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The impact of injection timing and pressure on a CRDI engine's combustion characteristics

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ABSTRACT

In this study, in which diesel (B0), pure biodiesel (B100) and diesel/biodiesel mixtures in four different ratios (B20, B40, B60, B80) are used as fuel, the effects of injection pressure and injection timing on a common rail direct injection (CRDI) engine were investigated. A single-cylinder CRDI engine with a volume of 1.12 litters was used for the engine tests. Combustion characteristics of the CRDI engine such as IMEP, combustion sound, cylinder gas pressure and heat release rate (HRR) were investigated with the experiments carried out at four different engine loads and at a constant engine speed of 1500 rpm. It was found that IMEP raised as the injection pressure increased. The highest increase was observed at 75% engine load and injection pressure of +200 bar. The IMEP values of B0, B20, B40, B60, B80 and B100 fuels were measured as 11.01, 10.13, 10.88, 10.34, 10.11 and 9.86 bar, respectively. The combustion noise values of B0, B20, B40, B60, B80 and B100 fuels at 75% engine load and at the original injection time were 93.73, 92.49, 91.63, 91.01, 92.82 and 92.27 dB. All fuels' combustion noise levels rose as a result of the shorter injection timing. A similar situation was observed when the injection pressure was reduced. The combustion noise generally decreased as injection timing and pressure were increased. Ignition delay values of B0, B20, B40, B60, B80 and B100 fuels at 50% engine load and STD injection timing were found to be 7.5, 6.5, 6, 5.5, 5 and 5.5 CA, respectively. However, increasing the injection timing decreased the ignition delay value for all fuels. Decreasing the injection pressure resulted in an increase of ignition delay for all fuels.

Introduction

Today, the number of internal combustion engines is quite large. As a result, the need for fuel is rising daily. Future predictions indicate that fossil fuel supplies will diminish. Therefore, studies on biofuels are being conducted all over the world. The most important thing about biofuel production is that it is made from non-food raw materials. Therefore, fuel production from waste is very important in terms of renewable energy. Another important issue is how efficiently the fuel can be used. Efficient use of fuel is very important in terms of pollution and resource management. For this reason, the engine that produces more power with less fuel and pollutes the environment less is on the rise all over the world.

Biodiesel has a higher viscosity and density than diesel. Atomization issues are brought on by these unfavourable characteristics of biodiesel. It can also have negative effects on the fuel system. It can also cause clogging in the fuel injectors [2,7,10,15]. To overcome these disadvantages of biodiesel, many researchers have tried to reduce the density and viscosity [1,8]. In the test system used in this study, a fuel temperature controller is present. In this way, the density differences caused by the temperature difference of the fuels are minimal. Biodiesel can be produced from many different sources. Some of these include oilseeds, waste oils, and animal fats. Biodiesel is an environmentally friendly fuel. However, along with these advantages, there are some negative characteristics. Some of them are low filter clogging points in cold weather, high production cost, high density and viscosity [3,4,14,19]. Transesterification method is mostly used in biodiesel production. In this process, heating can be done as classical, ultrasound and microwave assisted [17]. Low energy consumption and short production time are very important in the production of biodiesel. It is also important that the efficiency of biodiesel conversion is high. However, a minimum of alcohol and catalyst should be used in the production process. In internal combustion engines, biofuels can be employed either as pure form or in a

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Nomenclature

B0	Diesel
B10	%90 diesel+10% biodiesel
B20	%80 diesel+20% biodiesel
B40	%60 diesel+40% biodiesel
B55	Soybean Methyl Ester 50 +% Rapeseed Methyl Ester 50
B60	%40 diesel+60% biodiesel
B80	%20 diesel+80% biodiesel
B82	20% Rapeseed Methyl Ester+80% Soybean Methyl Ester
B100	100% biodiesel
BSFC	Brake specific fuel consumption
bTDC	Before top dead center
BTE	Brake thermal efficiency
CA	Crank angle
CI	Compression ignition
CNG	Compressed natural gas
CO	Carbon monoxide
CRDI	Common Rail Direct Injection
CO_2	Carbon dioxide
DF	Dual fuel
EGR	Exhaust gas recirculation
HC	Hydrocarbon
HRR	Heat release rate
ID	Ignition delay
IMEP	Indicated mean effective pressure
IP	Injection pressure
IT	Injection timing
I15B20	isobutanol-diesel–biodiesel
O_2	Oxygen
NO_x	Nitrogen oxides
rpm	Revolutions per minute
RME	Rapeseed Methyl Ester
SME	Soybean Methyl Ester
PME	Palm methyl ester
STD	Original injection pressure and time
TPME	Thevetia peruviana methyl ester

blend. The biggest benefit of using biofuels in engines is that they don't require structural changes. However, the biofuel used should be highly efficient and emit little pollution. The physical and chemical characteristics of biodiesel have an impact on combustion parameters, emissions, and engine performance. Therefore, it is crucial that the biodiesel adheres to EN 14214 criteria [9].

In addition to these, the operating parameters of diesel engines are also important. In this way, higher performance, lower emissions, and better combustion characteristics can be achieved. Better results can be obtained by changing the injection timing and pressure in a diesel engine. In this study, combustion characteristics of biodiesel and diesel mixtures at four different injection timing and four different injection pressures were investigated.

When the studies on the effect of injection timing or injection pressures in the literature are examined, it has been determined that there are few studies in which both variables are examined together. In their research, Mina et al. used biodiesel and diesel blends made from palm oil. For B10 fuel, larger quantities of nitrogen oxide were discovered despite higher levels of CO and CO_2 being detected. By including more biodiesel in the fuel blend, combustion was also improved. As a result, it was found that it is appropriate to reduce glycerides in blends with biodiesel and diesel fuel, while a significant reduction in performance and emissions was observed [18].

Nema et al. used diesel and four different biodiesels (SME, RME, B55, and B82). In experiments performed at different compression ratios, it has been determined that B82 provides lower thermal braking efficiency in the range of 4–7% compared to diesel. Moreover, at high compression ratios, the use of B82 has been shown to reduce the occurrence of knock. Safer combustion was made available in this technique. B82 was found to have nitrogen oxide emissions that were roughly 20% greater than those of diesel. Moreover, B82 emissions hydrocarbons between 7% and 62% fewer often than diesel. Furthermore, at high compression ratios, the B82 blend had a lower heat release rate and ignition retardation than diesel. Nema et al., ($year$) [13].

In another study using Jatropha biodiesel and hydrogen addition, the effects on combustion, performance and emissions of injection timing and pressure were investigated. Pilot injection pressure of test engine ranges from 500 to 1500 bars. The times for the pilot injection are 5, 11, and 17 bTDC. The thermal efficiency rose from 25.02% to 32.05% with the pilot injection of biodiesel (1500 bar and 17 bTDC). Higher injection times also lead to increased cylinder pressure and HRR. The drop in injection time yielded excellent HRR for mixtures of hydrogen and biodiesel. At 1500 bar and 11 bTDC, the HC emissions dropped by 59.52% and 46.15%, respectively. At 1500 pressure and 17 bTDC, NOx emissions similarly declined by 20.61%. As a result, it has been determined that high injection pressure and duration improve performance, combustion and emissions in an engine using jatropha biodiesel as pilot fuel and hydrogen as main fuel [12].

Researchers in a similar study examined the effects of oxygen additives, injection timing, and EGR (Exhaust Gas Recirculation) on the combustion, engine performance, and emission characteristics of a CRDi diesel engine fueled with sapota biodiesel/diesel blends. Injection by changing the IT from 25°CA to 21°CA It was found that the in-cylinder pressures and heat release rate (HRR) slowly decrease due to the time delay [11].

Shareef et al. Biodiesel derived from milkshake oil was blended with diesel at ratios of 10, 20, 30, and 100%. The injection pressure was kept constant at 210 bar during the tests. During the injection process, the blend of 20% biodieseland 80% diesel (DSB-20) exhibited a relatively low cylinder pressure value compared to pure diesel. The observed cylinder pressure of 54.16 bar is highest for diesel injected at 23 degrees btdc, followed by 53.12 bar for DSB-20 injected at 26 degrees btdc. It was found that by shifting the injection timing from 23 degrees btdc to 26 degrees btdc, the ignition delay phase is prolonged and the engine runs smoother. It can also be seen from the figure that the effect of advancing the injection timing to 26 degrees btdc on the performance of the engine with DSB-20 is very clear. Cylinder pressures for diesel-23 degrees btdc, DSB20–20 degrees btdc, DSB20–23 degrees btdc, DSB20-26 degrees btdc, and DSB20–29 degrees btdc were 54.16, 50.42, 51.11, 53.12. 50.64 bar for full load conditions. The injection timing of 26 degrees b tdc with the DSB-20 has a maximum cylinder pressure of 53.12 bar among the other different injection timings. At the beginning, it was found that the HRR ratio had slightly negative values during the ignition delay phase. At an injection of 26 degrees btdc, the heat release rate of DSB-20 is lower than that of diesel at 23 degrees btdc. Advancing the injection timing from 23 degrees btdc to 26 degrees btdc results in higher combustion efficiency. A reduction in HRR and temperature is observed when the injection timing is shifted from 23 deg b tdc to 19 deg b tdc. This is due to the reduction in ignition delay, which causes insufficient mixing of fuel and air. The values of heat release rate for diesel - 23 degrees btdc, DSB20 - 20 degrees btdc, DSB20 - 23 degrees btdc, DSB20 - 26 degrees btdc and DSB20 - 29 degrees btdc are 63.74, 51.63, 60.84, 61.11 and It was 58.66 respectively [16].

Gnanasekaran et al. studied the effects of injection timing on combustion. Tests were conducted on a 4.4 kW diesel engine at 1500 rpm, various loads, and 3 different injection timings (21, 24, and 27 bTDC).

The maximum cylinder pressure was achieved with diesel. This clearly shows that the cylinder pressure of biodiesel blends is lower than that of diesel due to the shorter ignition delay. The cylinder pressure decreases with the delay of the injection timing, and the maximum cylinder pressure at 21 bTDC is about 3 bar lower with diesel, 5 bar lower with B20, B40 and B60, and 3 bar lower with B80 and B100 than with 24 bTDC. It increases as the injection timing progresses. The maximum heat release rate for B20 and B100, 59.2 J/ CA and 50.2 J/ CA at 21 bTDC, 60.4 J/ CA and 49.8 J/ CA and 27 bTDC at 24 bTDC, respectively, 63.3 J/ CA and 55.3 J/ CA. It can be seen that the heat release for premixed combustion is higher for diesel engine at all injection timings, followed by B20, B40, B60, B80 and B100. At 24 bTDC, the maximum heat release rate of diesel is 62 J/ CA, while delaying the injection timing reduces it to 61.1 J/ CA and premixing increases it to 64 J/ CA. Delaying the injection timing reduces the ignition delay, resulting in lower premix combustion and a lower peak heat release rate [5]

Gowrishankar et al. evaluated a biodiesel-water emulsion produced from karanja oil and its emulsion with 18% water as a potential fuel for low temperature combustion in a diesel engine. Two different tests were performed for both early and late fuel injection. The results were compared with conventional diesel. It was observed that while early injection increased thermal efficiency and specific fuel consumption at 40% engine load, the performance of both fuels decreased at 60% load. Smoke and nitrogen oxide emissions decreased due to late injection. The thermal efficiency and absolute fuel consumption of the biodiesel-water emulsion were reduced by 8% and 6%, respectively. Biodiesel infusion and emulsion have been shown to reduce nitrogen oxide and smoke emissions by 85% and 80%, respectively, compared to diesel. In addition, both injection techniques have been found to significantly increase carbon monoxide and hydrocarbon emissions when compared to standard diesel [6].

When the studies in the literature are examined in detail, it is seen that injection pressure and timing are mostly used as variable parameters in studies using biodiesel. However, it has been determined that there is a limited number of studies investigating the injection timing and pressure at all loads in an engine for the same fuel. Biodiesel has different fuel properties due to its raw material and production method. For this reason, it is important to investigate too many variables for the same fuel type in studies to determine the usability of that fuel. In addition, most of the studies in the literature are DI diesel engines. The use of CRDI engines in today's passenger vehicles has become widespread. It is therefore important that the tests be performed on the CRDI engine. The test system has the ability to keep many parameters constant, such as fuel temperature, oil temperature, engine coolant temperature and intake air temperature. This minimizes the measurement errors that may be caused by these factors. In addition, the electronic adjustment of the injection pressure and timing reduces the errors that may occur here. The novelty aspect of this study is that both the experimental system is up-to-date, and the tests are multivariate.

In this study, biodiesel obtained from waste olive oil with the help of ultrasound was used as fuel. Test fuels were prepared by blending with diesel fuel in different blends, and experiments were carried out at four different injection timing and pressures. The changes in IMEP, combustion noise, maximum cylinder pressure and HRR were investigated in a high cylinder displacement CRDI engine. Combustion characteristics of biodiesel and its mixtures at different loads, both injection timing and injection pressure, were investigated in detail.

Material and methods

Tests fuels

The test fuel used was the biodiesel obtained from non-food grade waste olive oil using the ultrasound-assisted method in our previous study [17]. In the tests, diesel, pure biodiesel, and diesel/biodiesel blends were used as test fuel. Pure biodiesel is referred as B100 while diesel is named as B0. The proportion of biodiesel determines how mixed fuels are categorized (B20, B40, B60 and B80). Table 1 provides a list of some of the biodiesel's physical and chemical characteristics that were employed in the studies.

Test equipment

The schematic view of the test system is given in Fig. 1. The system consists of an eddy current dynamometer, fuel and air conditioners, coolant and engine oil conditioners, a CRDI diesel engine and a control unit. The accuracy of the measurement systems used in the experiments are presented in Table 2.

Test engine

A single cylinder CRDI engine with a displacement of 1.12 Liters was used in the experiments. The instruments used in test systems are electronically controlled and can make precise adjustments. The general view of the test system is shown in Fig. 2. Some technical specifications of the CRDI engine used in the experiments are given in Table 3.

In this study, in the tests engine performances were performed as described in ISO 14369The testing comprised keeping the engine lubricating oil temperature at 90 °C and the cooling water temperature at 70 °C. The injection pressure and timing of the test engine, where the fuel system is electronically controlled, has been optimized according to diesel fuel. Therefore, injection pressure and timing change at different engine loads and speeds. For example, in experiments performed at 50% engine load, the fuel system keeps the injection pressure constant at 900 bar, as seen in Table 5. This value is marked as standard (STD) on the charts. Values such as +2 CA and −100 bar seen in the test variables of injection pressure and timing mean the value added or decreased above this STD value. In this context, the values of the injection timing and injection pressures adjusted in the experiments, corresponding to different engine loads, are given in Tables 4 and Table 5, respectively.

The experiments were repeated three times to minimize the margin of error in the experimental results and to verify the results. The results of the error analyzes for combustion noise, IMEP, ignition delay, combustion duration, cylinder gas pressure and HRR were shown in Table 6.

Results and discussion

The effects on the combustion characteristics of a CRDI engine fueled with biodiesel produced from waste olive oil with high free fatty acid were investigated in detail. In this context, changes in the combustion characteristics of the engine such as cylinder gas pressure, HRR, combustion noise, IMEP, ignition delay and combustion duration were investigated depending on different injection pressure and timing. The results were analyzed separately according to 50% and 75% engine load. The results obtained from biodiesel and its blends were compared with diesel.

Combustioncharacteristics

IMEP (indicated mean effective pressure)

The changes in IMEP depending on different engine loads (50% and

Table 1
Some physical and chemical properties of test fuels.

Property	Units	En 14214	Biodiesel	Diesel
Density (at 15 °c)	kg m^{-3}	860–900	879.6	826.6
Kinematic viscosity (at 40 °c)	$mm^2\ s^{-1}$	3.5–5.0	4.852	3.21
Water content	ppm	max. 500	431.3	36.4
Iodine value	g I.100 g^{-1}	max. 120	81.47	-
Flash point	°C	min. 101	190	59.9
Cetane number	-	min. 51	57.9	55.3
Cold filter plugging point	°C	-	7.38	-18

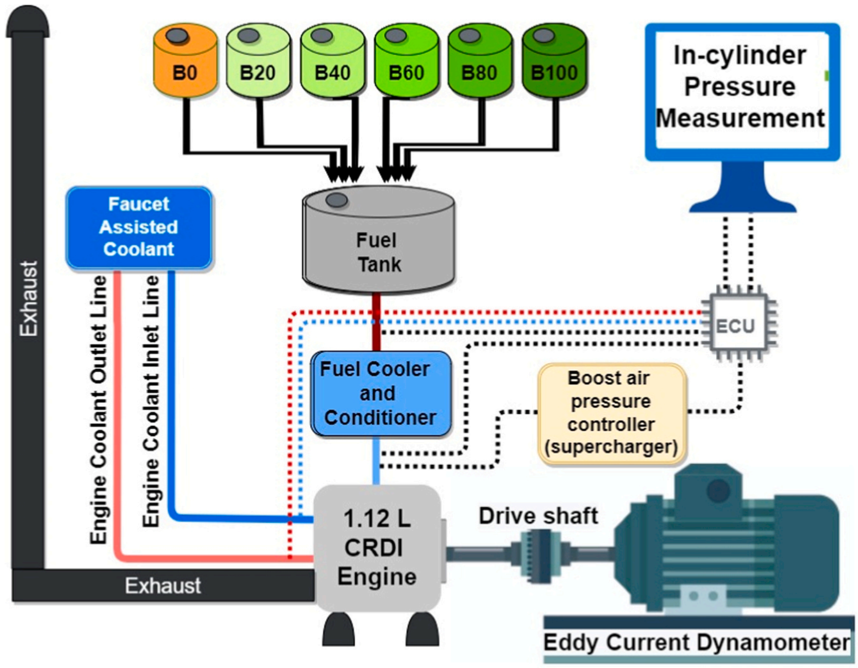

Fig. 1. Engine test system schematic view.

Table 2
The accuracy values of the test systems.

Measurement	Device	Accuracy
Torque	HBM Torque Flange	±0.1%
Engine Speed	AVL Encoder	≤±0.1CA
Test Cell Humidity	Vaisala – HMT 330	±1% RH
Test Cell Temperature	Vaisala – HMT 330	±0.2°C
In-cylinder Pressure	AVL Xion	0.05CA
Injection timing	Angle Encoder	±0.1CA
Supercharger – Boost Air Temperature	AVL 515X	±5°C
Supercharger – Boost Air Pressure	AVL 515X	±10mbar
Engine Coolant & Oil Conditioning	AVL-577	±1 K
Fuel Consumption	AVL-735	<0.15%
Temperature Sensors	PT100 (K Type)	≤±1%

Fig. 2. Test engine and dynamometer.

Table 3
Some technical specifications of the test engine.

Specification	Value
Engine type	4-stroke, single-cylinder
Cylinder diameter x stroke	106.5 ×127 mm
Engine displacement	1120 cm^3
Compression ratio	16.4:1
Maximum power	18 kW
Maximum torque	120 Nm
Maximum no-load rpm	2500 d/d
Fuel system	Direct injection Common rail-1800 bar
Fuel pump	Bosch 1.050 Bar high pressure mechanical pump
Cooling system	Water cooled with mains water
Number of intake and exhaust valves	2–1

Table 4
The injection timing values corresponding to test variables for different loads.

Engine load	Variables in injection timing experiments			
	-2 CA (bTDC)	STD (bTDC)	+2 CA (bTDC)	+4 CA (bTDC)
%50	14 CA	16 CA	18 CA	20 CA
%75	15 CA	17 CA	19 CA	21 CA

Table 5
The injection pressure values corresponding to test variables for different loads.

Engine load	Variables in injection pressure experiments			
	-100 bar	STD	+100 bar	+200 bar
%50	800 bar	900 bar	1000 bar	1100 bar
%75	1200 bar	1300 bar	1400 bar	1500 bar

75%), four different injection timing and four different injection pressures were given in Fig. 3. When the graph was examined, it was observed that IMEP generally raised with increasing engine load. The highest IMEP value was obtained with diesel fuel in all tests. In addition, the IMEP values of B0, B20, B40, B60, B80 and B100 fuels at 50% load were 6.53, 6.21, 6.48, 6.38, 6.22 and 5.84 bars, respectively. At 75% engine load, these values were measured as 10.48, 9.52, 9.77, 9.68, 9.41 and 8.97 bar.

This was because biodiesel has a low calorific value. Due to the reduction in injection time, the IMEP values of all fuels decreased. This

Table 6
Error analysis of test fuels.

	Combustion noise	IMEP	Ignition delay	Combustion duration	Cylinder gas pressure	HRR
Diesel	0.482	0.216	1.192	1.633	1.569	0.968
B20	0.502	0.151	1.242	1.565	1.756	0.836
B40	0.535	0.160	1.325	0.983	1.526	0.751
B60	0.468	0.212	1.159	1.623	1233	1.106
B80	0.446	0.148	1.104	1.527	1056	0.986
B100	0.507	0.317	1.256	1.945	1.175	0.967

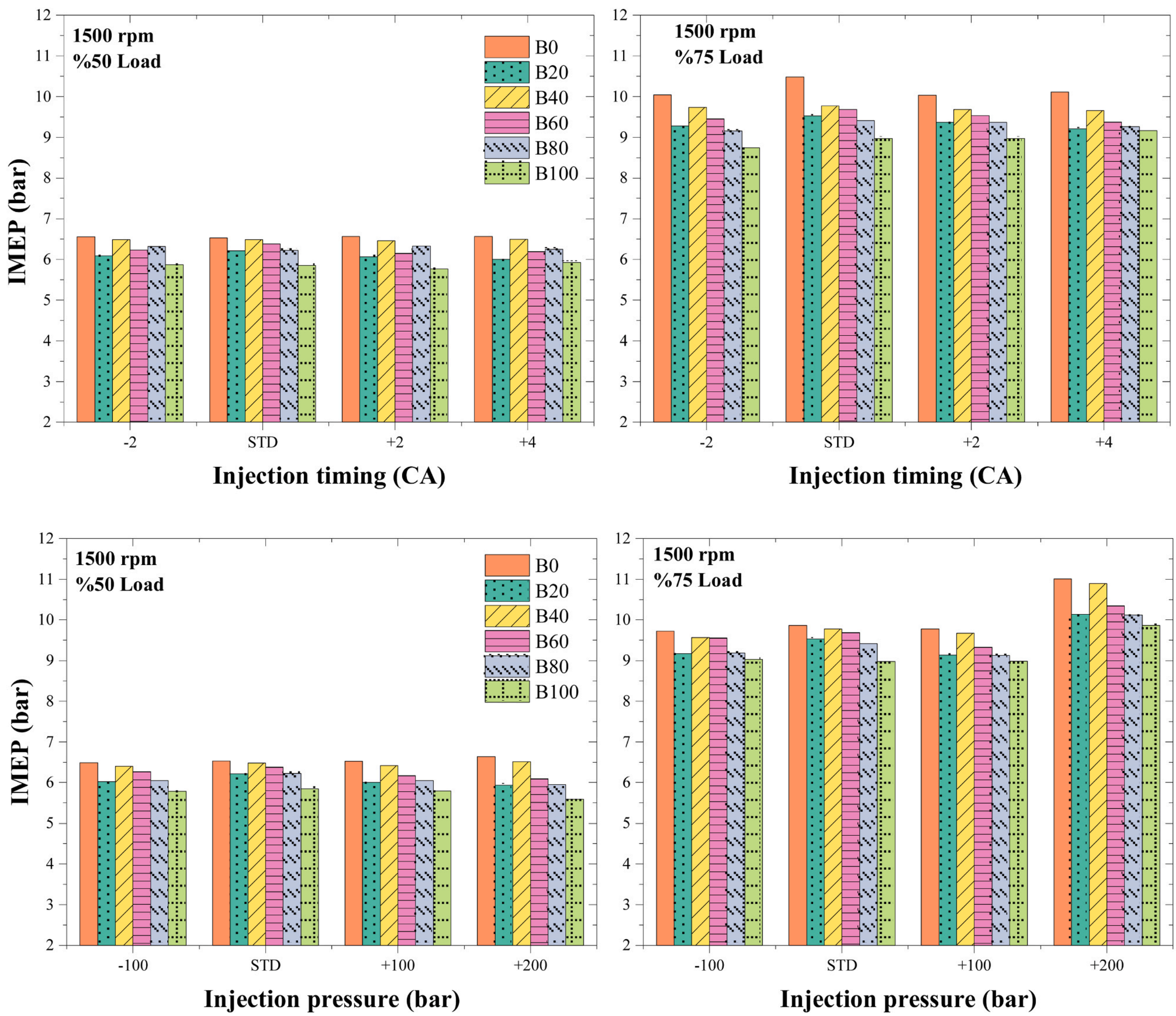

Fig. 3. Variations of IMEP at different engine loads according to injection timing and pressure.

leads to a reduction in burning time and worsens the combustion quality. As the injection time was reduced, the temperature and pressure in the cylinder decreased, resulting in a decrease in IMEP. The same situation occurred when the injection pressure was reduced. Reducing the pressure increased the diameter of the fuel droplets and worsened atomization. This led to a deterioration of combustion and a decrease in temperatures and pressures in the cylinder. As a result, the IMEP decreased due to these factors. It was found that IMEP raised as the injection pressure increased. The highest increase was observed at 75% engine load and injection pressure of +200 bar. The IMEP values of B0, B20, B40, B60, B80 and B100 fuels were measured as 11.01, 10.13, 10.88, 10.34, 10.11 and 9.86 bar, respectively

Combustion noise

Fig. 4. illustrates the changes in combustion noise at engine loads (50% and 75%), different injection timing and pressure. In graph, it is observed that the combustion noise raised with increasing engine load. Diesel (B0) produced the greatest combustion noise value across all experiments. In addition, the combustion noise values of B0, B20, B40, B60, B80 and B100 fuels at 50% engine load and at the original injection time were 91.49, 90.19, 89.35, 88.78, 90.51 and 89.97 dB. The combustion noise values of B0, B20, B40, B60, B80 and B100 fuels at 75% engine load and at the original injection time were 93.73, 92.49, 91.63, 91.01, 92.82 and 92.27 dB. All fuels' combustion noise levels rose as a result of the shorter injection timing. A similar situation was observed

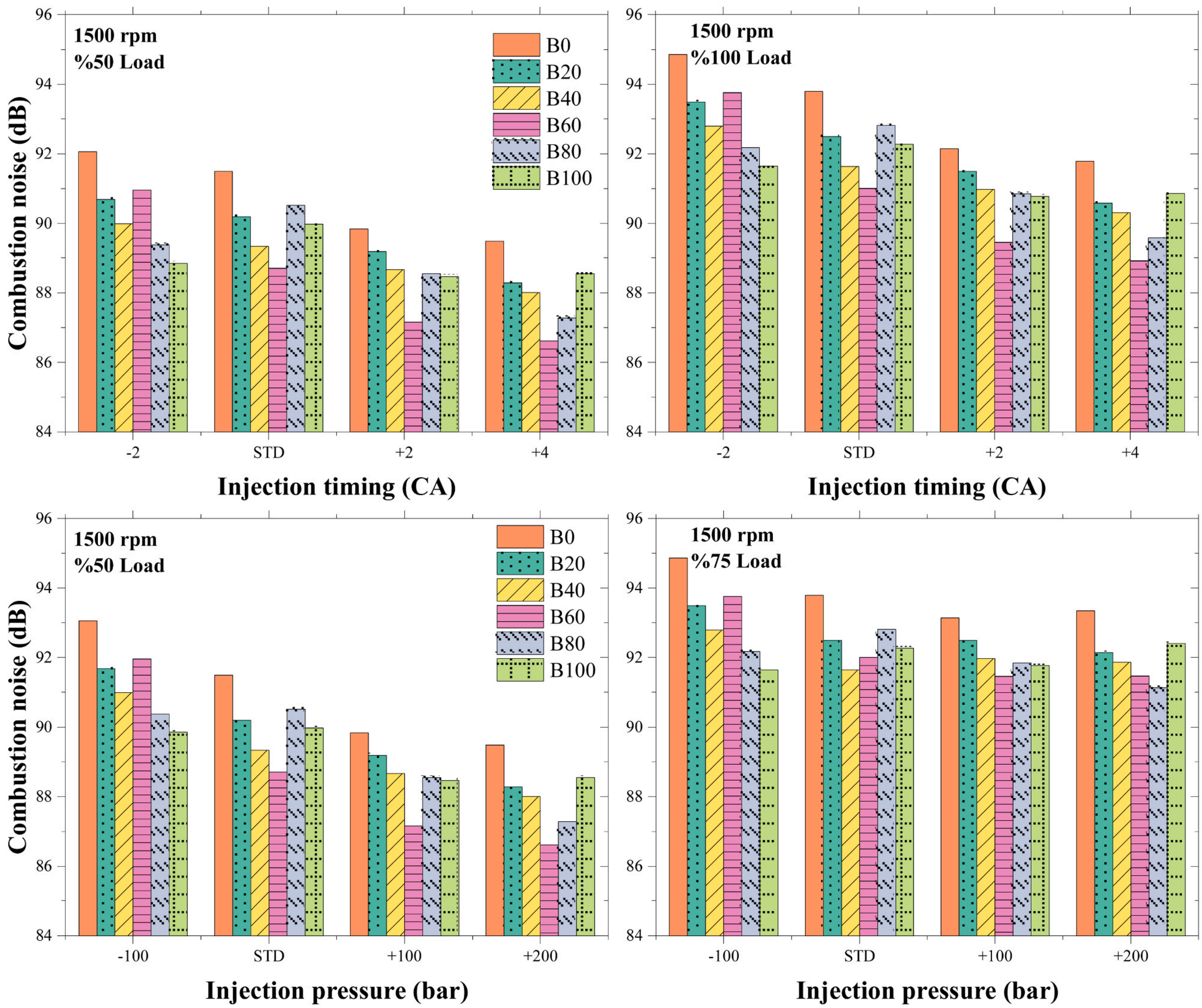

Fig. 4. Variations of combustion noise at different engine loads according to injection timing and pressure.

when the injection pressure was reduced. The combustion noise generally decreased as injection timing and pressure were increased.

Ignition delay and combustion duration

In Fig. 5, the variations of ignition delay and combustion duration depending on injection pressure and timing at different loads were presented. It was seen from the graph that the ignition delay decreases with increasing load. In tests conducted at 50% and 75% engine load, ignition delay reached its highest value in diesel fuel. Due to the presence of oxygen in the structure of biodiesel, the ignition delay decreased with the use of biodiesel. Ignition delay values of B0, B20, B40, B60, B80 and B100 fuels at 50% engine load and STD injection timing were found to be 7.5, 6.5, 6, 5.5, 5 and 5.5 CA, respectively. At 75% engine load and STD injection timing, the ignition delay values of B0, B20, B40, B60, B80 and B100 were obtained as 5, 4.5, 4.5 4, 4 and 4.5 CA, respectively. As can be seen in Fig. 5, decreasing the injection timing resulted in an increase of ignition delay for all fuels.

However, increasing the injection timing decreased the ignition delay value for all fuels. The earlier injection shortens the time between the injection of the fuel and the start of combustion. The combustion duration changed only slightly with increasing engine load. As can be seen in Fig. 5, the combustion duration of all test fuels are close to each other. Reducing the injection timing for all test fuels shortened the combustion duration. The late injection of the fuel extended the ignition delay period and the combustion started late. This resulted in a reduction in burn time. The burn time of all fuels was between 40 and 50 CA.

Fig. 6. illustrates the variations in ignition delay and combustion duration at two distinct engine loads (50% and 75%), four distinct injection durations, and four distinct injection pressures.

ID Values of B0, B20, B40, B60, B80 and B100 fuels at 50% engine load and original injection pressure: 6, 5, 5.5, 4.5,4 and 4.5 are CA. At 75% engine load and original injection pressure, the ignition delay values of B0, B20, B40, B60, B80 and B100 are 5.5,. 5.5, 5,.5, 4.5 and 4 respectively CA. As can be seen in Fig. 6, decreasing the injection presure resulted in an increase of ignition delay for all fuels. However, increasing the injection pressure decreased the ignition delay value for all fuels. The reduction in injection pressure worsened the atomization of the fuel. This caused the mixture to deteriorate and combustion to start late. Accordingly, the reduction of injection pressure led to a significant increase in ignition delay. In the study of Fig. 6, the ID value of B100 was lower than that of diesel in all tests. The ignition delay is shortened due to the oxygen content of biodiesel. Moreover, since the cetane number of biodiesel is high, combustion starts earlier and ignition delay decreases. As can be seen in Fig. 6, the combustion duration of all test fuels are close to each other. Reducing the injection pressure worsened the atomization of the fuel and increased the ignition delay. That's why the burning started late. The burn time of all fuels was between 40 and 50 CA.

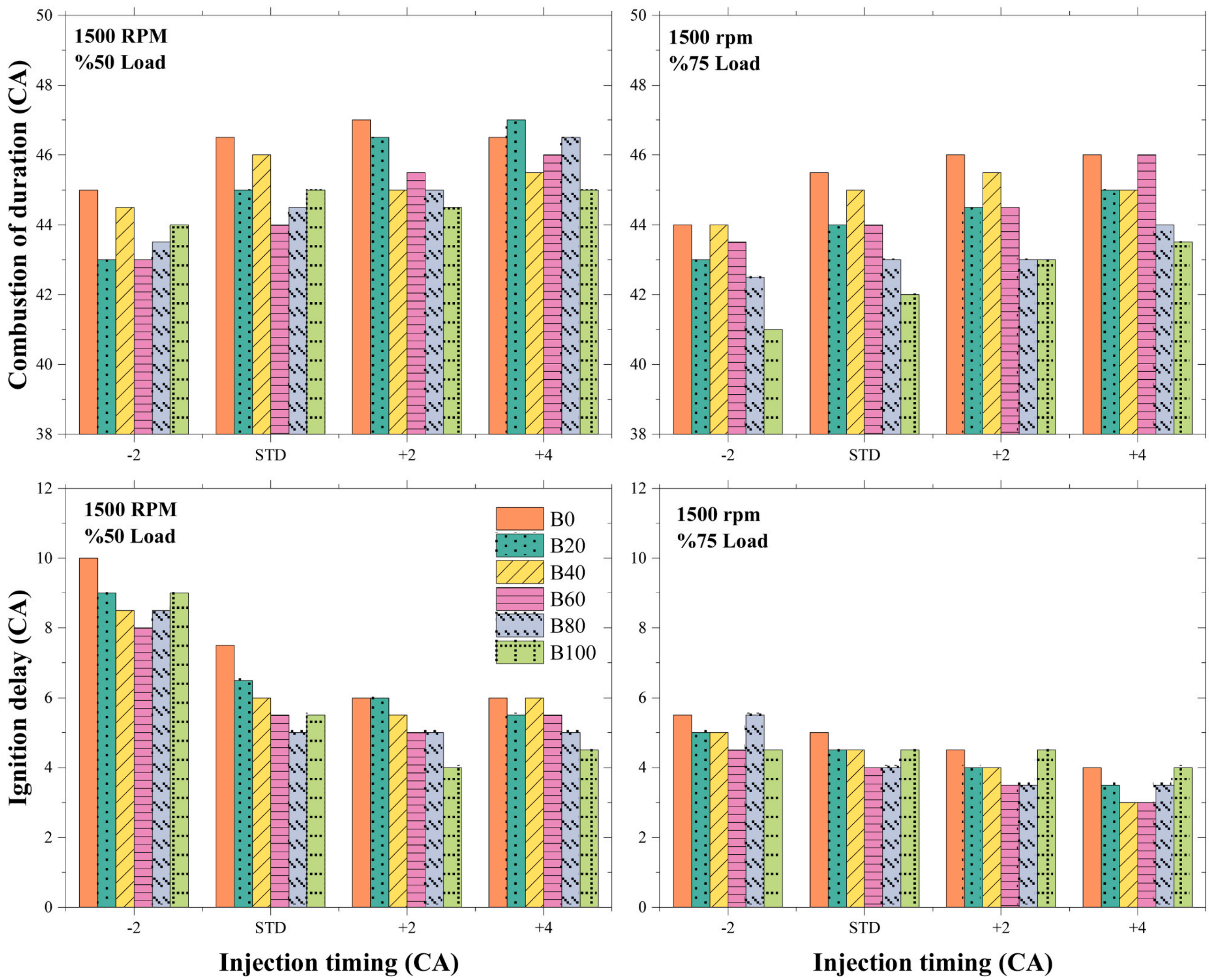

Fig. 5. Variations of ignition delay and combustion duration at different engine loads according to injection timing.

Combustion pressure and heat release rate (HRR)

Fig. 7 shows the changes in cylinder gas pressures and heat release rate (HRR) depending on injection timing at 50% and 75% engine load. An examination of the cylinder gas pressure curves showed that the regulated combustion phase occurred uniformly for all fuels. In tests with 50% and 75% engine load, the highest cylinder gas pressure values ranged from 3 to 9 CA. It was found that as the biodiesel concentration of blend fuels increased, the cylinder gas pressures reduced a little. For instance, at original injection timing and 50% engine load, the maximum cylinder gas pressure values and positions for B0, B20, B40, B60, B80, and B100 fuels were found to be 109.52 (6° CA), 108.11 bar (6° CA), 107.26 bar (5° CA), 107.34 bar (6° CA), 103.36 (6° CA), and 105.04 bar (7° CA), respectively.

The heat release rates started at a higher position with respect to the crank angle compared to diesel and their value persists at a lower level, it was discovered when the heat distribution curves of biodiesel and blended fuels were examined. For instance, the heat release rates of B0, B20, B40, B60, B80, and B100 fuels were calculated to be 104.86 J/ ° CA, 95.20 J/ ° CA, 98.30 J/ ° CA, 96.48 J/ ° CA, 91.17 J/ ° CA, and 88.79 J/ ° CA, respectively, at STD injection timing or 75% engine load.

The air/fuel mixture and atomization were harmed by the high viscosity of biodiesel. Additionally, the fuel's heating value was subpar when compared to diesel. These characteristics caused a shift in the maximum cylinder gas pressure from TDC, a longer combustion period, and lower pressure and heat release rate values. These fuel characteristics are assumed to be the reason for the general decreased in cylinder gas pressure and heat release rate to B0 as the concentration of biodiesel in the fuel mixtures increased. Under the STD injection timing operating conditions, all tested fuels demonstrated an increased in cylinder gas pressure and heat release rate values with increasing engine load.

Combustion temperatures raised as engine load increased. This creates an atmosphere where combustion can occur during successive engine cycles. A small drop in maximum cylinder gas pressures was noticed in the test engine when 2 °CA was reduced along with the reduction in injection timing. Although the variation in the cylinder gas pressures of the fuels was limited, the maximum cylinder gas pressure was found to occur further away from the TDC. As injection happens closer to TDC, combustion begins later as a result. The drop-in injection feed rate caused the heat release rate values for the diesel and biodiesel blends to vary when the injection timing was changed to −2° CA at 75% engine load. This is related to the fact that biodiesel has a shorter ignition delay time than diesel. Additionally, compared to diesel, the peaks of the heat release rate curves for biodiesel and its blends were wider. This can be explained by the fact that the evaporation curve of biodiesel is flatter than that of diesel.

When the injection timing was raised and the maximum pressure point moved closer to TDC, the maximum cylinder gas pressures typically increased as well. The burning period was increased by pushing the spray ahead of the initial injection timing, which caused the combustion

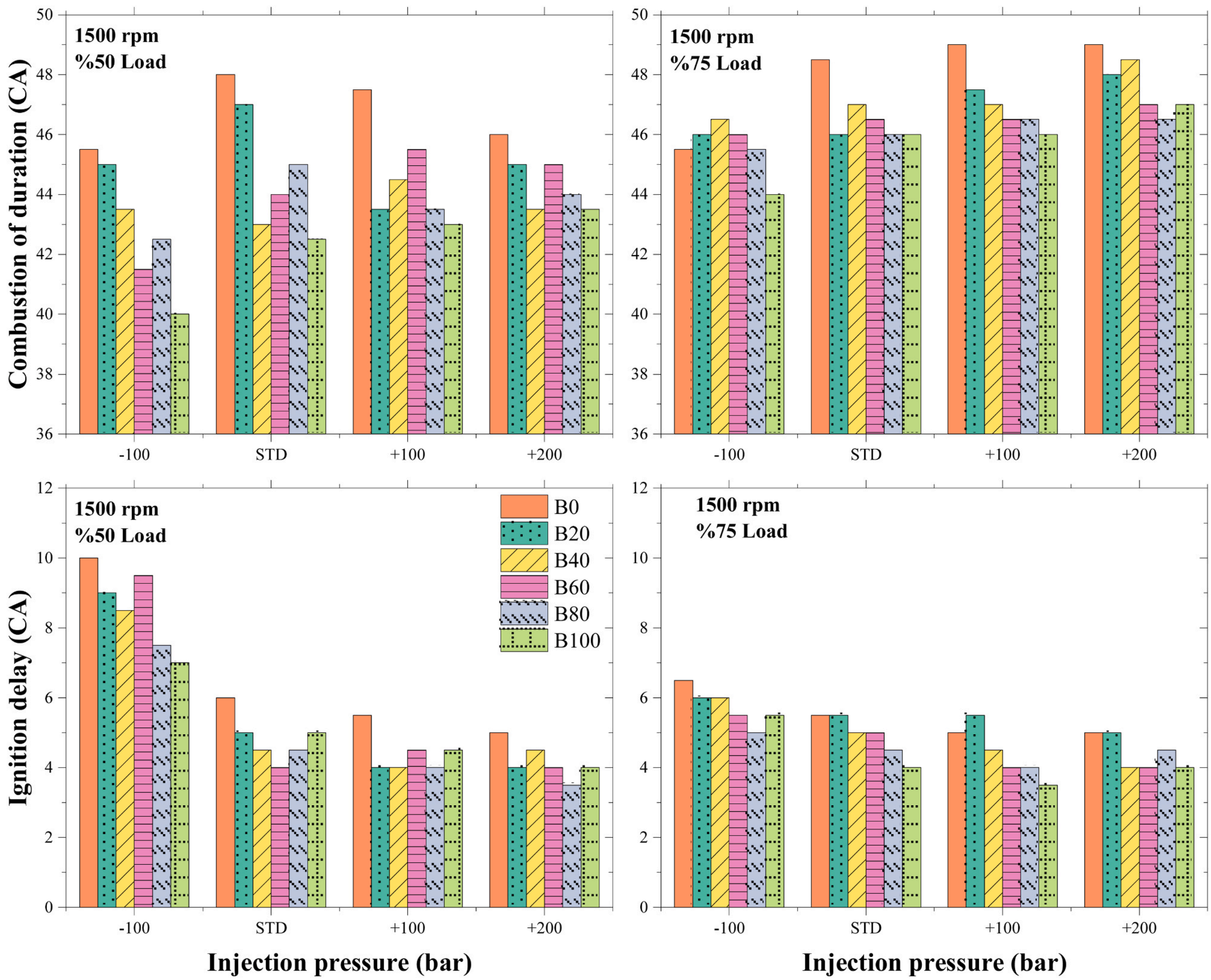

Fig. 6. Variations of ignition delay and combustion duration at different engine loads according to injection pressure.

to start sooner. In this way, the highest cylinder gas pressures were achieved. The position of the maximum cylinder gas pressure for biodiesel blends is closer to TDC. The oxygen content of biodiesel reduces the ignition delay, which results in the fuel burning more quickly than diesel. The use of electronically controlled injectors in the test system was thought to have a limit on the early injection effect that could be brought on by the high viscosity. It was found that the maximum cylinder pressure occurred across a larger range when using biodiesel and its blends than when using diesel. This was because diesel has a lower boiling point than biodiesel.

For all fuels except biodiesel, the heat release rate was achieved before diesel with an increase in flow rate. High volatility fuels can delay ignition as more heat is drawn from the combustion chamber during the evaporation stage. The ignition timing is delayed because of diesel's greater volatility when compared to biodiesel. As a result, biodiesel blends begin to emit heat earlier. The oxygen component of biodiesel also accelerates the combustion and combustion process. B80 and B100 fuels with significant biodiesel concentrations in the blend have lower heat release rates than diesel. This is because biodiesel has a low calorific value.

The variation of HRR and cylinder gas pressures with respect to injection pressure at 50% and 75% engine load is shown in Fig. 8. At all loads, it was observed that the cylinder gas pressures decreased as the amount of biodiesel in the fuel mixture increased. For example, the maximum cylinder gas pressure values and positions obtained with B0, B20, B40, B60, B80 and B100 fuels at STD injection pressure for 50% load are 109.52 (6 CA), 108.11 bar (6) CA), 107 respectively.26 bar (5 CA), 107.34 bar (6 CA), 103.36 (6 CA) and 105.04 bar (7 CA). This is because using biodiesel reduces the ignition delay time. Additionally, the air/fuel mixture is made worse by biodiesel's high density and viscosity characteristics. As a result, the maximum cylinder gas pressure and the combustion duration both widen in relation to TDC. Examining the HRR of biodiesel and mixed fuels reveals that they start later than diesel and maintain a lower level throughout. For instance, the HRR of B0, B20, B40, B60, B80, and B100 fuels is computed as 104.86 J/o CA, 95.20 J/o CA, 98.30 J/o CA, 96.48 J/o CA, 91.17 J/o CA, and 88.79 J/o CA, respectively, at the STD injection pressure for 75% engine load.

Because biodiesel has less volatility, the ignition starts, and HRR happen sooner. Additionally, biodiesel's high oxygen content makes the ignition and combustion stages happen quickly. Furthermore, since HRR depends on these two parameters, biodiesel's lower heating value and higher maximum cylinder gas pressure are not advantageous. Additionally, because biodiesel has a lower heating value than diesel, it has a lower HRR. Cylinder gas pressure and HRR increased for all fuels as injection pressure and engine load increased. The reason for the rise in cylinder gas pressures is the increase in fuel consumption per unit of time, which leads to an increase in temperature and pressure after combustion.

When Fig. 8 is examined, it is observed that the maximum cylinder gas pressures increase as the engine load increases at low injection

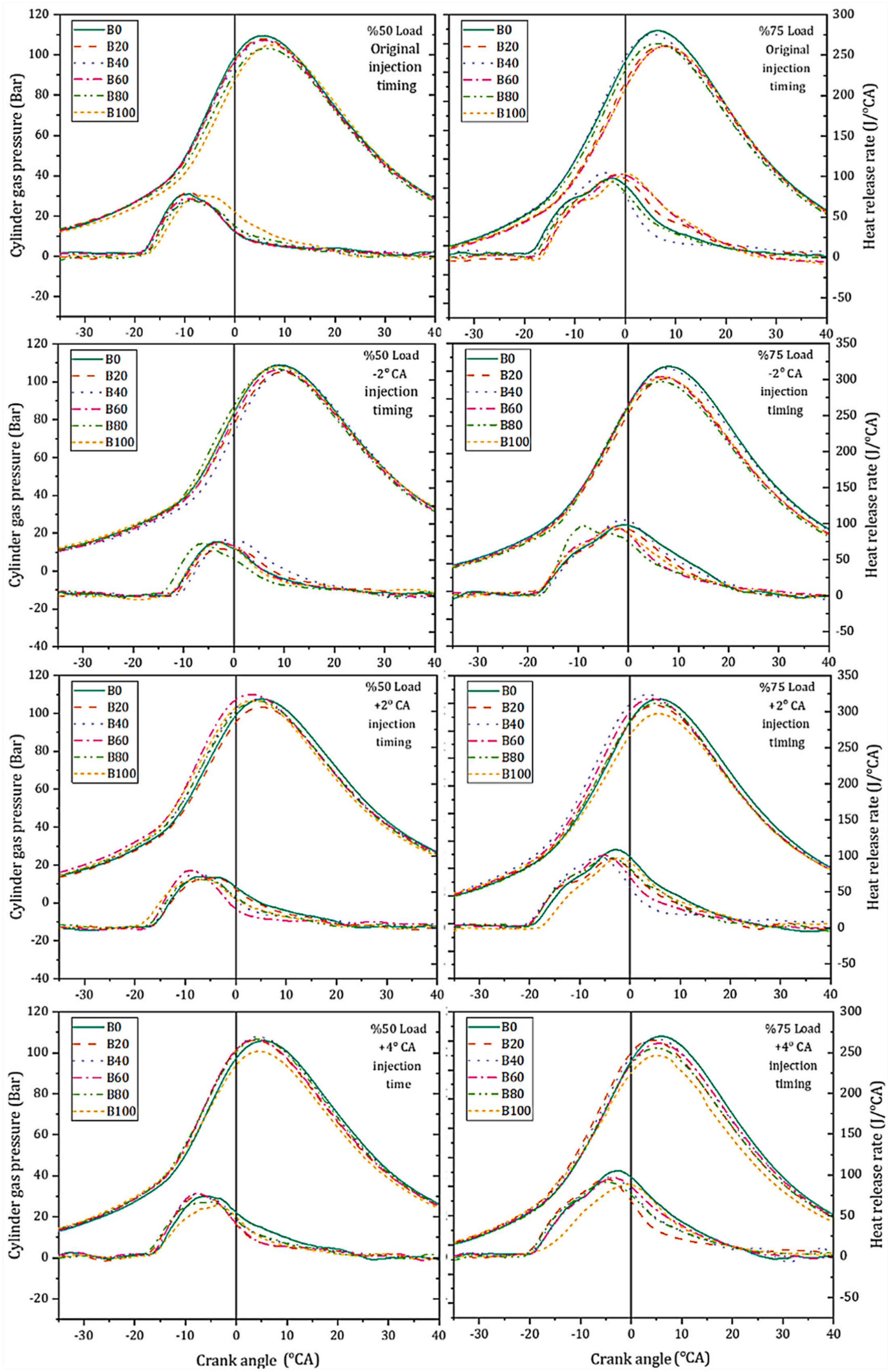

Fig. 7. Variations of cylinder gas pressure and HRR depending on injection timing at different loads.

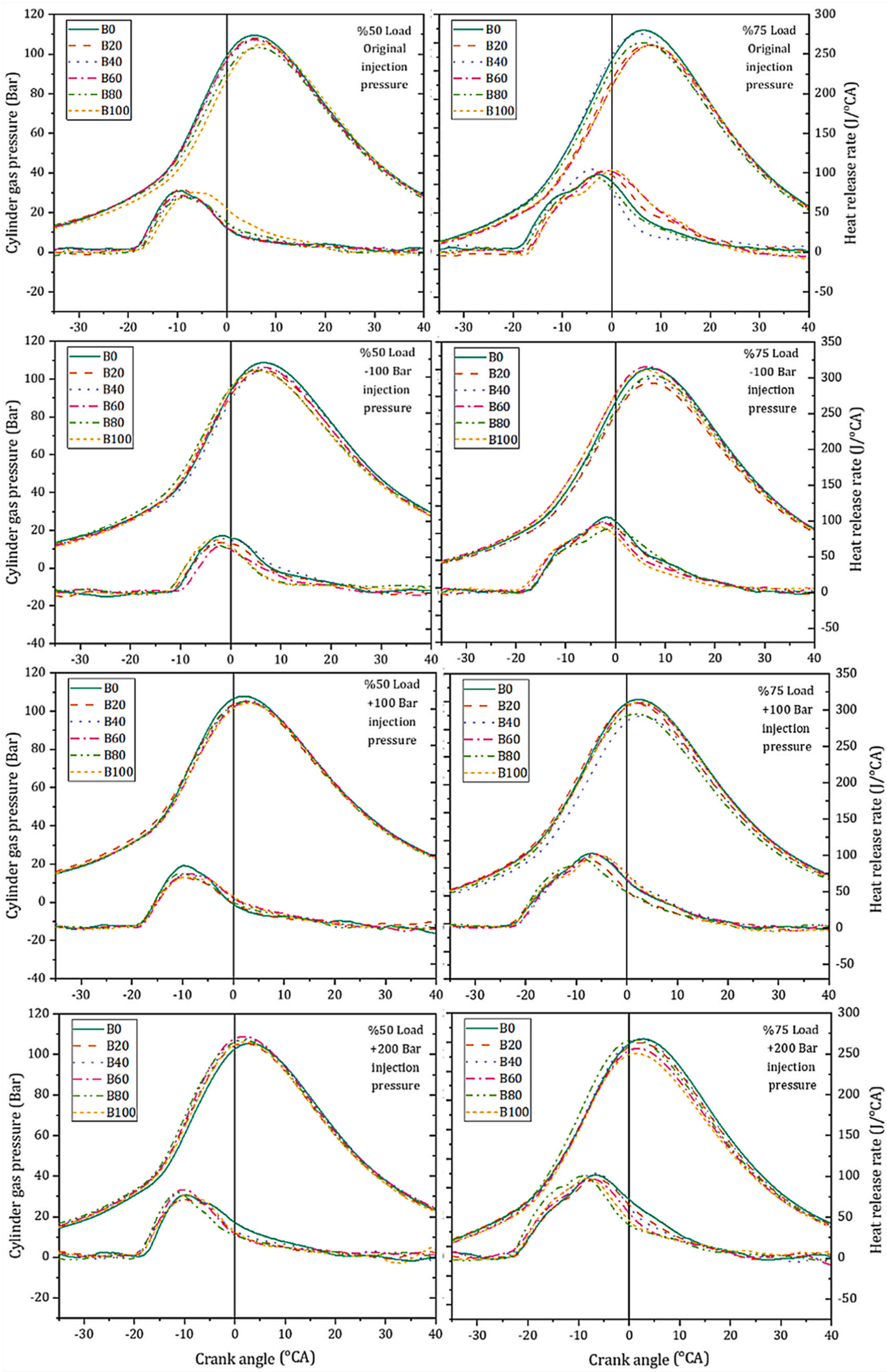

Fig. 8. Variations of cylinder gas pressure and HRR depending on injection pressure at different loads.

pressures. For instance, the maximum cylinder gas pressure values for the B0, B20, B40, B60, B80, and B100 fuels were as follows at the −100 bar injection pressure and 75% engine load: 160.71 (7 CA), 150.07 bar (7 CA), 153.33 bar (7 CA), 162.15 bar (6 CA), 155.27 (8 CA), and 159.33 bar (5 CA), respectively. For example, the HRR of B0, B20, B40, B60, B80, and B100 fuels is computed as 105.64 J/° CA, 97.38 J/° CA, 99.50 J/° CA, 98.30 J/° CA, 98.87 J/° CA, and 91.76 J/° CA, respectively, at the −100 bar injection pressure and 75% engine load. The increase in injection pressure caused two different trends in cylinder gas pressures. It was determined that the maximum cylinder gas pressures of B0 and B20 decreased, while B80 and B100 increased.

The maximum cylinder gas pressures for the biodiesel blends were higher than those for diesel. Particularly at high injection pressures, lower density fuels atomize more than is desirable. Fuels that evaporate in the combustion chamber before a particular temperature is reached have lower maximum cylinder gas pressures. The assumption is that the disadvantage of biodiesel's high viscosity. Furthermore, the higher injection pressure resulted in a greater proximity of the TDC to the maximum cylinder gas pressure. At higher injection pressure, biodiesel fuels experience their HRR sooner than diesel fuel does. Because of the higher injection pressure's ability to achieve complete atomization, the HRR of biodiesel develops early.

In general, it has been found that as the engine load increases, the maximum gas pressure in the cylinders increases and approaches the TDC. For instance, the maximum cylinder gas pressure values and positions for the B0, B20, B40, B60, B80, and B100 fuels are as follows at the +200 bar injection pressure for 75% engine load: 162.24 (3 CA), 159.61 bar (2 CA), 162.36 bar (2 CA), 155.78 bar (2 CA), 161.59 (1 CA), and 152.30 bar (1 CA), respectively. For example, the HRR of B0, B20, B40, B60, B80, and B100 fuels is computed as 101.72 J/o CA, 976.75 J/o CA, 104.01 J/o CA, 96.93 J/o CA, 100.667 J/o CA, and 97.96 J/o CA, respectively, at the −100 bar injection pressure for 75% engine load.

Conclusions

- Increasing the biodiesel content in the mixture resulted in a decrease in IMEP, combustion noise, ignition delay, and cylinder gas pressure.
- At an injection timing of −2 CA, IMEP, combustion noise, and burn duration decreased, while ignition delay increased. At an injection timing of +4 CA, cylinder gas pressures of all fuels increased, and the point at which maximum pressure occurred approached top dead centre.
- Ignition delay and combustion noise increased at an injection pressure of −100 bar. At an injection pressure of +200 bar, the cylinder gas pressure increased and the point at which maximum pressure occurred approached top dead centre. The increase in injection pressure caused the HRR to start before the diesel for biodiesel blends. In addition, the injection pressure of +100 bar and +200 bar resulted in an increase in IMEP, a decrease in combustion noise, and a delay.
- The disadvantage of biodiesel due to its high density and viscosity can be reduced by using biodiesel in high pressure CRDI engines.
- Improvements in IMEP, combustion noise, ignition delay were observed with the use of biodiesel blends. When biodiesel is used as an alternative fuel in CRDI engines; High injection pressure and high injection timing will improve combustion parameters.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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