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Experimental investigation of injection timing effect on RCCI Engine using waste oil biodiesel as high reactive fuel

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ABSTRACT

Three major threats that endanger human life and the planet are the escalating pollution levels, the intensifying global warming, and the rapid depletion of fossil fuel resources. These challenges have prompted researchers to explore the use of alternative fuels that are widely available, renewable, and have lower pollution emissions. Biodiesel obtained from waste oil has almost all these characteristics. Considering the objectives of the sustainable development goals in increasing the use of biodiesel in the future, it is essential to investigate the performance of this fuel in next-generation internal combustion engines such as reactivity-controlled compression ignition (RCCI) engines. The start of injection (SOI) parameter in RCCI engines is important to find suitable performance intervals and optimize the emission of these engines; however, the effect of this parameter has not been investigated in experimental studies of RCCI gasoline/biodiesel combustion. Consequently, the changes in the injection timing of waste oil biodiesel (combined with diesel), as a high-cetane fuel and high-octane gasoline fuel, in an RCCI engine were investigated experimentally in this research. The results indicated that SOI changes in the completely steady operation range of the engine can cause a change of around 9.2% in brake thermal efficiency when the engine operates in RCCI mode with a premixed fuel ratio of 27%. Also, it was found that the SOI timing of 30°bTDC can lead to a lower level of NOx emission than the other injection angles while maintaining relatively higher values of brake power.

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1- Introduction

The depletion of fossil fuel reserves, increasing emissions, and the worsening effects of global warming pose significant threats to humanity's and the planet's survival. Consequently, the advancement of clean energy technologies and the adoption of alternative fuels have become crucial. Alternative fuels, widely available across the globe, renewable in nature, and characterized by lower emissions, play a significant role in overcoming these challenges. [1-3]. According to the International Energy Agency website, renewable fuels should account for 64% of total renewable energy by 2030. Between 2010 and 2019, biofuel consumption increased by an average of 5% per year. Thus, this value requires an average annual growth of 14% between 2021 and 2030 to be aligned with the predicted value of the Sustainable Development Scenario (SDS). This agency has strongly emphasized enhancing the conditions necessary for producing and utilizing biofuels [4].

One of the most important alternative fuels that is very effective in reducing some emissions is biodiesel. Biodiesel or methyl fatty acid is a fuel with combustion properties similar to diesel fuel. It is generally produced by a transesterification process from vegetable seed oil, animal fats, and waste oils [5]. Low oxidation stability and high cloud point make storing biodiesel and maintaining the engines that use it arduous. Blending biodiesel with diesel can improve these characteristics to an acceptable extent, according to the volume percentage of the blend [6, 7].

The combustion of biodiesel presents challenges primarily associated with power generation and emissions. Due to the lower volumetric calorific value of biodiesel compared to that of diesel, biodiesel has generally faced the problem of reducing the power output, which, of course, is less significant than the difference in the calorific value of the two fuels. Higher cetane number, better lubrication, and various other reasons are brought forward to explain this. It is noteworthy that when biodiesel is combined with diesel, the difference is greatly reduced, and in some engine operation conditions, the output power is even slightly improved [8]. In a study conducted by Lin et al. [9] on the performance of biodiesel fuel derived from palm oil in a compression ignition engine, a decrease of 3.5% in engine power output was observed compared to when diesel fuel was used. This reduction was found to be lower than the decrease in the calorific value of biodiesel compared to diesel. When operating with a blended fuel consisting of 20% biodiesel and 80% diesel (B20), the study found that the power reduction was approximately 1%. Zhu et al. [10] conducted a study aimed at enhancing the combustion process by investigating the impact of combining biodiesel derived from waste oil with ethanol in a compression ignition engine. They added ethanol to the fuel to reduce the viscosity and density of biodiesel and consequently improve the atomization and injection process. Based on the results, Brake brake-specific fuel Consumption (BSFC) was increased with a mixture of 95% biodiesel and 5% ethanol compared to that with diesel, but as the effective average brake pressure was increased, the difference was reduced. The thermal efficiency was also increased compared to diesel, and the difference was raised with the increase of Brake Mean Effective Pressure (BMEP). Seraç et al. [11] researched engines with biodiesel fuel derived from soybean oil. In their findings, it was observed that when operating with B20 fuel, the brake thermal efficiency at 3.6 kW power was lower compared to that with diesel. However, at 10 kW power, the B20 fuel demonstrated an improvement in this parameter by approximately 3.1% compared to that with diesel fuel.

Regarding biodiesel emissions in compression ignition engines, Gopal et al. [12] reported that by using biodiesel obtained from waste oil (B100) instead of diesel fuel, unburned hydrocarbons (UHC) and carbon monoxide (CO) emissions are reduced by 57 and 31%, respectively, while the level of the nitrogen oxides (NOx) emission is raised by 18%. Of course, for NOx, there were fluctuations in different loads and ratios of different compounds, and sometimes, this emission was reported to be lower for cases with biodiesel than those with diesel. Gad et al. [13] reported a 20% and 25% reduction in UHC and CO emissions, as well as a 40% increase in NOx emissions, for the combustion of biodiesel from waste oil (B100) compared to diesel fuel. Raman et al. [14] investigated engine performance at maximum power with biodiesel derived from rapeseed oil and observed that with biodiesel, UHC and CO emissions decreased by 42% and 35%, respectively, and NOx level increased by 33%, compared to when diesel fuel was used. Of course, there have been studies in which NOx level was reduced by using biodiesel. Al-lwayzy et al. [15] reported a 7.4% reduction for NOx in B100 combustion with chlorella-derived biodiesel. On the other hand, the PM emission was reduced with biodiesel due to the oxygen content present in the structure of this fuel [16].

The use of biodiesel has been successful in reducing particulate matter (PM), UHC, and CO emissions. Most of the reports, however, indicate the increase of NOx emission levels in the combustion of this fuel. Apart from the engine condition, the presence of oxygen in the links of this fuel is one of the most important reasons for more complete combustion and, as a result, the reduction of PM, UHC, and CO emissions, and sometimes the reason for the increase of NOx emissions. Given that the emission of NOx in diesel fuel combustion is already a significant challenge, it is important to recognize NOx level as a major concern in biodiesel combustion.

When choosing a base oil for biodiesel, it is crucial to take into account various factors such as economics, climate, and the environment. These considerations hold significant importance as they can greatly influence the advancement and widespread adoption of biodiesel globally [17]. The increasing production of biodiesel from vegetable oils can pose significant economic and social challenges in the future. To address this, a viable solution would be to replace a substantial portion of biodiesel derived from vegetable oils with biodiesel from waste oil. This alternative is advantageous due to its widespread availability worldwide [18]. Apart from the abundant availability of waste oils, the significantly low cost of the base oil, and the potential for enhancing the process of collecting discarded cooking oil at the city level, there are additional significant benefits to using this oil. These advantages include positive environmental impacts and improvements in public health [19].

Given the general goal of elevating the usage of biodiesel in the forthcoming years, it is vital to thoroughly assess its performance in next-generation internal combustion engines. Among various strategies, low-temperature combustion (LTC) engines are considered one of the most effective approaches for minimizing NOx and PM emissions due to the homogenization and diminished regional concentration of fuel in the combustion chamber, even though there is a slight reduction in engine power [20]. The Reactivity-Controlled Compression Ignition (RCCI) strategy represents a highly advanced approach among LTC engines. This combustion technique involves adjusting the proportion of fuel with different reactivity levels based on the engine's operating conditions, thereby mitigating the operational limitations encountered in other LTC engine types. In these engines, low-reactivity fuel is injected through the manifold, while high-reactivity fuel is injected directly into the combustion chamber. The utilization of two fuels with different reactivity levels not only addresses the challenges associated with initiating combustion but also promotes improved fuel stratification within the chamber [21, 22]. Research on RCCI engines has demonstrated a decrease in NOx and PM emissions, while there may be an increase in CO and UHC emissions to some extent [23]. In a general sense, without delving into the specifics of combustion parameters, biodiesel usage and the RCCI combustion strategy both contribute to improvements in PM emissions. Moreover, in terms of CO, UHC, and NOx pollutants, they can also exhibit complementary effects. This initial observation served as the primary motivation for further research and a comprehensive review of the potential of biodiesel utilization in RCCI engines.

The ratio of premixed fuel and the direct fuel injection timing are crucial parameters in the performance evaluation of RCCI engines, which have been extensively studied by researchers [24]. Regarding the premixed fuel ratio, numerous studies have focused on biodiesel fuel and provided generally consistent results. However, RCCI engines face challenges at lower loads due to the low reactivity of high-octane fuels like gasoline. To control combustion and reduce pollutants such as CO and UHC, an increased amount of energy associated with biodiesel is required. In certain cases, substituting diesel with biodiesel results in better performance at low loads and even reduces the energy percentage of the premixed fuel less significantly, which is due to biodiesel's higher cetane number and its superior ability to oxygenate the mixture. It is important to note that the impact of biodiesel on NOx emissions can vary, as biodiesel has a higher adiabatic flame temperature compared to diesel. However, increasing the energy contribution of high-octane fuel, which is more homogenized, can reduce NOx emissions while also lowering PM levels. It should be noted that these observations can be influenced by engine performance conditions, and certain studies have reduced the premixed fuel portion to achieve specific performance points with biodiesel. At higher loads, to obtain smoother engine performance and reduce the knock phenomenon, the share of high-octane fuel is usually increased to enable stratified combustion due to its higher sensitivity to equivalence ratio [25-31].

The influence of the start of injection (SOI) timing on biodiesel combustion in RCCI has attracted less research interest from scholars. In three numerical studies [26, 32, 33], the SOI was considered as a side parameter while investigating the effects of altering the premixed fuel ratio and piston bowl geometry at two or three different direct fuel injection timings. In the experimental study conducted by Zheng et al. [34], the effect of SOI, the premixed fuel ratio, exhaust gas recirculation (EGR), and the type of high-octane fuel were examined in an RCCI engine. Three fuels, namely ethanol, butanol, and dimethylfuran, were individually tested as port fuel, while biodiesel was used as a direct-injection fuel. When the SOI was varied from 2° bTDC to 16° bTDC, the combustion process and emissions exhibited similar trends for all three fuels. Moreover, ethanol combustion demonstrated better NOx and PM reduction, while butanol combustion exhibited higher efficiency.

In another study conducted by Zheng et al. [35], butanol/biodiesel fuels were compared in RCCI and blend modes. The researchers investigated the effects of varying parameters such as EGR, low-reactivity fuel mass fraction, injection timing, and engine load. The results showed that by using the blend of the fuels, the CO, UHC, and soot emissions are better reduced while the level of NOx emission increases. It is important to note that neither in this study nor in the two other studies that will be mentioned as follows was gasoline considered a high-octane fuel.

Zhou et al. [36] numerically investigated the knock phenomenon in RCCI engines. They observed that the use of cooled EGR, retarding fuel injection, and reducing methanol mass fraction can contribute to reducing this phenomenon.

Ghaffarzadeh et al. [37] investigated the natural gas/biodiesel and natural gas/diesel RCCI combustions by changing the liquid fuel injection timing. They also investigated the effect of biodiesel composition (B0, B5, and B20) and premix ratio. To improve the knock phenomenon with the increased ratio of the premixed fuel, direct fuel injection was retarded. Also, based on the engine's operating conditions, different SOIs were selected for each premix ratio and each biodiesel/diesel blend. They reported that fuel injection timing has a considerable impact on engine performance and emissions. In the graphs presented in that research, it can be observed that, in general, early fuel injection leads to a slight reduction in thermal efficiency and a significant decrease in NOx emission, while it usually results in a rise in CO and UHC emission levels. Also, based on the findings, increasing the premix ratio generally decreases the thermal efficiency and CO emission, while it increases the UHC emission significantly.

Based on the literature review, limited research has been conducted on the utilization of biodiesel in engines employing the RCCI combustion strategy. This research gap is even more notable when the biodiesel is produced from waste oil in such a way that, to the extent of the author’s knowledge, the investigation of waste oil biodiesel in an RCCI engine fueled with high-octane gasoline has not been investigated. Furthermore, the fuel injection timing parameter, which is one of the two crucial parameters in RCCI combustion, has received relatively less attention, particularly concerning biodiesel, compared to the premixed fuel ratio parameter, which is one of the other important parameters. In addition, there is a lack of experimental investigation into the effect of direct fuel injection timing in the RCCI combustion of gasoline/biodiesel blends. This study aims to experimentally examine the impact of waste oil-derived biodiesel/diesel blend (B20) injection timing as high-cetane fuel alongside high-octane gasoline in an RCCI engine. The study focuses on extracting important data such as in-cylinder pressure, fuel consumption, efficiency, and CO, UHC, and NOx emissions.

2- Research Method

In this research, after collecting the cooking waste oil, 500-micron filters were used to filter the oil and remove the food and particles. The Biopro190 device was used to produce biodiesel. In addition to the base oil, the blend was supplemented with methanol at a ratio of 1:6 concerning the oil quantity. Furthermore, potassium hydroxide was included in the blend at a concentration of 1% relative to the weight of the oil. Additionally, sulfuric acid was added to the mixture at a ratio of 1:1000 with the oil volume. Finally, biodiesel was produced by two-stage transesterification (one stage with an acid catalyst to reduce the free fatty acids of waste oil and one main production stage) and three stages of rinsing with water. The results of the gas chromatography test of the obtained biodiesel are shown in Table 1. Due to challenges such as cold-flow characteristics, high viscosity, and oxidation stability, a combination of biodiesel fuel and diesel was utilized in a specific ratio of 20% biodiesel to 80% diesel, commonly referred to as B20. The experimental research conducted by Bahari et al. [38] investigated the impact of varying volume compositions of biodiesel derived from waste oil and diesel fuel on a conventional compression-ignition engine with a mechanical fueling system.

Table 1 Gas chromatography analysis of biodiesel fatty acids

Type of fatty acid	Weight percent
Palmitic C16:0	24.8
Palmitoleic C16:1	0.27
Stearic C18:0	32.98
Linoleic C18:2	26.55
Linolenic C18:3	1.57
Nonendocytic C19:0	7.39
Other	6.45

All necessary steps for establishing a suitable platform capable of achieving an engine with RCCI combustion functionality were taken in the internal combustion engine test room within the Sea-Based Energy Research Center at Babol Noshirvani University of Technology in Iran. The basic engine used in this research is a single-cylinder compression ignition engine with direct injection, manufactured by Daedong Company in South Korea, with a maximum power of 11 hp. This naturally aspirated engine has a water-cooling system. The engine specifications are given in Table 2.

Table 2 Engine specifications

Characteristics	Description/ Value
Manufacturer	Daedong
Type	Single-cylinder, four-stroke, water-cooled, direct-injection
Connecting rod length (m)	0.15
Compression ratio	17.1
Bore diameter (m)	0.0918
Stroke length (m)	0.0955
Displacement volume (m^3)	0.00063
Maximum power (hp)	11

To create RCCI combustion mode, a Pride's gasoline injector was mounted on a suitable point on the air manifold body. Then, the mechanical fueling system of the engine was replaced with the common rail fueling system with a solenoid injector. Also, an electronic control unit (ECU) was designed to control direct and port fuel injections. The comparison of the engine performance with a mechanical fueling system and a common rail fueling system with a solenoid injector is presented in the work of Ghaedi et al. [39]. Bosch DLLA144-p-2273 seven-hole injector was selected and used for direct fuel injection. To achieve the required injection pressure, a Bosch CP1 high-pressure pump was employed. There is a flow control valve at the top of this pump. The common rail fueling system, which was made by the Bosch Company, was connected to a piezoelectric pressure gauge on its end to develop the ECU design. To rotate the fuel pump, a three-phase Motogen 100L4B electric motor was employed, which had a rated speed of 1450 rpm. Since the nominal speed was high, to easily control the pressure inside the rail, a Shenzhen GD100-004G-4 inverter was used to adjust the speed of the electric motor. For the ECU design, to determine the exact position of the crankshaft, an encoder with a 0.1-degree accuracy and 3600 pulses per cycle was used. To adjust the SOI timing and fuel injection duration, a circuit was designed that allowed the parameters to be adjusted with the help of Arduino, which is an open-source hardware and software platform. Also, the control of the injection pressure was performed using the PID controller designed in MATLAB Simulink.

A water-brake dynamometer was used for the tests, which was equipped with a torque meter with a measurement accuracy of 0.1 Nm. To obtain the data and the pressure-crank angle diagram, a Kistler 6613CA pressure gauge connected to the cylinder head and a rotary encoder with an accuracy of 0.1 degrees and 3600 pulses per revolution were used. A coupling was used to connect the encoder to the main axis, where the dynamometer was connected. The combustion processor extracted pressure data in terms of crank angle, each 0.1 crank degrees. An HG-550 5-gas analyzer was employed to measure the emissions. Table 3 shows the technical properties of the equipment used and the uncertainties of calculated parameters. Figure 1 shows the general schematic of the test room.

Table 3 Properties of the equipment used of calculated parameters

Parameter/Unit	Systematic error	Measurement	Resolution	Uncertainty
In-cylinder pressure/MPa	±0.5%	0-25	0.0001	-
CO emissions/vol%	–	0-9.999	0.001	-
UHC emission/ppm vol	-	0-10000	1	-
NOx emission/ppm vol	-	0-5000	1	-
Brake power	-	-	-	1.15%
Fuel consumption	-	–	-	1.50%
Brake thermal efficiency	-	-	-	1.89%

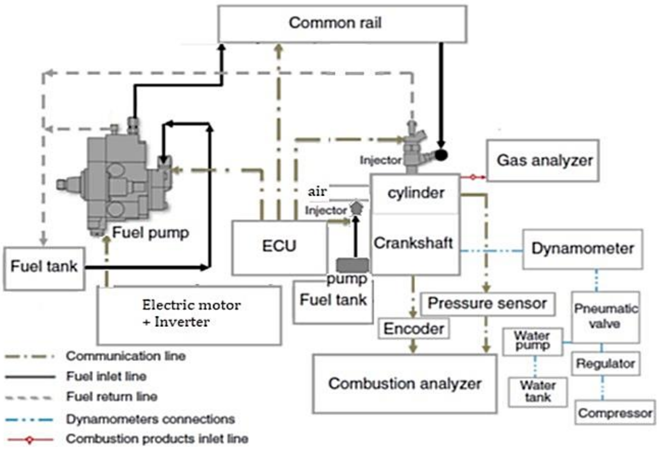

Figure 1 General schematic of the test room

According to the measurement of torque and speed in each test, the brake power of the engine can be calculated using Equation (1):

$$P_b = 2\pi NT/60000 \tag{1}$$

Considering the combustion of two fuels in the combustion chamber, the BSFC, which is given in Equation (2), is used:

$$BSFC = m_{f_i}/P_b \tag{2}$$

Also, the brake thermal efficiency is calculated from Equation (3):

$$\eta_T = P_b/\left(m_{B20}LHV_{B20} + m_g LHV_g\right) \tag{3}$$

Moreover, the ratio of the premixed fuel is obtained from Equation (4):

$$Pr = \left(m_g LHV_g\right)/\left(m_{B20}LHV_{B20} + m_g LHV_g\right) \tag{4}$$

After starting the engine, a period of 30 minutes was allowed for the engine to reach a steady state. Each in-cylinder pressure data is the average of the values of 50 working cycles, and each test is done in triplicates. Tests have been performed at the speed of 1050 rpm with constant fuel mass intake. The start of injection timing of the directly injected fuel (SOI) was studied in the range of 10° bTDC10 to 50° bTDC in intervals of 5°, although, it is necessary to note that at the SOI timings of 10° bTDC and 50° bTDC, the engine did not exhibit a desirable performance at this speed with these fuel injection conditions, or the speed was not accessible. Additionally, the B20 fuel injection pressure was 300 bar.

3- Results and Discussion

The calorific value and density of the B20 fuel were measured and calculated to be 41.5 MJ/kg and 3840 kg/m^3, respectively. Similarly, the calorific value and fuel density of gasoline were measured and calculated to be 43.5 MJ/kg and 3780 kg/m^3. Based on these measurements, it can be determined that the proportion of premixed fuel in the blend is 27%.

Figure 2 illustrates the in-cylinder pressure at different crank angles, while Figure 3 depicts the engine brake power corresponding to the studied SOI timings. Fuel mass and fuel injection pressure are constant in all tests, and the differences occurred only due to the change of the SOI timing. With the same input conditions, the engine performance with the SOI of 10° bTDC and 50° bTDC was not desirable at the speed of 1050 rpm, or the speed was not available. With the SOI timing of 15° bTDC, the engine operating condition with the speed of 1050 rpm was similar to that in idle condition. With the SOI timing of 45° bTDC, the engine performance fluctuated slightly at the speed of 1050 rpm, and it was not quite desirable. By advancing the SOI timing, ignition occurs earlier. The maximum in-cylinder pressure and the highest engine brake power occur with the SOI timing of 40° bTDC. Advancing the SOI timing to 45° bTDC causes the peak pressure and power to drop. As compared to when the SOI timing of 40° bTDC was used, this SOI advancement provides the fuel energy release at a piston position where more fuel is released before TDC is reached, which aggravates the combustion conditions. Also, advancing the injection timing leads to fuel injection at a time when the temperature and pressure inside the cylinder are lower. If the advancement is considerable, it increases fuel penetration and reduces evaporation, which can contribute to the reduced power output at the SOI timing of 45° bTDC.

From the SOI timing of 20° bTDC to 40° bTDC, by advancing the SOI, the brake power virtually increases. In comparison with the SOI timing of 20° bTDC, with the SOI timing of 25° bTDC, the second peak of the RCCI combustion phase seems to be better in terms of fuel stratification inside the chamber. Despite the slightly higher first pressure peak with the SOI timing of 20° bTDC, the combustion duration with the SOI of 25° bTDC is longer and the power is increased. Only with the SOI timing of 35° bTDC, a slight power loss observed, which can be attributed to the fact that since, compared to the SOI timing of 30° bTDC, the fuel is injected at a lower temperature and pressure, it can have a slightly weaker initial evaporation. Also, compared to the SOI timing of 40° bTDC, fuel energy is released in a piston position (relative to TDC) where it leaves less energy ready to be released at TDC.

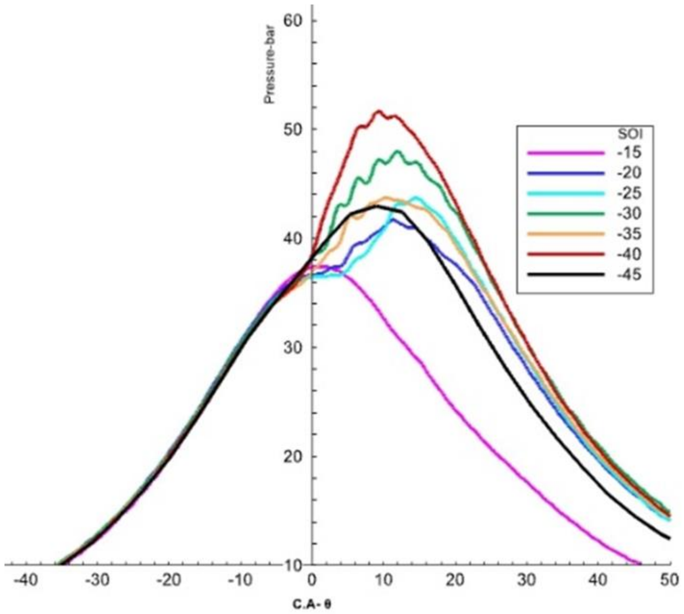

Figure 2 In-cylinder pressure diagram with different SOI timings

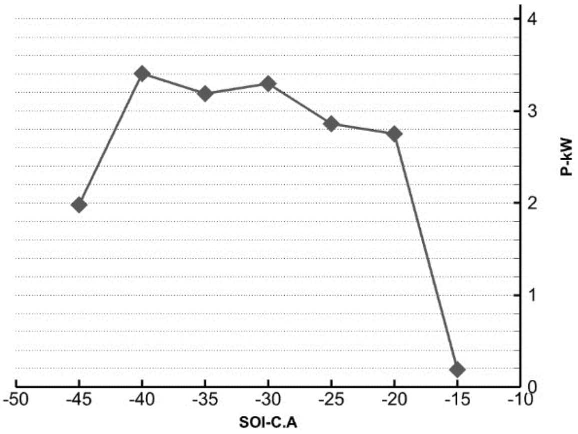

Figure 3 Brake power values with various SOI timings

Figure 4 illustrates the BSFC values, while Figure 5 presents the brake thermal efficiency for different SOI timings. Since with the SOI timing of 15° bTDC, the engine operating condition was similar to that in idle condition, neither the BSFC nor the brake thermal efficiency values are taken into consideration. Since the injected fuel mass or fuel energy input remains constant throughout the tests, the analysis of BSFC and efficiency behaves similarly to the analysis conducted for engine brake power. The highest recorded BSFC value is 311 g/kWh, and the lowest brake thermal efficiency is 27%, which is obtained with the SOI of 45° bTDC. Both these values are obtained based on the specific operating conditions of the engine with that SOI timing. Within the more stable SOI timing range from 20° bTDC to 40° bTDC, the highest BSFC value is 224 g/kWh, while the lowest brake thermal efficiency is 38.5% with the SOI timing of 20° bTDC. Conversely, the lowest BSFC value is 180.6 g/kWh, and the highest brake thermal efficiency is 47.4% with the SOI timing of 40° bTDC. When the engine operates in RCCI mode with a premixed fuel ratio of 27%, variations in the SOI timing within the completely steady operating range of the engine lead to a 9.2% change in brake thermal efficiency.

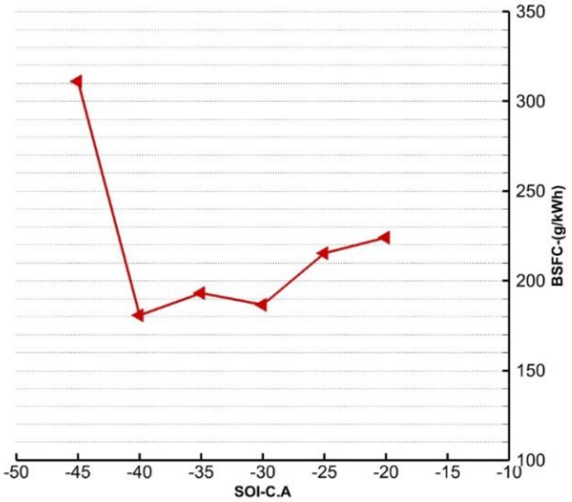

Figure 4 BSFC values with different SOI timings

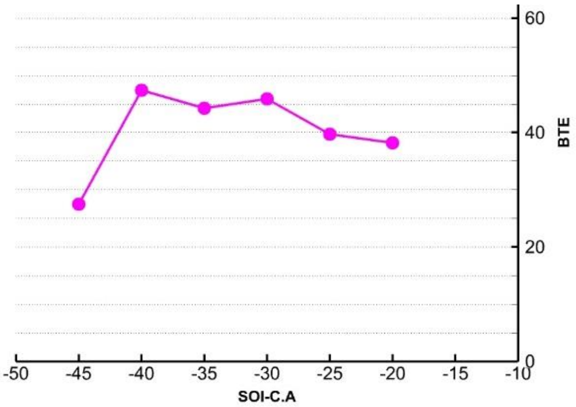

Figure 5 Brake thermal efficiency values with various SOI timings

Figure 6 visually represents the NOx emission level with each SOI timing. It can be observed that with the SOI timing of 40° bTDC, the highest level of NOx emission is 250 ppm, which is attributed to the elevated in-cylinder pressure, resulting in higher temperatures. An observation that is worth mentioning is the NOx emission level of 156 ppm with an SOI of 30° bTDC. Injecting fuel at this SOI, despite exhibiting higher brake power compared to preceding and subsequent SOIs, displays lower NOx emissions. Advancing injection timing helps to homogenize the mixture and provides better fuel stratification, but when the ratio of premixed fuel is about 27%, a large ratio of energy is released by B20 fuel itself, and as a result, the position and time of B20 fuel energy release is also effective in the in-cylinder temperature and NOx emission level. As a result, these points have caused the lowest NOx emission level with the SOI timing of 30° bTDC relative to the resulting brake power. With the SOI timing of 15° bTDC, since the engine is almost in an idle condition and the in-cylinder temperature is low, the NOx emission level is negligible. Compared to the SOI timing of 30° bTDC, with the SOI timing of 25° bTDC, the homogenization level is lower due to the advancement of the injection; therefore, the NOx emission level is higher. But as compared to the combustion with the SOI timing of 25° bTDC, with the SOI timing of 20° bTDC, due to the lower power output and the shorter combustion duration, NOx emission level is lower.

Figure 7 shows the UHC emission level, while Figure 8 indicates the CO emission level with various SOI timings. As the fuel injection is advanced, since the in-cylinder temperature is lower during the injection, the penetration of the fuel spray is greater, and some fuel is placed in the gaps and corners, which increases UHC and sometimes CO emission. On the other hand, combustion conditions and higher in-cylinder temperatures help to reduce UHC and CO emissions. The combination of these two points can provide a partial explanation for the low emission levels with the SOI timing of 25° bTDC and the slight upward trend in emissions from the SOI timing of 30° bTDC to 40° bTDC. The combustion with the SOI timing of 20° bTDC provides the highest UHC emission of 369 ppm. With the SOI timing of 20° bTDC, it is clear from the pressure diagrams that the fuel stratification in the chamber was not somehow that the combustion duration was as long as that with the SOI of 25° bTDC, where the second peak of RCCI combustion is clearly defined.

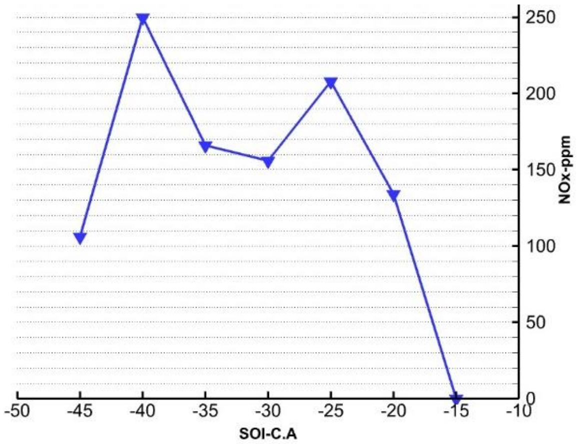

Figure 6 NOx emission level with different SOI timings

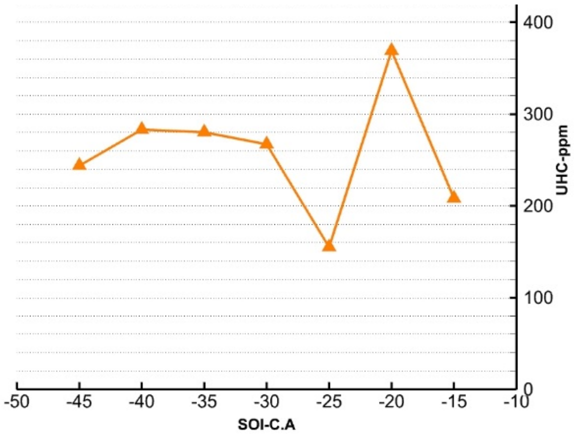

Figure 7 UHC emission level with different SOI timings

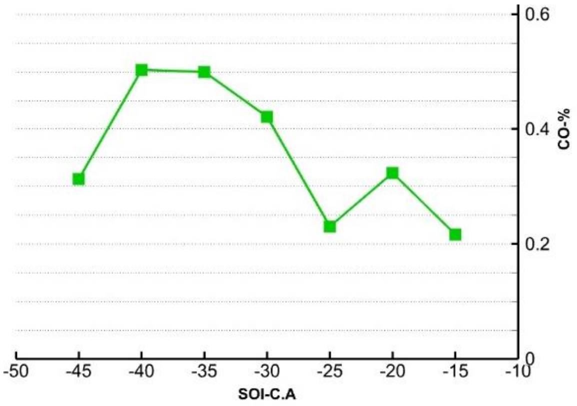

Figure 8 CO emission level with various SOI timings

Also, the energy release time, like with the SOI timing of 40° bTDC, was not somehow that more energy is released at TDC. This means that the energy is released faster at a lower temperature, which has caused a sharp increase in the UHC emission level. With the SOI timing of 45° bTDC, speed fluctuations and linear speed changes of the piston have affected air turbulence and mixing and have slightly reduced the amount of fuel trapped in the gaps. With the SOI timing of 15° bTDC, which has the lowest CO emission of 0.216%, fuel injection in dense air with higher temperatures increases the initial vaporization of the fuel and greatly reduces its penetration into the crevices due to the lower penetration of the fuel spray. From this point of view, the mixing process of fuel and air can be improved and reduce the CO emission level. Of course, due to the relatively late start of combustion with this SOI, the in-cylinder temperature is relatively lower, which prevents a larger amount of fuel from combustion and increases the UHC emission. The lowest UHC corresponds to the case with the SOI timing of 25° bTDC with an emission level of 155 ppm.

4- Conclusions

Limited research has been conducted on the utilization of biodiesel in engines employing the RCCI combustion strategy. This research gap is even more notable when biodiesel is produced from waste oil. In addition, there is a lack of experimental investigation into the effect of direct fuel injection timing in the RCCI combustion of gasoline/biodiesel blends. This research aims to investigate the impact of varying SOI timing on the performance and emissions of an RCCI engine with B20 fuel derived from waste oil, with a premixed fuel ratio of 27%. The purpose of choosing a premix ratio of 27% is to investigate mid-to-low-engine loads where the relative percentage of biodiesel fuel is higher. The main findings of this research can be summarized as follows:

- Advancing the injection in the completely steady operating range of the examined RCCI engine with a premixed fuel ratio of 27% virtually raises the brake power.
- When the engine is operating in RCCI mode with this premixed fuel ratio, variations in SOI timing over the completely steady operating range can cause around a 9.2% change in brake thermal efficiency.
- It was found that the SOI timing of 30°bTDC has a lower NOx emission level than other injection timings while maintaining relatively higher values of brake power.
- The advancement of the injection timing in the fully stable operating range of the examined RCCI engine with a premixed fuel ratio of 27% virtually increases the UHC and CO emission levels. Of course, due to the increase in the power obtained from advancing the fuel injection at some points, the rise in UHC emissions is sometimes insignificant.

In general comparison with research close to the subject of this article, the change in fuel stratification in the combustion chamber was well observed with advancing injection timing, so that an optimal SOI for engine performance was found, and the trend of results was not fully upward or downward with advancing injection timing. Also, compared to a previous study conducted on this engine with different fuels (investigation of diesel fuel injection timing) [23], the engine's stable performance range was shorter, and the diagrams had optimum points, unlike that study, which had almost monotonous diagrams.

References

[1] IEA. Renewables 2019. Market analysis and forecast from 2019 to 2024. [Internet]. Paris: 2019. Available from: https://www.iea.org/reports/renewables-2019/transport

[2] Ellen Bourbon. Clean Cities Alternative Fuel Price Report. [Internet]. Washington: 2020. Available from: https://afdc.energy.gov/files/u/publication/alternative_fuel_price_report_october_2020.pdf

[3] Shafaghat R, Talesh Amiri S, Jahanian O. Numerical study of the effect of adding water with different temperatures to low-reactivity fuel in a reactivity controlled compression ignition (RCCI) engine. Fuel and Combustion. 2020 Dec 21;13(4):43-62. doi: 10.22034/jfnc.2020.120861

[4] IEA. Transport Biofuels. [Internet]. 2020. Available from: https://www.iea.org/reports/transport-biofuels

[5] Zarenezhad Ashkezari A, Pourtaghi Yousefdeh S. Experimental investigation of the combination of ethanol-biodiesel, ethanol-diesel, and ethanol-biodiesel-diesel emulsion blends on performance and emissions of direct injection diesel engines. The Journal of Engine Research. 2022 Mar 21;66(66):3-21. doi: 10.22034/ER.2022.697909 [In Persian]

[6] Leng L, Li W, Li H, Jiang S, Zhou W. Cold flow properties of biodiesel and the improvement methods: a review. Energy & Fuels. 2020 Aug 3;34(9):10364-83. doi: 10.1021/acs.energyfuels.0c01912

[7] Wan Ghazali WN, Mamat R, Najafi G, Sapee S. Investigation of blended palm biodiesel-diesel fuel properties with water emulsification. The Journal of Engine Research. 2020 Feb 20;57(57):65-74.

[8] Lapuerta M, Armas O, Rodriguez-Fernandez J. Effect of biodiesel fuels on diesel engine emissions. Progress in energy and combustion science. 2008 Apr 1;34(2):198-223. doi: 10.1016/j.pecs.2007.07.001

[9] Lin YC, Lee WJ, Wu TS, Wang CT. Comparison of PAH and regulated harmful matter emissions from biodiesel blends and paraffinic fuel blends on engine accumulated mileage test. fuel. 2006 Dec 1;85(17-18):2516-23. doi: 10.1016/j.fuel.2006.04.023

[10] Zhu L, Cheung CS, Zhang WG, Huang Z. Combustion, performance and emission characteristics of a DI diesel engine fueled with ethanol–biodiesel blends. Fuel. 2011 May 1;90(5):1743-50. doi: 10.1016/j.fuel.2011.01.024

[11] Seraç MR, Aydın S, Yılmaz A, Şevik S. Evaluation of comparative combustion, performance, and emission of soybean-based alternative biodiesel fuel blends in a CI engine. Renewable Energy. 2020 Apr 1;148:1065-73. doi: 10.1016/j.renene.2019.10.090

[12] Gopal KN, Pal A, Sharma S, Samanchi C, Sathyanarayanan K, Elango T. Investigation of emissions and combustion characteristics of a CI engine fueled with waste cooking oil methyl ester and diesel blends. Alexandria Engineering Journal. 2014 Jun 1;53(2):281-7. doi: 10.1016/j.aej.2014.02.003

[13] Gad MS, El-Seesy AI, Radwan A, He Z. Enhancing the combustion and emission parameters of a diesel engine fueled by waste cooking oil biodiesel and gasoline additives. Fuel. 2020 Jun 1;269:117466. doi: 10.1016/j.fuel.2020.117466

[14] Raman LA, Deepanraj B, Rajakumar S, Sivasubramanian V. Experimental investigation on performance, combustion and emission analysis of a direct injection diesel engine fuelled with rapeseed oil biodiesel. Fuel. 2019 Jun 15;246:69-74. doi: 10.1016/j.fuel.2019.02.106

[15] Al-lwayzy SH, Yusaf T. Diesel engine performance and exhaust gas emissions using Microalgae Chlorella protothecoides biodiesel. Renewable Energy. 2017 Feb 1;101:690-701. doi: 10.1016/j.renene.2016.09.035

[16] Ogunkunle O, Ahmed NA. A review of global current scenario of biodiesel adoption and combustion in vehicular diesel engines. Energy Reports. 2019 Nov 1;5:1560-79. doi: 10.1016/j.egyr.2019.10.028

[17] Anwar M. Biodiesel feedstocks selection strategies based on economic, technical, and sustainable aspects. Fuel. 2021 Jan 1;283:119204. doi: 10.1016/j.fuel.2020.119204

[18] Gui MM, Lee KT, Bhatia S. Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. Energy. 2008 Nov 1;33(11):1646-53. doi: 10.1016/j.energy.2008.06.002

[19] Paulson J, Iijima M. Biofuels Annual 2018. [Internet]. Tokyo: 2018. Available from: https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels%20Annual_Tokyo_Japan_11-5-2018.pdf

[20] Jiaqiang E, Pham M, Zhao D, Deng Y, Le D, Zuo W, Zhu H, Liu T, Peng Q, Zhang Z. Effect of different technologies on combustion and emissions of the diesel engine fueled with biodiesel: A review. Renewable and Sustainable Energy Reviews. 2017 Dec 1;80:620-47. doi: 10.1016/j.rser.2017.05.250

[21] Kokjohn SL. Reactivity controlled compression ignition (RCCI) combustion [dissertation]. The University of Wisconsin-Madison; 2012.

[22] Li J, Yang W, Zhou D. Review on the management of RCCI engines. Renewable and Sustainable Energy Reviews. 2017 Mar 1;69:65-79. doi: 10.1016/j.rser.2016.11.159

[23] Motallebi Hasankola SS, Shafaghat R, Jahanian O, Nikzadfar K. An experimental investigation of the injection timing effect on the combustion phasing and emissions in reactivity-controlled compression ignition (RCCI) engine. Journal of Thermal Analysis and Calorimetry. 2020 Feb;139(4):2509-16. doi: 10.1007/s10973-019-08761-0

[24] Nazemi M, Shahbakhti MJ. Modeling and analysis of fuel injection parameters for combustion and performance of an RCCI engine. Applied Energy. 2016 Mar 1;165:135-50. doi: 10.1016/j.apenergy.2015.11.093

[25] Zhou DZ, Yang WM, An H, Li J, Shu C. A numerical study on RCCI engine fueled by biodiesel/methanol. Energy conversion and management. 2015 Jan 1;89:798-807. doi: 10.1016/j.enconman.2014.10.054

[26] Li J, Yang WM, An H, Zhao D. Effects of fuel ratio and injection timing on gasoline/biodiesel fueled RCCI engine: A modeling study. Applied Energy. 2015 Oct 1;155:59-67. doi: 10.1016/j.apenergy.2015.05.114

[27] Işık MZ, Aydın H. Analysis of ethanol RCCI application with safflower biodiesel blends in a high load diesel power generator. Fuel. 2016 Nov 15;184:248-60. doi: 10.1016/j.fuel.2016.07.017

[28] Işik MZ, Aydin H. Investigation on the effects of gasoline reactivity controlled compression ignition application in a diesel generator in high loads using safflower biodiesel blends. Renewable Energy. 2019 Apr 1;133:177-89. doi: 10.1016/j.renene.2018.10.025

[29] Gawale GR, Srinivasulu GN. Experimental investigation of ethanol/diesel and ethanol/biodiesel on dual fuel mode HCCI engine for different engine load conditions. Fuel. 2020 Mar 1;263:116725. doi: 10.1016/j.fuel.2019.116725

[30] Sonachalam M, PaulPandian P, Manieniyan V. Emission reduction in diesel engine with acetylene gas and biodiesel using inlet manifold injection. Clean Technologies and Environmental Policy. 2020 Dec;22:2177-91. doi: 10.1007/s10098-020-01968-y

[31] Harari PA, Banapurmath NR, Yaliwal VS, Khan TY, Soudagar ME, Sajjan AM. Experimental studies on performance and emission characteristics of reactivity controlled compression ignition (RCCI) engine operated with gasoline and Thevetia Peruviana biodiesel. Renewable Energy. 2020 Nov 1;160:865-75. doi: 10.1016/j.renene.2020.07.009

[32] Li J, Yang WM, Zhou DZ. Modeling study on the effect of piston bowl geometries in a gasoline/biodiesel fueled RCCI engine at high speed. Energy Conversion and Management. 2016 Mar 15;112:359-68. doi: 10.1016/j.enconman.2016.01.041

[33] Wenming Y, Meng Y. Phi-T map analysis on RCCI engine fueled by methanol and biodiesel. Energy. 2019 Nov 15;187:115958. doi: 10.1016/j.energy.2019.115958

[34] Zheng Z, Xia M, Liu H, Wang X, Yao M. Experimental study on combustion and emissions of dual fuel RCCI mode fueled with biodiesel/n-butanol, biodiesel/2, 5-dimethylfuran and biodiesel/ethanol. Energy. 2018 Apr 1;148:824-38. doi: 10.1016/j.energy.2018.02.015

[35] Zheng Z, Xia M, Liu H, Shang R, Ma G, Yao M. Experimental study on combustion and emissions of n-butanol/biodiesel under both blended fuel mode and dual fuel RCCI mode. Fuel. 2018 Aug 15;226:240-51. doi: 10.1016/j.fuel.2018.03.151

[36] Zhou DZ, Yang WM, An H, Li J. Application of CFD-chemical kinetics approach in detecting RCCI engine knocking fuelled with biodiesel/methanol. Applied Energy. 2015 May 1;145:255-64. doi: 10.1016/j.apenergy.2015.02.058

[37] Ghaffarzadeh S, Toosi AN, Hosseini V. An experimental study on low temperature combustion in a light duty engine fueled with diesel/CNG and biodiesel/CNG. Fuel. 2020 Feb 15;262:116495. doi: 10.1016/j.fuel.2019.116495

[38] Bahari R, Shafaghat R, Jahanian O, Ghaedi A. The influence of biodiesel with high saturated fatty acids on the performance of a CI engine fuelled by diesel and biodiesel blend fuels at low loads. International Journal of Ambient Energy. 2022 Dec 31;43(1):7643-56. doi: 10.1080/01430750.2022.2075927

[39] Ghaedi A, Shafaghat R, Jahanian O, Motallebi Hasankola SS. Comparing the performance of a CI engine after replacing the mechanical injector with a common rail solenoid injector. Journal of Thermal Analysis and Calorimetry. 2020 Feb;139:2475-85. doi: 10.1007/s10973-019-08760-1

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مقاله پژوهشی

مطالعهٔ تجربی سوخت زیست‌دیزل روغن پسماند در موتوری RCCI، برای ارزیابی اثرات لحظهٔ شروع پاشش سوخت با واکنش‌پذیری شدید

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اطلاعات مقاله

کلیدواژه‌ها:
زیست‌دیزل
روغن پسماند
موتور RCCI
لحظهٔ شروع پاشش سوخت
آلایندگی

چکیده

افزایش آلایندگی در کنار تشدید گرمایش زمین و کاهش شدید منابع انرژی سنگواره‌ای، سه محور اصلی پرخطر برای زندگی انسان‌ها و کرهٔ زمین هستند. این موارد پژوهشگران را به سمت استفاده از سوخت‌های تجدیدپذیر جایگزینی که در بیشتر نقاط جهان یافت شوند و آلایندگی کمتری داشته باشند، انگیزه داده است. زیست‌دیزل حاصل از روغن پسماند تقریباً تمام خواص ذکر شده را دارد. با توجه به هدف‌گذاری‌های روند توسعهٔ پایدار در افزایش استفاده از زیست‌دیزل، بررسی عملکرد این سوخت در موتورهای آینده نظیر موتورهای اشتعال تراکمی با واکنش‌پذیری تنظیم شده، بسیار مهم است. شاخص زاویهٔ شروع پاشش سوخت در موتورهای RCCI برای یافتن بازه‌های عملکردی مناسب و بهینه‌یابی مقدار انتشار آلاینده‌ها حائز اهمیت است. این درحالی است که تأثیر لحظهٔ پاشش سوخت مستقیم در احتراق RCCI بنزین/ زیست‌دیزل، به روش تجربی توسط محققین بررسی نشده است. در این پژوهش تغییرات زمان پاشش سوخت ستان بالای زیست‌دیزل روغن پسماند در یک موتور RCCI با سوخت اکتان بالای بنزین به صورت تجربی بررسی شد. داده‌های فشار داخل استوانه، عملکرد موتور و میزان انتشار آلاینده‌های NOx، UHC و CO از آزمون‌ها استخراج و تحلیل شدند. نتایج نشان داد که تغییرات SOI در بازهٔ عملکرد کاملاً پایدار موتور می‌تواند حدود ۹٫۲٪ در بازده حرارتی ترمزی، زمانی که موتور در حالت RCCI با نسبت سوخت پیش‌آمیخته ۲۷٪ کار می‌کند، تغییر ایجاد کند. همچنین پاشش در زاویهٔ ۳۰ CAD bTDC توانست در کنار حفظ مقادیر قویتری توان ترمزی، مقدار NOx کمتری از دیگر زوایای پاشش داشته باشد.

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