimulate low, mid and mid-high load conditions. Experimental results showed that with increase of Rp, unburned HC and CO emissions increased while smoke opacity decreased significantly (up to about 95% in case of 0.60 Rp and 60% engine load) in gasoline/diesel RCCI compared to CDM. Though NO_x emissions decreased at low engine loads with RCCI strategy, they started to increase with increase of Rp at high loads.

Keywords: Reactivity Controlled Compression-Ignition (RCCI); Emissions; Combustion; Low Temperature Combustion (LTC); Diesel engines.

1. Introduction

In recent years, engine manufacturers and researchers have focused on reducing fuel consumption and exhaust emissions from internal combustion engines. In this context, studies such as the use of alternative fuels, exhaust after treatment systems and advanced combustion concepts have been carried out. Among these, alternative fuels especially bio fuels have been extensively researched and applied in internal combustion engines with promising results in emissions and a high amount of literature presented the significant benefits for using biodiesel and alcohol fuels in diesel engines [1-3]. On the other hand, the importance of studies on the reduction of emissions with exhaust after treatment systems has increased due to the increasingly tighter emission standards [4]. Although the studies in this field have mostly improved, it remains insufficient to achieve a successful fuel economy simultaneously with the meeting of the regulation limits [5]. For this reason, the research has mostly focused on the low temperature combustion strategy (LTC), which provides the opportunity to both reduce emissions and improve fuel economy [6]. The LTC concept is a combustion strategy based on the principle of lowering the in-cylinder temperature and improving the combustion process, with minor adjustments directly on the engine [7]. As LTC strategies: HCCI (Homogeneous Charge CI), PCCI (Premixed Charge CI) and RCCI (Reactivity Controlled CI) concepts have led to an important area in the literature. It has been stated that HCCI and PCCI give important results in achieving high efficiency and low emission, but there may be difficulties to overcome such as not being able to form a fully homogeneous charge, working at high loads, inability to control the start of combustion and high rate of pressure rise [8, 9]. RCCI is a combustion concept that emerged to eliminate the negativities of these concepts [10, 11]. The basic principle of RCCI systems, which is the most up-to-date LTC concept and also referred to as a dual fuel system, is based on the injection of low and high reactivity fuels into the cylinder at different times with separate injectors [12]. Low reactivity fuel is sent to the cylinder from the intake manifold, while the high reactivity fuel is sprayed through the injector inside the cylinder. Thus, by controlling the combustion process and combustion phases, significant improvements occur in emission values [13, 14]. For example, Curran et al. [15] stated that the thermal efficiency of RCCI improved by 7% compared to conventional diesel combustion and reached up to 39%, while NOx emissions decreased, HC and CO increased. On the other hand, when compared to HCCI, with its optimized premixed ratio, RCCI is a more promising way in terms of higher fuel efficiency, low ringing index and emissions, and a more stable operation over a wide load and speed range [16]. In another study, Dempsey et al. [17] found that RCCI has a longer burning time and a lower pressure increase rate than HCCI. Wang et al. [18] reported that both strategies showed very similar performance under low and medium loads while RCCI would stably operate under high load condition and maintained relatively low NO_x and soot emissions. Despite the advantages of RCCI listed above, the problem of operating at high loads, which is limited by the high rate of pressure rise and soot emissions, is needed to be solved before applying it to practical engines. Injection strategy, system and fuel optimization are ways to extend high load RCCI operation via extending the reactivity gradient between premixed and DI fuels in cylinder [19]. For example, Molina et al. [20] reported that the RCCI operating range can be extended from low to full load with suitable settings such as fuel blending ratio, injection timings and pressure. Similarly, Benajes et al. [21] reported that it was possible to reach up to 80% of the engine load with conventional diesel combustion without exceeding the limits of the rate of pressure rise and the maximum peak pressure while achieving extremely low levels of NO_x and soot emissions. Ma et al. [22] determined that this combustion mode has the ability to obtain high efficiency with NO_x and soot emissions close to zero when the early injection timing is applied. On the other hand, since low and high reactivity fuels have a significant effect on RCCI combustion, their choice is very important in terms of RCCI operation, and because of the physical properties of gasoline and diesel, they are primarily preferred in RCCI applications as shown in previous studies [23]. Therefore, in the present study, an experimental study is conducted to explore the effects of Rp of low reactivity fuel on a RCCI operated CRDI under different loads. In contrast to the alternative fuels, gasoline was used as the low reactivity fuel while diesel was the high reactivity fuel for keeping the original RCCI concept and simulating a typical RCCI engine with the benefit of a higher energy content compared to gasoline-or diesel-like fuels such as alcohol and gaseous fuel and biodiesel etc. In conclusion, the aim of this study is to examine the variation in engine performance and emissions using the RCCI mode over a wide load range. In addition to, gasoline is easier to obtain than alcohol-based fuels, has a higher energy content and being one of the most widely utilized fuels at the internal combustion engines. So, the results of the experiments are expected to contribute to the development of the RCCI mode.

2. Material and Methods

For the experiments, a single-cylinder and four-stroke common-rail diesel engine was used by being modified to operate in RCCI mode. The experiments were carried out in the experimental setup which was established in the Engine Laboratory of the Automotive Engineering Department of the Fırat University. The general view of the experiment set is given in Figure 1.

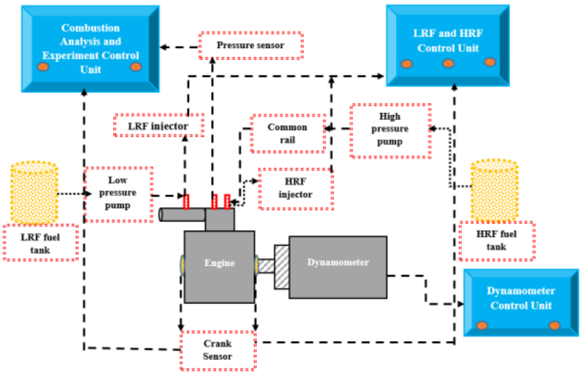

Figure 1. Schematic view of the experimental setup.

The engine was connected to the Gensan GSA 271 S / 4 model electric dynamometer and the loading was performed. The amount of load was measured with a Zemic L6W brand load cell. The tests were carried out under load conditions of 0% (no load), 20%, 40% and 60% of the maximum engine torque and at a fixed engine speed of 2400 rpm. Under each experimental condition, measurements were made by repeating three times and the results were averaged. The properties of the engine used in the experiment are given in Table 1.

Table 1. Technical characteristics of the engine.

Definations	Descriptions
Engine type	Single-cylinder CRDI
Diameter x stroke	86 mm x 70 mm
Cylinder volume	406 cm^3
Compression ratio	18.1:1
Maximum torque @ rpm	25.7 Nm @ 2400 rpm
Injection pressure and timings	300 bar @21 °CA BTDC
Intake valve opening and closing	9 °CA BTDC/93 °CA BTDC
Exhaust valve opening and closing	145 °CA ATDC/ 2 °CA ATDC
E_{total} (J/cycle)	190@no load; 310@20%; 440@40%; 590@60%

In this study, low reactivity fuel (gasoline) was sprayed into the suction channel at 0.5 MPa pressure using a port fuel injection (PFI) system under RCCI conditions. The PFI timing is set 25°CA after the intake valve is opened. High reactivity fuel (conventional diesel) was directly injected into the cylinder at 21 °CA BTDC via CRDI system. The amount of fuel is adjusted using the fuel control system on the control panel. During the experiments, the volumetric consumption of the fuel was calculated depending on the time and the volumetric fuel flow rate of the engine was found. The mass flow rate of the engine was determined by multiplying this volumetric fuel flow rate with the density of the fuel. Conventional diesel and gasoline used as high- and low- reactivity fuels were provided from commercial suppliers. Some properties of the fuels used in the experiments are shown in Table 2.

Table 2. Fuel Specifications.

Properties	Diesel	Gasoline
Density (kg/m³)	829.4	744.4
Boling point (°C)	180-350	38-204
Flash point (°C)	67	-45/-35
Kin. Viscosity (mm^2/s)	2.889	0.55
Lower heating value (MJ/kg)	43.14	44.1
Latent heat of vaporization (kJ/kg)	358	---
Self-Ignition temperature (°C)	210-250	228-470
Cetane number	56	0-10
Octane number	-	96

As the pressure sensor, Optrand brand sensor and a Kübler brand encoder are used. The data obtained were transferred to a data collection card and analyzed with Febris combustion Analyser Software. In-cylinder gas pressure was averaged over 200 consecutive cycles for each operating point. Heat release is calculated by the software using the values of in-cylinder pressure and volume with the first law of thermodynamics. The knock intensity was determined by the second derivative method. In this study, the amount of energy at an engine load in the case of RCCI is determined according to the total amount of energy generated depending on the mass flow consumed by the CDM at this load. The energy given to the engine per cycle was kept constant and premixed ratio was calculated over this energy. For this, the product of the low reactivity fuel's mass flow rate and its lower heating value is divided by the sum of the products of the low and high reactivity fuels mass flow and their lower heating values.

Premixed ratio for the tests were 0%, 15%, 30%, 45% and 60%. For example, it has been determined that when using high reactivity fuel at 60% engine load, a total energy of 590 J/cycle is given to the engine per cycle. For 30% Rp application at the same load; 30% of the total energy value of 590 J/cycle given to the engine at 60% load in CDM was given to the engine with low reactivity fuel (gasoline) and the remaining 70% with high reactivity fuel. In this case, it was stated that the experiment was carried out where the Rp = 30% at 60% engine load. Therefore, it can be calculated by following formula:

$$R_p = \frac{M_L x Hu_L}{M_L x Hu_L + M_H x Hu_H} \tag{1}$$

where M and Hu represent mass flow and lower heating value (LHV) of the tested fuel, respectively. The subscripts L and H denote low- and high- reactivity fuel, respectively.

During the experiments, the intake pressure is about at 1 atm while temperature is 26 ± 2 °C. in addition, the fuel temperatures were 65 ± 2 °C and 40 ± 2 °C, for HRF and LRF, respectively. The exhaust gas emissions and smoke opacity were monitored by Bosch BEA 350 exhaust analyzer. The measured parameters and their accuracy were listed in Table 3.

The uncertainties of some data used in the experiments were considered to be important. Therefore, the square root technique proposed by Singh was used to calculate the uncertainties [29]. The equation (2) was used for this method;

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n}\right)^2\right]^{1/2} \tag{2}$$

and overall uncertainty was calculated as √(uncertainty of CO)^2+(uncertainty of HC)^2+(uncertainty of NOx)^2+(uncertainty of Smoke opacity)^2=√(0.016)^2+(0.021)^2+(0.013)^2+(0.037)^2 =√(0.002236) = 0.0473= %4.73.

3. Results and Discussion

Figure 2 shows the change of exhaust gas emissions and smoke opacity depending on the premixed ratio and engine load. As seen in Figure 2, CO emissions have increased steadily with the increase of premixed ratio. However, except for 60% load situation, there has been a significant increase in CO emissions compared to CDM status with the application of RCCI strategy.

Table 3. Accuracies of the measurements.

Measured parameters	Accuracy
Engine speed, rpm	±3
Engine torque, Nm	±0.1
Cylinder pressure, psi	±0.0004
Fuel consumption, kg/h	±0.01
CO, %	±0.001
HC, ppm	±1
NO_x, ppm	±1
Smoke opacity, %	±0.1

With the addition of gasoline from the intake manifold in RCCI mode, the delay of the combustion to the expansion stroke due to the prolongation of the ignition delay causes the cylinder temperature to decrease and the incomplete combustion emissions to increase. Benajes et al. [24] also reported the higher CO emissions with diesel/gasoline RCCI under the low loads. Similarly, the variation of unburned HC emissions with premixed ratio and engine load has been shown in Fig. 2. The figure shows that unburned HC emissions increased from no-load to 40% load, but declined at 60% load. Unburned HC emissions also increase due to the relatively low in-cylinder temperature under low load conditions. However, as a result of burning more fuel at loads such as 60%, in-cylinder temperature and exhaust gas temperature are more suitable for the oxidation of HC, resulting in a decrease in unburned HC emissions. The increase in unburned HC emissions with engine load when biodiesel was used was reported by Man et al. [25] On the other hand, unburned HC emissions increased almost linearly with the increase in premixed ratio of gasoline at each load stage, except at 60% load and Rp=0.60. In other words, with the application of RCCI, unburned HC emissions have increased significantly according to CDM. With the increase of Rp under RCCI conditions, the formation of HC emissions increases as a result of the enrichment of the gasoline premixed amount mainly in the wall quenching layers and around the crevice regions whereas it was previously reported that the quantity of LRF was related to unburned HC emissions [26, 30]. Figure 2 also shows the change of smoke opacity depending on the engine load and the premixed ratio of gasoline. Smoke opacity increased with increasing engine load. Although the smoke generation did not change much from no load to 40% load, the smoke amount increased significantly at 60% load. The reason for this can be shown as a significant increase in fuel consumption and hence the equivalence ratio under 60% loads conditions. In this case, since the premixed ratio was the same, the ignition delay remained almost the same and thus more diffusion combustion period increased the smoke formation. On the other hand, with the application of RCCI, smoke formation has clearly decreased compared to CDM as seen in Fig. 2. With the increase of Rp, the smoke opacity decreased by 30% and 95% at each load stage compared to CDM. Under RCCI conditions, sending LRF to the engine during the suction time and increasing Rp and increasing the premixed combustion phase, which is mostly lean, causes less smoke formation. In this case, the smoke opacity can only be formed by the direct injection of the less effective diesel fuel with the increase of the premixed ratio. This situation can be seen more clearly in Figure 2 under 60% load conditions. In literature, significant reductions in soot emissions using gasoline/diesel by LTC strategies were reported [27]. Regarding the NO_x emissions, a different trend with engine load was observed. Up to% 20 load, applying the RCCI strategy reduced NO_x emissions compared to CDM with magnitude of 16%-59% depending on load and premixed ratio. However, at 40% and% 60 loads, NO_x emissions were started to increase with increase of Rp. At 40% and 60% loads, an increase of up to 50% and 60% occurred depending on Rp. This may also be due to the local in-cylinder temperature, which decreases first due to the evaporation of the LRF and then increases again due to a greater proportion of premixed combustion and improved CA50 [28, 34]. On the other hand, it is seen in Figure 2 that there is a simultaneous decrease in NO_x and smoke opacity values with the increase in Rp and in no-load and 20% load conditions. This indicates that the trade-off between NO_x and soot is partially broken at light loads with the exemption of the high load where NO_x emissions are in increasing trend. In Figure 3, the effect of premixed ratio of low reactivity fuel on mean gas temperature (MGT) in RCCI engine under different loads is shown. The graph was analyzed as two regions, the section up to TDC and after.

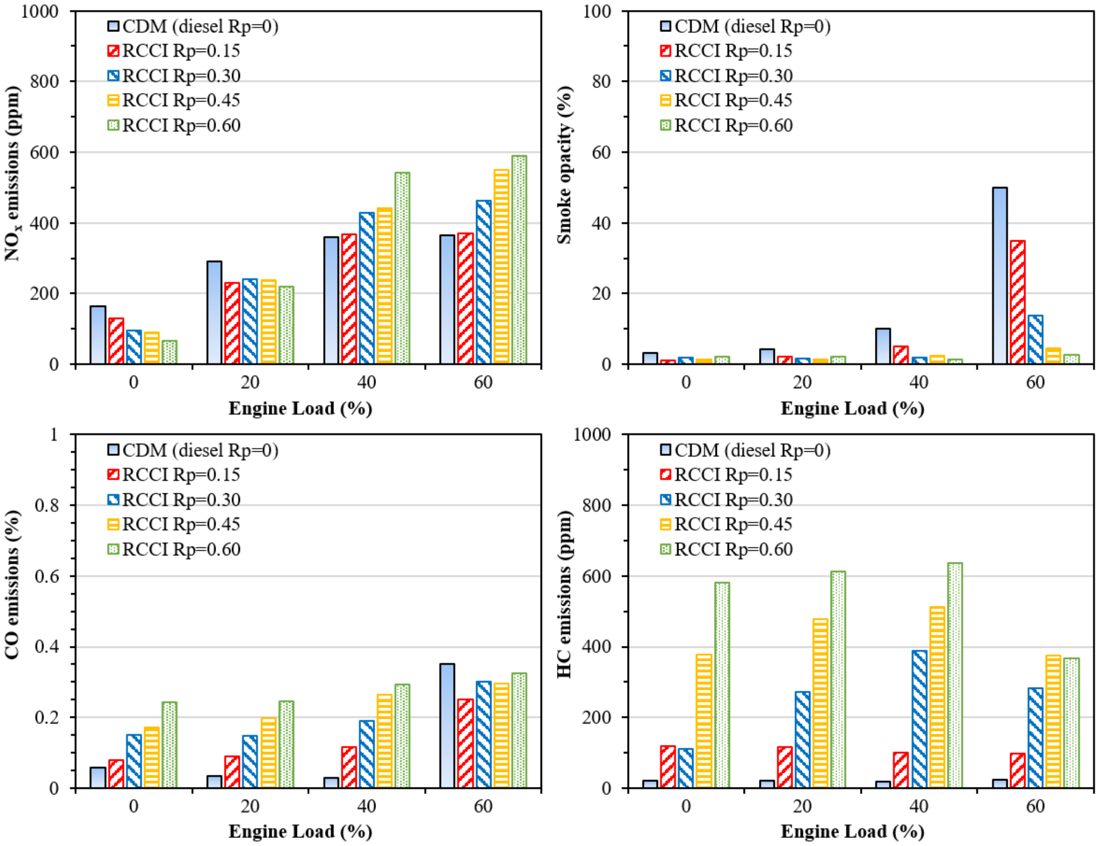

Figure 2. The change in exhaust emissions with premixed ratio (Rp) at different loads.

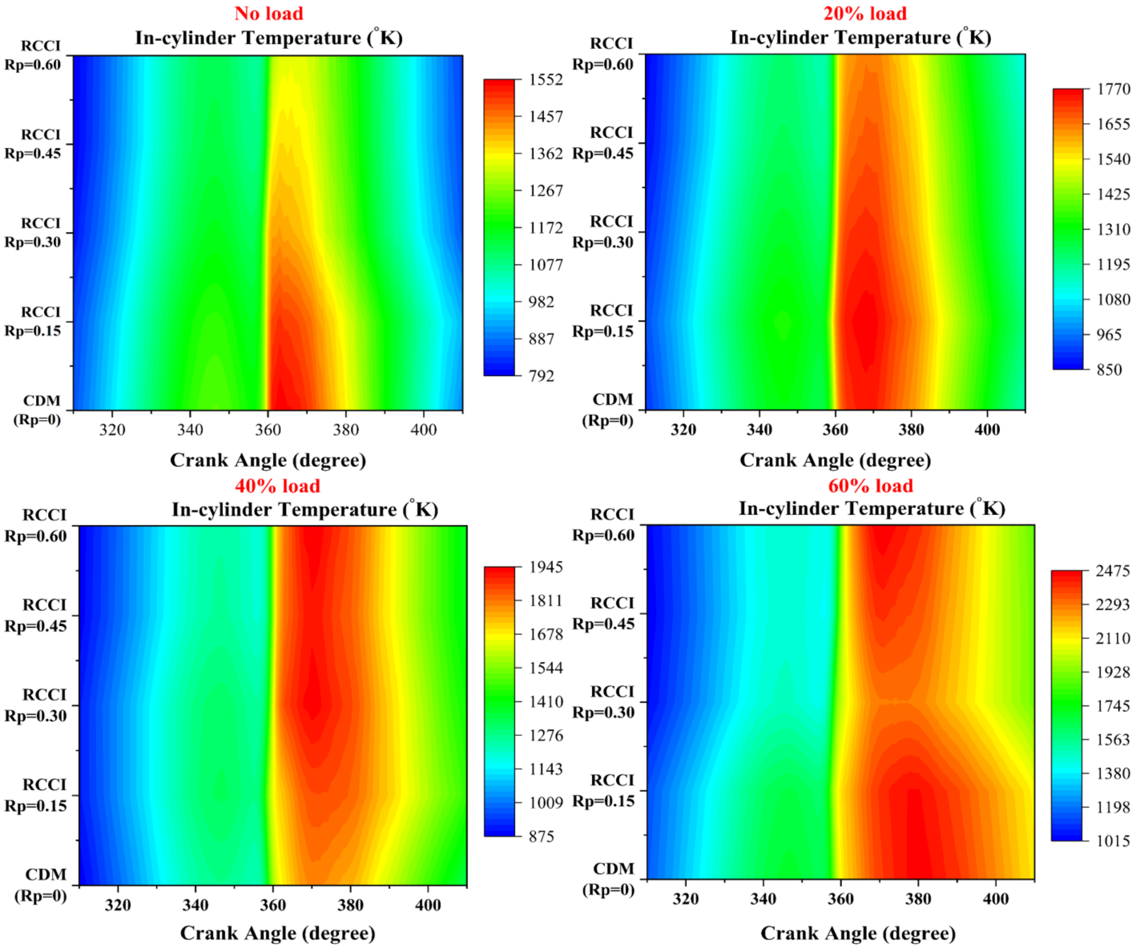

Figure 3. The change in maximum temperature with premixed ratio (Rp) at different loads.

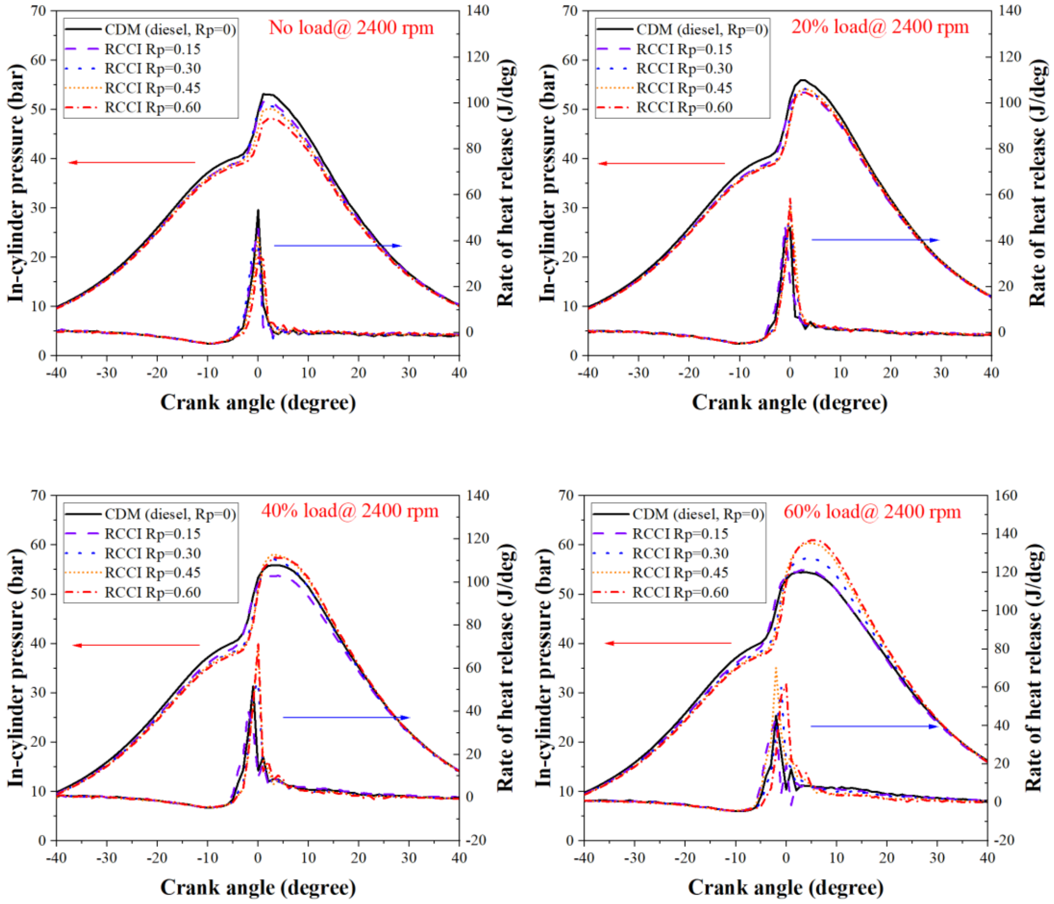

Figure 4. The change in cylinder pressure and rate of heat release with premixed ratio (Rp) at different loads.

In general, it is seen in Figure 3 that the temperature decreases with the use of low reactivity fuel under RCCI conditions [31]. It is thought that the increase in the LRF ratio and the decrease in the HRF ratio, that is, the main igniter fuel, make it difficult to burn the cold regions formed in the cylinder and the temperature therefore undergoes sudden changes. In addition, as a result of the delayed combustion process due to the high octane content of LRF, the temperature value in the cylinder is suppressed and decreased due to the increasing mixing ratio. The higher amount of filler at this load created both rich mixing zones and cold zones in the cylinder and reduced the temperature. Due to the increasing amount of filler and the rich air/fuel mixture formed in the cylinder, the combustion reaction temperature suddenly increased, but it was subjected to sudden decreases due to uncontrolled combustion. As a result, in the study, it was determined that the temperature change was controlled in 20% engine load experiments with the RCCI concept application, in which no load was applied to the motor, this control partially continued at 40% and 60% load.

Figure 4 shows the effect of premixed ratio on in-cylinder pressure and heat release rate under different load conditions. As can be seen in the figure, in-cylinder pressure and heat release values have increased due to the increase in fuel consumption with the increase in engine load. However, with the increasing load, the effect of Rp was more pronounced. In no-load and 20% load conditions, the in-cylinder pressure with RCCI application was lower than CDM. The ignition delay increased as Rp increased at these loads, delaying the beginning of combustion. When combustion began, the piston passed TDC and began to move downwards at this point. When a result, as Rp increased, the pressure decreased. At 40% load, it is seen that the in-cylinder pressure increases at rates other than the low premixed ratio such as 15%, and at 60% load, in-cylinder pressure and heat release increase significantly with RCCI strategy. At 60% load and Rp = 0.45, the rate of heat release increased by 55%. Wang et al. stated that the RCCI mode causes an increase in pressure at high loads [33]. On the other hand, with the application of RCCI in all load levels, the start of the combustion was later. As a result of the increase in fuel consumption with the increase in engine load, the increase in the premixed ratio of LRF increases the ignition delay (as seen in Figure 5) and at the same time increases the in-cylinder pressure. The high octane number of gasoline shortens the ignition delay. Singh et al. stated in their study that the high heat of vaporization and octane content of the fuels caused the delay of the combustion phase [32].

In Figure 6, the changes of some combustion characteristics depending on the engine load and premixed ratio are given. As shown in the figure, the peak cylinder pressure did not change significantly with the engine load. With the increase of premixed ratio at 60% load, the peak cylinder pressure has increased and then decreased at other load levels. The highest increase in peak cylinder pressure was up to 11.5% according to CDM at Rp = 0.60 at 60% load. In the same way (Figure 6), when the values of the rate of pressure rise (RoPR) are examined, it is seen that there is a decrease (up to approximately 27%) with the increase of the premixed ratio in the unloaded state.

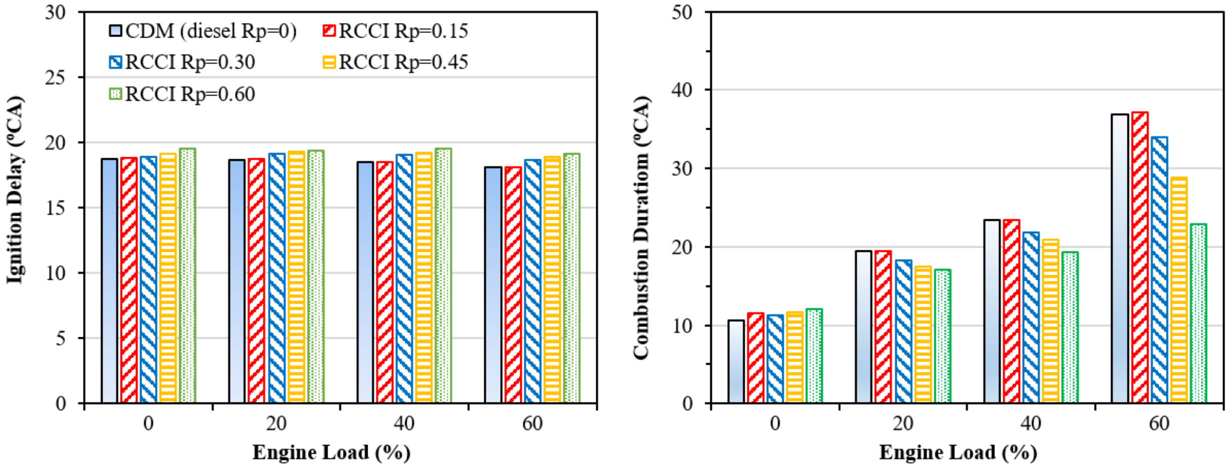

Figure 5. The change in ignition delay (ID) period and combustion duration with premixed ratio (Rp) at different loads.

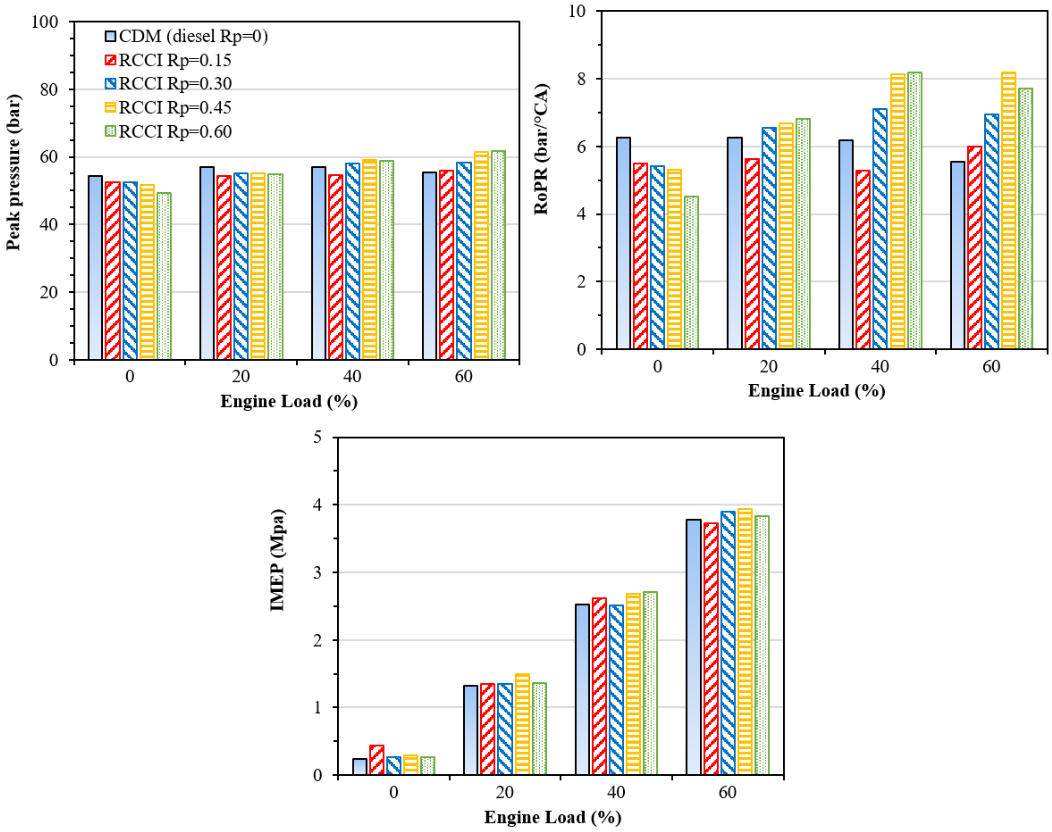

Figure 6. Peak pressure (PP), rate of pressure rise (RoPR) and indicated mean effective pressure (IMEP) with premixed ratio (Rp) at different loads.

However, with the increase of premixed ratio in other load cases, RoPR has also increased. The highest increase was around 47% at Rp = 0.45 at 60% load. The high RoPR values which are at high Rp with increase in load correlates with the fact that more premixed combustion is observed and the burn duration becomes shorter. Besides in general, RoPR is acceptable levels even at high Rp values. Indicated mean effective pressure (IMEP), on the other hand, increased significantly with the increase of engine load, as expected. However, the effect of RCCI strategy on IMEP change was low. With the RCCI application, according to CDM, the increase in IMEP was the most in unloaded situation. When the comparison is made between the loaded situations, the highest increase was approximately 13% at 20% load at Rp = 0.45. The reason for this can be that increased Rp lead to later ignition timing to get combustion reaction close to the top dead center (TDC) which increases the useful work.

4. Conclusion

An experimental investigation was conducted to investigate the effects of premixed ratio of low reactivity fuel (gasoline) in a single-cylinder common-rail engine operated on RCCI mode with compared with CDM using EN590 diesel. The main conclusions of the study can be given in brief as follows:

It was determined that IMEP changed and increased more steadily when 45% and 60% Rp were used at all loads. In-cylinder pressure, heat release rate, ignition delay, and combustion duration all changed as Rp increased, with the greatest change occurring at 60 % Rp. The emissions of CO and unburned HC were found to be higher with RCCI than CDM and increased with an increasing fraction of gasoline. The increase in premixed ratio of gasoline reduced NO_x emissions up to 59% at low engine loads in RCCI combustion while increased at higher loads compared with CDM. Also, a substantial reduction in smoke opacity with increase of Rp was observed up to about 95% when Rp was increased to 0.60 at 60% load. Moreover, by applying RCCI strategy, smoke opacity and NO_x emissions were reduced simultaneously at light loads. In summary, it is thought that when RCCI mode is used, IMEP does not decrease at all loads and increases especially at high loads will shed light on future studies. Furthermore, when utilizing 15% Rp at 40% and 60% loads, the simultaneously decrease of NOx and smoke opacity has been evaluated to be significant.

CRediT authorship contribution statement

Müjdat Fırat: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Şehmus Altun:** Conceptualization, Funding acquisition, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Mutlu Okcu:** Conceptualization, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Yasin Varol:** Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing. **Şafak Melih ŞENOCAK**: Conceptualization, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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