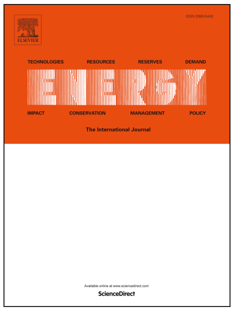

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Authors' contributions

Mustafa Vargün: Investigation, Methodology, Data processing, Writing – original draft.

Ahmet Necati Özsezen: Writing – review & editing, Conceptualization, Visualization, Supervision, Project administration.

Evaluation of the effect of the fuel injection phase on the combustion and exhaust characteristics in a diesel engine operating with alcohol-diesel mixtures

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Abstract

The purpose of this study is to investigate the effect of the fuel injection phase on the combustion and exhaust characteristics of a diesel engine using alcohol-diesel mixtures. Engine tests were performed by fixing many control parameters to provide homogeneous operating conditions for each cycle. In the result of the study, it was observed that the cylinder gas pressure was improved by advancing the fuel injection timing. Also, the heat release rate rose with an increased alcohol rate in blended fuels. In addition, it was determined that the chemical energy of the fuel is converted into heat energy in a shorter time with the use of alcohol-diesel mixtures. The ignition delay increased by 1.14 ^{o}CA with alcohol-diesel blends, while the ignition delay increased by 0.5 ^{o}CA with the advancing fuel injection time for all test fuels. Also, a significant decrease occurred in combustion duration with alcohol-diesel blends. The knocking tendency increased with the use of blended fuel, and at some point, values obtained with blended fuels were higher than the upper limit. It was monitored that the use of blended fuels caused a significant decrease in CO and NH_3 emissions. Moreover, it was detected that changes in the fuel injection timing effectively reduced CO_2 and NO_x emissions.

Key Words: Alcohol fuels; diesel engine; fuel injection phase; combustion; exhaust emissions.

1. Introduction

According to the expectation of the International Energy Agent, while fossil-based fuels, which are the first energy resources in list demand, was 13.7 billion toe (tonne of oil equivalent), it is anticipated that there will be an increase of around 30% to 19.3 billion toe. In 2016, while fossil fuels were used to supply 81% of energy consumption, fossil-based fuel usage is expected to decrease to 79% related to countries' policies by 2040. Also, International Energy Agent estimates that the use of renewable energy resources will go up [1], [2]. In this context, while the usage of fossil-based fuels as an energy resource is limited, regulations are published to encourage the usage of biofuels by consortiums, such as the Europe Union. On Dec 11th, 2018, renewable fuel use was encouraged by a directive published by the Europe Union [3]. According to this directive, it is planned that the minimum share, the contribution of advanced biofuels and biogas produced from the feedstock as a share of final consumption of energy in the transport sector shall be at least 0.2% in 2022, at least 1% in 2025 and at least 3.5% in 2030. The regulation, which was published in an official newspaper in Turkey, obligates that ethanol, produced from local agricultural materials, must be added to imported fossil fuel at least 3% (Vol.) [4], [5]. In some studies, [6] life-cycle analysis of transport systems has also been carried out for regions outside of Europe.

Ethanol is a simple alcohol that can quickly dissolve in water and other organic compounds [7]. Biofuel can ensure long-term engine durability and the materials of diesel engines [8]. One of the most critical problems of ethanol as a fuel is phase separation, it may occur immediately when ethanol and fossil-based diesel fuels (FBDF) are blended at atmospheric conditions. While ethanol-FBDF are easily separated below 10°C, dry ethanol mixes easily with FBDF in high ambient temperatures. As shown by Liu et al. [9], in the diagrams of the ternary liquid–liquid phase, moisture content and temperature have an essential effect on the stability of the mixture, along with the need for co-solvent to prevent phase separation. Increasing water content in ethanol-FBDF blends causes ethanol to separate from diesel fuel at low mixing ratios [10]. Polar molecules in ethanol and water can form hydrogen bonds [11]. This lowers the upper limit of blending alcohols with low carbon numbers to fossil-based fuels without using a co-solvent [7], [12]. As the ethanol content of the fuel mixture increases, it was determined [13], [14] that the phase separation time occurred faster.

In the literature, some long-chain alcohols such as *iso*-propanol, *n*-propanol, *n*-butanol are used to prevent the phase separation between ethanol and fossil diesel and to be homogeneity in the mixture. In our study, the test results showed that adding 2-butanol (or butan-2-ol) to the fuel mixture slows the phase separation between fossil diesel and ethanol. Some researchers stated [10], [15] that using iso-propanol, *n*-propanol, iso-butanol, and *n*-butanol increases the rate of ethanol usage in ethanol-diesel mixtures by using additives preventing phase separation and also makes ethanol-diesel blends more stable. This is because alcohols with higher carbon numbers become less polar with longer non-polar hydrocarbon chains [16].

Depending on the engine load and mixing method, specific proportions of alcohol fuels can be used in compression ignition engines in addition to diesel without any modification [17]–[19]. One of the most important properties of alcohol fuels is having a higher cooling effect and more oxygen content than fossil diesel fuels. The properties of ethanol compared to fossil fuels, such as high flame rate, high evaporation temperature, and high-octane number, allow higher compression ratio and shorter burning time in the cylinder [20], [21]. Studies have shown that using up to 10% ethanol in diesel-ethanol mixtures does not cause a significant change in engine performance compared to fossil-diesel fuel [22]. It was observed that combustion improves with the use of alcohol by creating a mixture with fossil diesel fuel [15], [23]. It was noticed that using low amounts of alcohol fuels with a mixture of fossil diesel reduces exhaust emissions without affecting engine performance. In the use of mixtures with high alcohol content, when the same energy input has been provided, fuel consumption increases with alcohol-diesel blends, since the heating value of alcohol fuels is lower than that of neat fossil diesel. In such studies, many researchers [24]–[26] stated that the use of alcohol-diesel blends resulted in a decrease in unburned HC and CO emissions and an increase in cylinder gas pressure. These results indicated that combustion performance in diesel engines increases with the use of alcohol-diesel blends. The cetane number, oxygen content, and viscosity of the fuel are the primary factors affecting the ignition delay [27], [28]. Due to the lower cetane number of ethanol than the fossil diesel, the diesel engine’s knock tendency increases with the ethanol rate in the mixture. In addition, as the ethanol ratio level increases in ethanol-diesel blends, ignition delay time also increases [29], [30].

Fuel injection timing is one of the most crucial parameters to control performance, combustion development, and emissions in an internal combustion engine [31], [32]. Guedes et al. [30] stated that the maximum cylinder pressure increased by 9% when the fuel was injected earlier (advancing), and the specific fuel consumption decreased by 4% just by adjusting the start of injection (SOI) timing on a Motoren Werke Mannheim brand 4.10 TCA model diesel engine. The maximum indicated mean effective pressure was obtained at the earliest injection progression. By changing the SOI timing, it was seen that the nitrogen oxides (NO_x) and carbon dioxide (CO_2) exhaust emissions were decreased, and the optimum performance and combustion values were obtained with the study [33]. Li et al. [34] investigated the performance, combustion, and emission characteristics of a diesel engine using isopropanol-butanol-ethanol-diesel (15% isopropanol-butanol-ethanol 85% diesel (IBE15) and 30% isopropanol-butanol-ethanol 70% diesel) and pure diesel fuels. In the study, pilot (25, 30, 35, 40, and 45 ^{o}CA BTDC) and main (6, 9, 12, 15, and 18 ^{o}CA BTDC) injection times were changed, and tests were performed. As the main injection time in all test fuels was taken from 6 ^{o}CA to an angle of 15 ^{o}CA, carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions decreased while CO and UHC emissions increased at an angle of 18 ^{o}CA. When compared to diesel fuel, it was observed that the ignition delay increased as the isopropanol-butanol-ethanol ratio in the blend increased at all main injection times. Liu et al. [35] have used fossil diesel fuel and a different proportion of ethanol-diesel fuel blends (E10 and E20) and applied different fuel injection strategies (2.5 - 22.5 ^{o}CA BTDC) to investigate the effect on combustion and exhaust emission in a four-cylinder diesel engine. It was observed that the cylinder gas pressure increased by advancing the injection timing from the top dead center (TDC). While the maximum ignition delay time for all fuel types was obtained at 2.5 ^{o}CA BTDC, at the same time, as the ethanol ratio in the blend ratio increased, compared to the fossil diesel fuel, the ignition delay time increased, and the combustion time decreased. Vargün et al. [36] investigated the effect of alcohol-diesel blends on performance, combustion, and exhaust emissions in a diesel engine with common rail fuel injection system. It was stated that alcohol-diesel fuel blends significantly reduced combustion duration but prolonged ignition delay. In addition, it was reported that the cylinder gas pressure was improved with the use of fuel blends. Duan et al. [37] examined the effect of injection timing on combustion parameters in a diesel engine using ABE fermentation products and fossil diesel fuel mixtures. They observed that the cylinder gas pressure, the heat release rate, the mean cylinder pressure, and NO_x emissions increased with the earlier SOI timing. In another study, Li et al. [38] reported that early injection timing increases the ignition delay and premixed combustion percentage, with combustion occurring earlier than the top dead center, resulting in higher peak pressures and temperatures in the cylinder.

As mentioned in the above studies, phase separation occurs quickly due to the density differences between ethanol and fossil-based diesel fuel mixtures. In the literature, various methods are proposed to prevent phase separation, such as using solvents, fumigation, heating, micro-emulsions, mechanical mixing, etc. One of the aims of this study is to demonstrate the effectiveness of the joint use of ethanol and butanol. In this study, ethanol-butan-2-ol-FBDF blends were chosen as alternative fuels, and the start of the fuel injection phase was selected as the engine parameter. In order to be compared fuel types with each other, the homogeneous charge conditions in the combustion chamber were provided by the fixed start of injection timing, the fixed fuel amount every cycle, the fixed intake manifold temperature, and the fixed intake air pressure. After stable test conditions were provided, it was experimentally investigated both the fuel type and the start of injection timing influence the combustion and exhaust emission values. As a result of this study, it was seen that the start of injection timing has a significant effect on CO_2 and NO_x emission formations. In contrast, the amount of alcohol in the mixture significantly impacts CO and NH_3 emission formations.

2. Material and methods

2.1. The preparations of test fuels

In this study, FBDF complied with EN590 standards were supplied from a national fuel station in Turkey. The ethanol and butan-2-ol (2-butanol) are products of J.T. Baker and Merck, respectively. In the experiments, two different fuel blends were prepared, and the fuels were named according to the ratio of the ethanol and 2-butanol in fuel blends. To prevent the phase separation between ethanol and FBDF, 2-butanol was added in a 20% volumetric ratio of ethanol in fuel blends. The percentage distribution of the blend fuels is as follows: In the content of E5B1; contains 5% ethanol + 1% butan-

2-ol + 94% FBDF, and in E10B2; there is 10% ethanol + 2% butan-2-ol + 88% FBDF by volume. The properties of the fuels used in the experiments are given in Table 1. Fuel properties are obtained from FBDF and alcohol manufacturers.

Table 1. Fuel properties of FBDF, Ethanol, and 2-Butanol

Properties	**FBDF**	**Ethanol (C_2H_6O)**	**2-Butanol ($C_4H_{10}O$)**
Purity	-	≥ 0.99	≥ 0.99
Density (kg/m^3)	820 – 845	790	805
Kinematic viscosity (mm^2/sec, 40^{o}C)	2.0 – 4.5	1.13	3.1
Lower heating value (MJ/kg)	42.6	26.7	34.4
Heat of evaporation (kj/kg)	250	920	670
Boiling point (^{o}C)	160	78	102
Melting point (^{o}C)	-	-114.5	-115
Flashpoint (^{o}C)	≥ 55	12	20,5
Water content (%)	0,020	≤ 0.2	≤ 0.2
Cetane number	≥ 51	-	-
Auto-ignition temperature (^{o}C)	≈ 210	361	405

The literature explained that *n*-butanol is a better co-solvent than *iso*-butanol and 2-butanol for ethanol-FBDF fuel blends based on the phase behavior in the ternary system [39], [40]. On the other hand, in another study [41], it was reported that to mix water and isomers of butanol, the use of ethanol was suggested. In the study by Jin et al [39], the usability of butanol and its derivatives as co-solvents was demonstrated based on the ternary phase diagrams. As a result of that study, it was shown that the straight chain butanol as a co-solvent has a superior solubility performance in the system than the branched chain ones. While *n*-butanol is a popular co-solvent in ethanol-FBDF blends [42], few studies reported on 2-butanol and iso-butanol [43]. In this study, 2-butanol was used as a co-solvent to investigate the effects of co-solvent on the solubilities between FBDF and ethanol (C_2H_5OH). The fuel blends were kept in glass containers with no contact with air and observed for a long time. After fuel observation, significant phase separation was seen in about 20 minutes in anhydrous ethanol-FBDF mixtures formed without adding 2-butanol. However, more than 240 hours of observations were made on fuels formed by adding 2-butanol up to 20% of the ethanol ratio in mixed fuels to ethanol-FBDF mixtures and the phase separation was not seen. Therefore, it can be said, the use of 2-butanol as a co-solvent between ethanol and FBDF blends in the future is a good option for research.

2.2 Engine test setup and conditions

In this study, engine tests were carried out at 1600 rpm (±2 rpm) constant engine speed and 50% engine load (±1 Nm) by changing the SOI timing of a single-cylinder diesel engine which has 4-stroke, supercharged (±10 mbar), water cooling and equipped with a common rail direct injection fuel injection system. The main specifications of the diesel engine are given in Table 2. Fuels were first injected into the cylinder at 10.4 °CA BTDC, which is the main SOI timing of the engine for 1600 rpm specified by the engine manufacturer, and then by changing the main injection timing ± 2 °CA in accordance with the injection strategies. The received data was interpreted regarding the standard SOI timing and pure FBDF.

Table 2. Engine specification

Engine Type	Single Cylinder – 4 stroke
Fuel System	Common Rail Direct Injection – 1800 bar
Cylinder Volume	1205 cm^3
Valves	3 (2 intake – 1 exhaust) – (OHV)
Max. Cylinder Pressure	190 bar
Max. Engine Speed	2500 rpm
Max. Power	50 kW
Max. Torque	160 Nm
Bore	106.5 mm
Stroke	127 mm
Compression Ratio	16.14

The main components of the engine test bench are an eddy current dynamometer (error ±0.1%), fuel injection system (including common rail, injector, fuel filter, and fuel pump), and engine control unit. Oil and cooling pumps are the parts of the engine test bench. The engine test bench stabilized the oil and cooling water (error ±1K%) conditions. Hence parasitic loads, other than fuel pump, are eliminated. The change of the SOI timing was controlled by the drive system that allows map change by connecting to the engine control unit. Since the engine control unit is open to the user, the SOI timing, the main injection amount, and the rail pressure map can be controlled, so its effects on the engine can be observed instantly. The engine is equipped with an in-cylinder pressure measuring device to detect the cylinder gas pressure level. The interface of the control system with the test cell and eddy current dynamometer is schematically shown in Fig. 1.

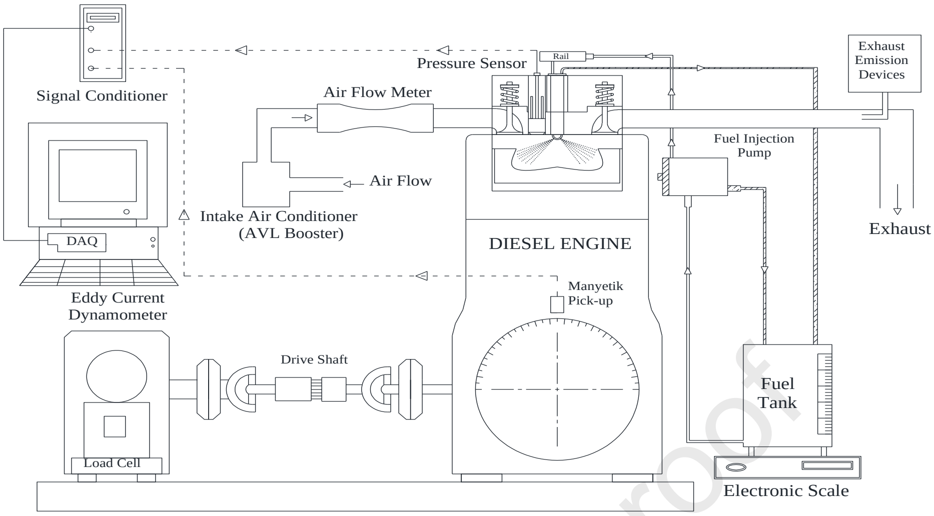


Fig.1. Schematic view of the experiment setup

While performing these tests, the power measurement was made as described in ISO EN 14396, with requirements for exhaust emission tests in accordance with ISO EN 8178. In the experiments, until the engine’s oil temperature reached 90°C, the engine was operated with diesel fuel, thus allowing the engine to come to stable conditions. During the engine tests, air intake pressure was adjusted at 240 mbar, air intake temperature 25°C, fuel temperature 20°C, oil temperature 90°C, and cooling water temperature 70°C. In addition, the data was collected at 0.1 °CA (error ±0.1 ^{o}CA) resolution, and the total cycle number was brought to average. Information summarizing the test conditions is given in Table 3.

Table 3. Fixed engine input parameters

Input Parameters	**Unit**	**Value**
Engine speed	*rpm*	1600
Fuel blends	*Vol.*	FBDF, E5B1, E10B2
Engine load	*%*	50
Engine coolant temperature	*°C*	70
Engine oil temperature	*°C*	90
Air intake pressure	*kPa*	24
Air temperature	*°C*	25
Total injected fuel quantity	*mg/stroke*	45
Main SOI timing	*BTDC °CA*	10.4
The change of SOI timing	*BTDC °CA*	± 2

For each fuel used in the tests, the fuels were sprayed at 10.4 °CA BTDC at the main SOI timing, and then the SOI timing was changed by ± 2 °CA. In addition, for each test injection condition, the duration of injection was 1.4 ms. During the engine tests, Bosch CP4 (with the product number of 0445010509) was used. The injection phases are shown in Fig. 2.

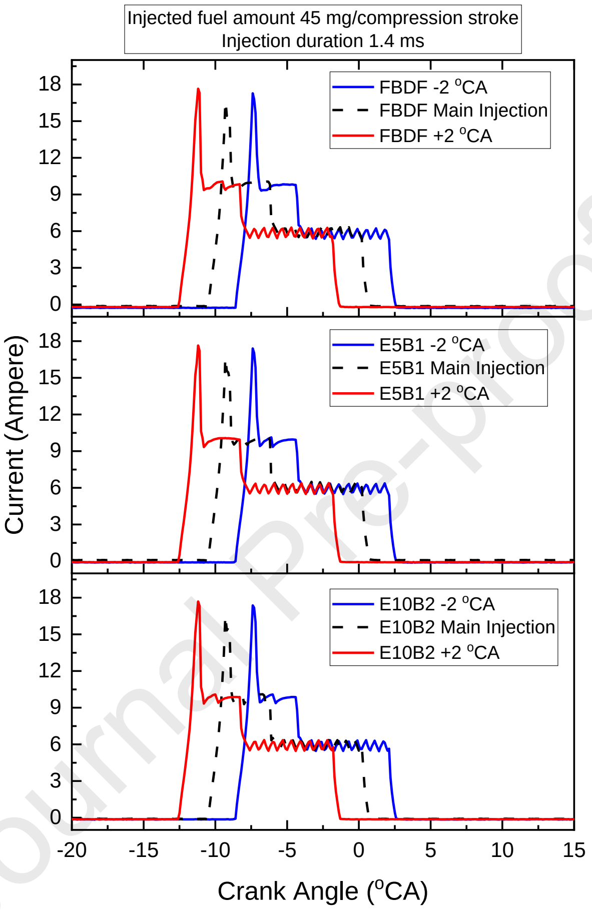


Fig.2. The phases of fuel injection

Work of the engine system is fully integrated with the dynamometer and the equipment of the test cell, and all systems are operated with a controller. In the engine tests, mass air flow was measured using AVL brand ultrasonic air flow meter (error <±0.25%) with kg/hour scale. Specific fuel consumption was scaled in volumes from g/kWh unit with the AVL-735 model measuring device (error <±0.15%) and the data was collected with a precision of 1gr. In addition, CO_2, CO, NH_3, and NO_x emission measurements were made by connecting the AVL-FTIR emission device to the test cell. Exhaust emission values are calculated by comparing the instrument signal with the signal produced using a calibration gas of precisely known concentration. The information about the exhaust emission measurement methods is given in Table 4.

Table 4. The exhaust emission measurement methods

Measuring values	**Measurement method**	**Range**	**Accuracy**
CO	Non-dispersive infra-red (NDIR)	0-3000 ppm	≤ ±0.5%
CO_2	Non-dispersive infra-red (NDIR)	0-20%	≤ ±0.5%
NH_3	Laser diode spectrometer (LDS)	0-15 ppm	≤ ±3%
NO_x	Chemiluminescence Detector (CLD)	0-10000 ppm	≤ ±1%

2.3. Uncertainty analysis

The uncertainty analysis describes the degree of goodness of a measurement or experimental result. N successive measurements of X (CO, NO_x etc.), and the mean value of $\bar{X}$ is calculated from Eq.1.

$$\bar{X} = \frac{1}{N}\sum_{i=1}^{N} X_i \quad (1)$$

The standard deviation (S_x) was calculated for each measurement value with Eq.2., and it is an estimate of the influences on the measured variable X of all the elemental error sources that varied during the measurement period [44]. The calculated uncertainty values for each variable are given in Table 5.

$$S_x = \left(\frac{1}{N-1}\sum_{i=1}^{N}(X_i - \bar{X})^2\right)^{1/2} \quad (2)$$

Table 5. The experimental uncertainties

Measuring Value	**Uncertainties**
Engine Speed	< 1%
Temperature	< 1%
IMEP	0.68
BSFC	1.1%
CO	2.84%
CO_2	1.1%
NH_3	4.6%
NOx	2.07%

In this study, the engine tests were carried out at 50% pedal opening position at the same engine speed. Since the alcohol content in the mixture is a maximum of 12%, the variations in the fuel consumption of the engine and the indicated mean effective pressure remained below 1.1%. The calculated standard deviations also include such variations.

3. Result and Discussion

3.1. Brake specific fuel consumption (BSFC)

In this study, the total amount of injected fuel in each cycle is 45 mg/stroke. The amount of energy released in the cylinder differed according to the alcohol added to the FBDF fuel. Therefore, the cylinder gas pressure of the engine has changed in each cycle. This change has revealed a change in the *BSFC* values. Fig.3 shows the change in *BSFC* values according to fuel type and the fuel injection phase.

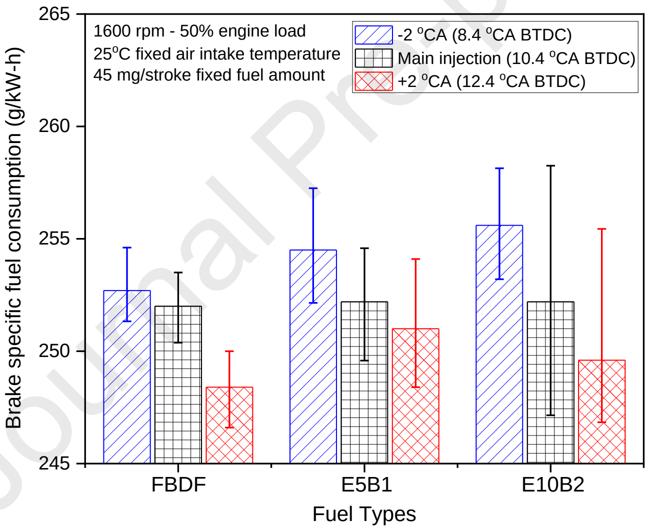


Fig.3. The effect of the fuel injection phase on BSFC

At the main SOI timing, the minimum *BSFC* was monitored with FBDF use, while the maximum *BSFC* value was measured with E10B2 use. The maximum *BSFC* values for all fuels were obtained by retarding the SOI timing, and the minimum *BSFC* values for all fuels were determined by advancing the SOI timing, compared to the main SOI timing. In literature, similar *BSFC* trends were observed by some researchers [45], [46] who stated that change in *BSFC* value depended on the lower heating value of used alcohol fuel (see Table 1). The minimum *BSFC* value obtained using FBDF is based on having a greater lower heating value of the fuel compared to blends fuels. Considering the *BSFC* values in the error analysis, it was seen that the error range was lower in the use of FBDF, while the error rate increased with the addition of ethanol-butan-2-ol in the fuels.

3.2. Combustion characteristics

The combustion phenomenon is the most important factor that significantly affects the thermal efficiency of an internal combustion engine. Wiebe function [47] was used to describe the fraction of fuel burned. This study calculated the mass fraction burned (MFB) values to explain the rate of conversion of chemical energy of fuel to thermal energy.

$$MFB = \frac{m_b}{m_f} = 1 - exp\left[-a\left(\frac{\theta - \theta_{SOC}}{\Delta\theta_{DOC}}\right)^{m+1}\right] \tag{3}$$

In Eq.3, θ_{SOC} refers to the crankshaft angle at the start of combustion (SOC) and θ refers to the instantaneous crank angle, while $\Delta\theta_{DOC}$ $(\theta_{EOC} - \theta_{SOC})$ refers to the duration of combustion (DOC). SOC is accepted as the point where the heat release rate is positive. AVL Concerto software was used to calculate the combustion parameters; such that HRR and SOC. This formulation is calibrated by 2 factors: m indicates the formation factor and a indicates the yield factor. MFB stands for the mass fraction of the burned, m_b stands for the mass of fuel burned and m_f represents the amount of fuel in the cylinder.

The combustion characteristics obtained based on the calculations are given in Table 6. MFB values are named as the crank angle point of 50% fuel mass burned (CA50), and the crank angle point of 90% fuel mass burned (CA90) is also accepted as the end of combustion. The difference between SOC and CA90 is called combustion duration. CA50 represents where the MFB is 50%, which means 50% of the injected fuel is converted to energy. The difference between the SOI and SOC timing is known as the ignition delay (ID).

Table 6. Combustion characteristics

Change in SOI Timing	Fuels	SOC	CA50 [°CA ATDC]	CA90 [°CA ATDC]	ID [°CA]	MFB50 [°CA]	DOC [°CA]
(-2°CA)	FBDF	0.7 °CA BTDC	12.9	39.6	7.7	13.6	40.3
	E5B1	0.08 °CA ATDC	11.6	36.5	8.48	11.52	36.42
	E10B2	0.5 °CA ATDC	11.3	35.8	8.9	10.8	35.3
Main	FBDF	2.4 °CA BTDC	10.8	38.1	8	13.2	40.5
	E5B1	1.2 °CA BTDC	9.6	34.9	9.2	10.8	36.1
	E10B2	1.1 °CA BTDC	9.2	34.5	9.3	10.3	35.6
(+2°CA)	FBDF	4.2 °CA BTDC	8.3	36	8.2	12.5	40.2
	E5B1	3.1 °CA BTDC	7.2	33.4	9.3	10.3	36.5
	E10B2	3 °CA BTDC	7	32.5	9.4	10	35.5

Fig. 4 shows the use of alcohol-FBDF fuels and the effect of SOI on ignition delay. Generally, it was seen that the addition of alcohol fuels to the FBDF prolonged the ID at all SOI. At the main SOI, ID with FBDF was determined as 8 °CA, but it caused the ID to be extended up to 9.3 °CA when the alcohol fuel ratio was 12% in the blended fuel. Also, the alcohol fuels are blended to FBDF, and the ID increases due to the high evaporation latent heat and low cetane number of alcohols [48], [49]. In addition, it was found that advancing the SOI from the TDC for all fuel types prolongs the ID. The shortest ID values were found to be 7.7 °CA for FBDF, 8.48 °CA for E5B1 and 8.9 °CA for E10B2, with the fuels injected at 8.4 °CA BTDC. The prolongation of the ID with an earlier SOI can be explained by the lower temperature and pressure in the cylinder [50], [51] .

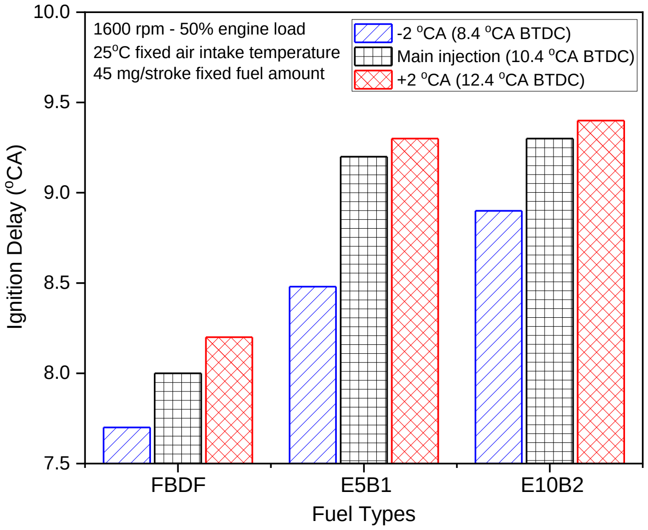


Fig.4. The effect of the fuel injection phase on ignition delay

The effect of SOI and blended fuels on MFB50 can be seen in Fig. 5. As a result of controlling the point where 50% of the fuel in the cylinder is burned, which is one of the essential combustion parameters, the control of fuel consumption and emissions [52]. At all fuel injection start times, an increase in the rate of alcohol in blended fuels shortened the time of point where MFB50 was obtained. Among the test fuels, the longest MFB50, at 8.4 °CA BTDC SOI was seen with FBDF as 13.6 °CA and at the same SOI, E5B1 and E10B2 caused a decrease MFB50 to 11.52 °CA and 10.8 °CA, respectively. In addition, compared to MFB50 values determined at main SOI, from the longest MFB50 to the shortest MFB50 sorted as FBDF, E5B1, and E10B2 (13.2 °CA, 10.8 °CA, and 10.3 °CA, respectively). Reduction in MFB50 with the use of blended fuels can be explained the amount of oxygen that alcohol fuels have to provide rapid combustion in the cylinder. Moreover, compared to retarded SOI, advanced SOI for all test fuels caused a significant reduction in MFB50. The shortest MFB50 was obtained using fuel containing a maximum alcohol ratio as 10 °CA at BTDC 12.4 °CA. It is thought that decrease of MFB50 is because of having better combustion in cylinder with advanced SOI.

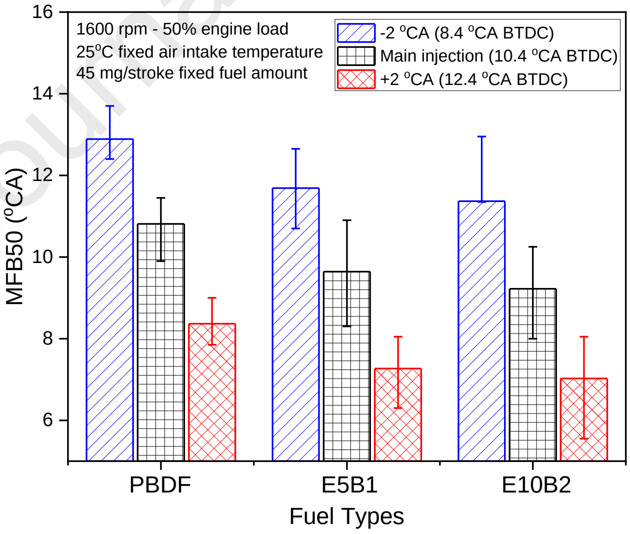


Fig.5. The effect of the fuel injection phase on MFB50

Fig. 6 shows the use of alcohol-FBDF fuels and the effect of SOI on DOC. In addition, a significant decrease trend was detected in DOC values with blended fuels. The longest DOC was obtained in the main SOI with FBDF as 40.5 °CA. When the fuels were injected at BTDC 12.4 °CA SOI, the shortest DOC was found to be 35.5 °CA with E10B2, while using E5B1 and FBDF, 36.5 °CA and 40.2 ^{o}CA were obtained, respectively. This is thought to be due to the fact that the amount of oxygen in alcohol fuels accelerates the combustion in the cylinder [36], [53]. Moreover, SOI being retarded or advanced, there was not much change in DOC, and it was determined that the DOC values were close to each other for the same fuel type.

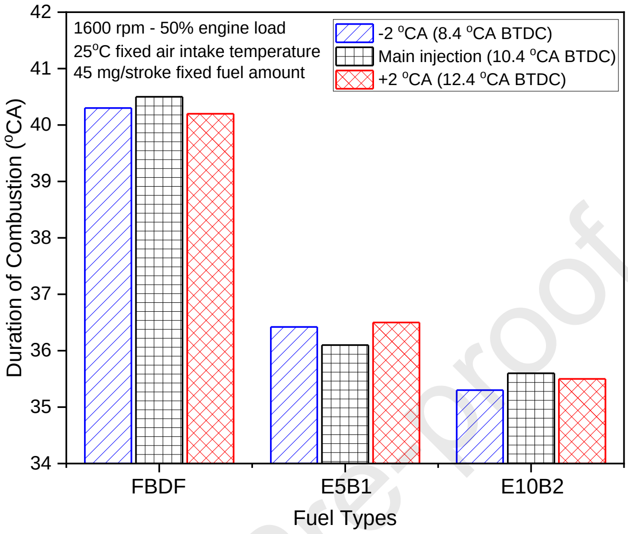


Fig.6. The effect of the fuel injection phase on DOC

The pressure rise rate (PRR) expresses the pressure exerted on the piston at each crank angle by the pressure formed after the combustion event in the cylinder. Generally, an increased pressure of more than 10 bar per crank angle indicates the engine knocking [54], [55]. As seen in Fig. 7, it was determined that the increase in the alcohol fuel ratio in the blended fuels causes an increase in the PRR at the same injection start timing. At the main SOI, the maximum PRR was 6.83 bar/^{o}CA with FBDF, 9.15 bar/^{o}CA for E5B1 fuel and 11.74 bar/^{o}CA for E10B2. It is thought that the increase in ID as a result of the use of blended fuels causes more fuel to burn together and the maximum PRR increases, as the reason for the increase in the knocking tendency of the use of alcohol fuels.

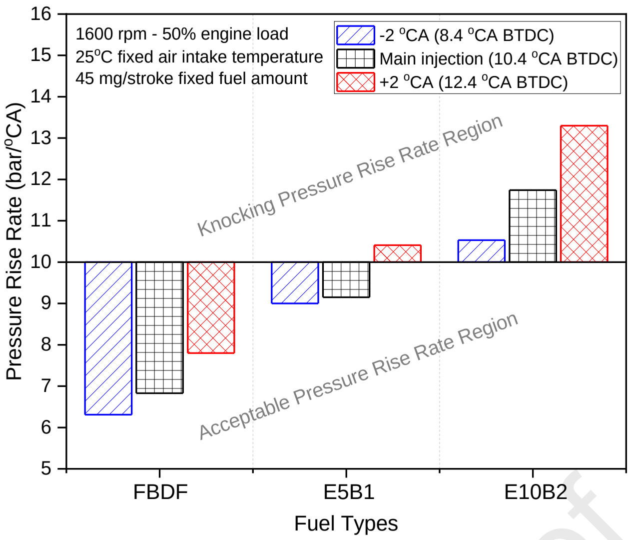
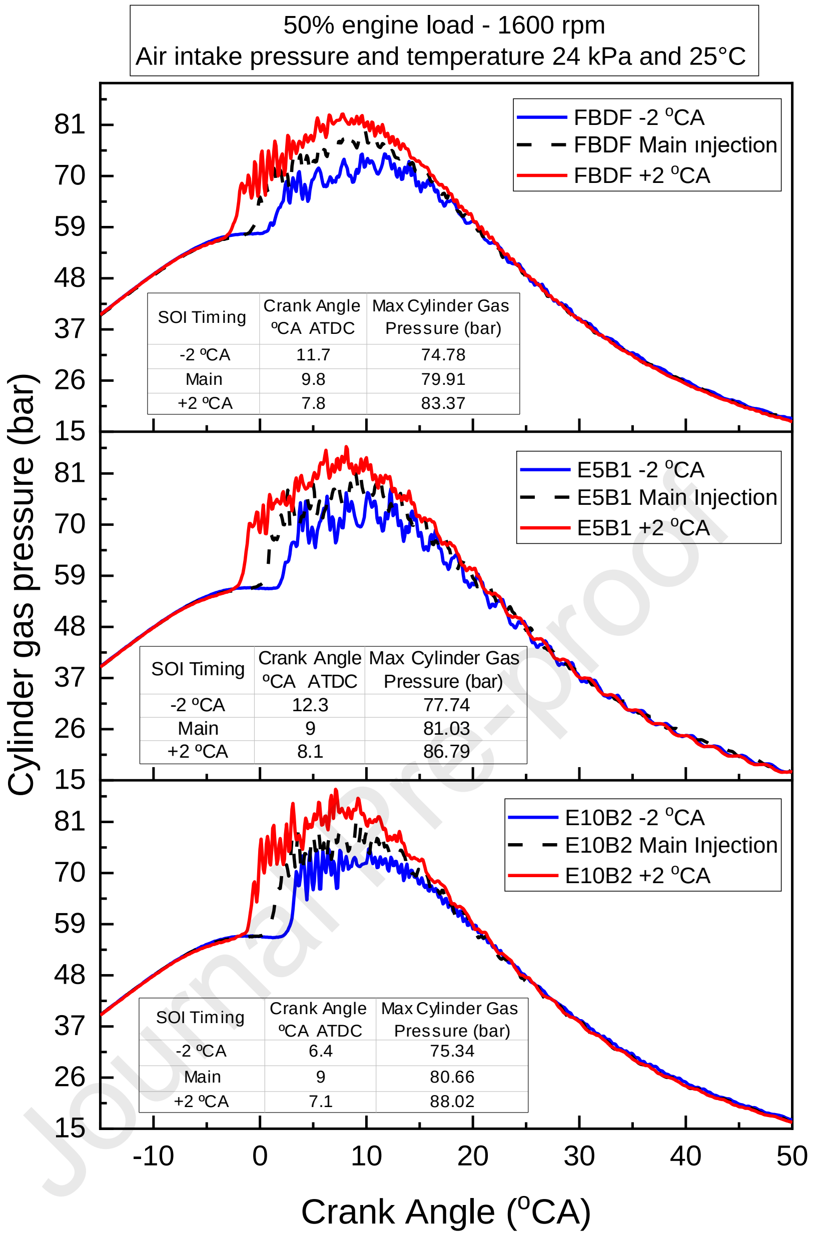


Fig.7. The effect of the fuel injection phase on PRR

Retarding the SOI for all fuel types was seen to control the maximum PRR, while advancing the injection start timing caused an increase in maximum PRR and the engine knocking tendency. It was determined that the use of FBDF and E5B1 kept the maximum PRR at acceptable values by retarding the ignition start timing (6.31 bar/°CA and 9 bar/°CA, respectively), while the maximum PRR was found to be 10.5 bar/°CA in the use of E10B2. It is thought that maximum PRR can be controlled because ID tends to shorten due to retarding the fuel injection start timing.

As seen in Fig. 8, it was observed that the alcohol-diesel blends were higher in cylinder pressure than those of FBDF at all SOI timings. The maximum cylinder gas pressure with E10B2 (88 bar), approximately 5% increase was observed in injection time at BTDC 12.4 °CA in comparison to FBDF (83.4 bar). Maximum cylinder gas pressure with E5B1 was determined as 86.8 bar by advancing the injection time 2° CA from TDC.



SOI Timing	Crank Angle °CA ATDC	Max Cylinder Gas Pressure (bar)
-2 °CA	11.7	74.78
Main	9.8	79.91
+2 °CA	7.8	83.37

SOI Timing	Crank Angle °CA ATDC	Max Cylinder Gas Pressure (bar)
-2 °CA	12.3	77.74
Main	9	81.03
+2 °CA	8.1	86.79

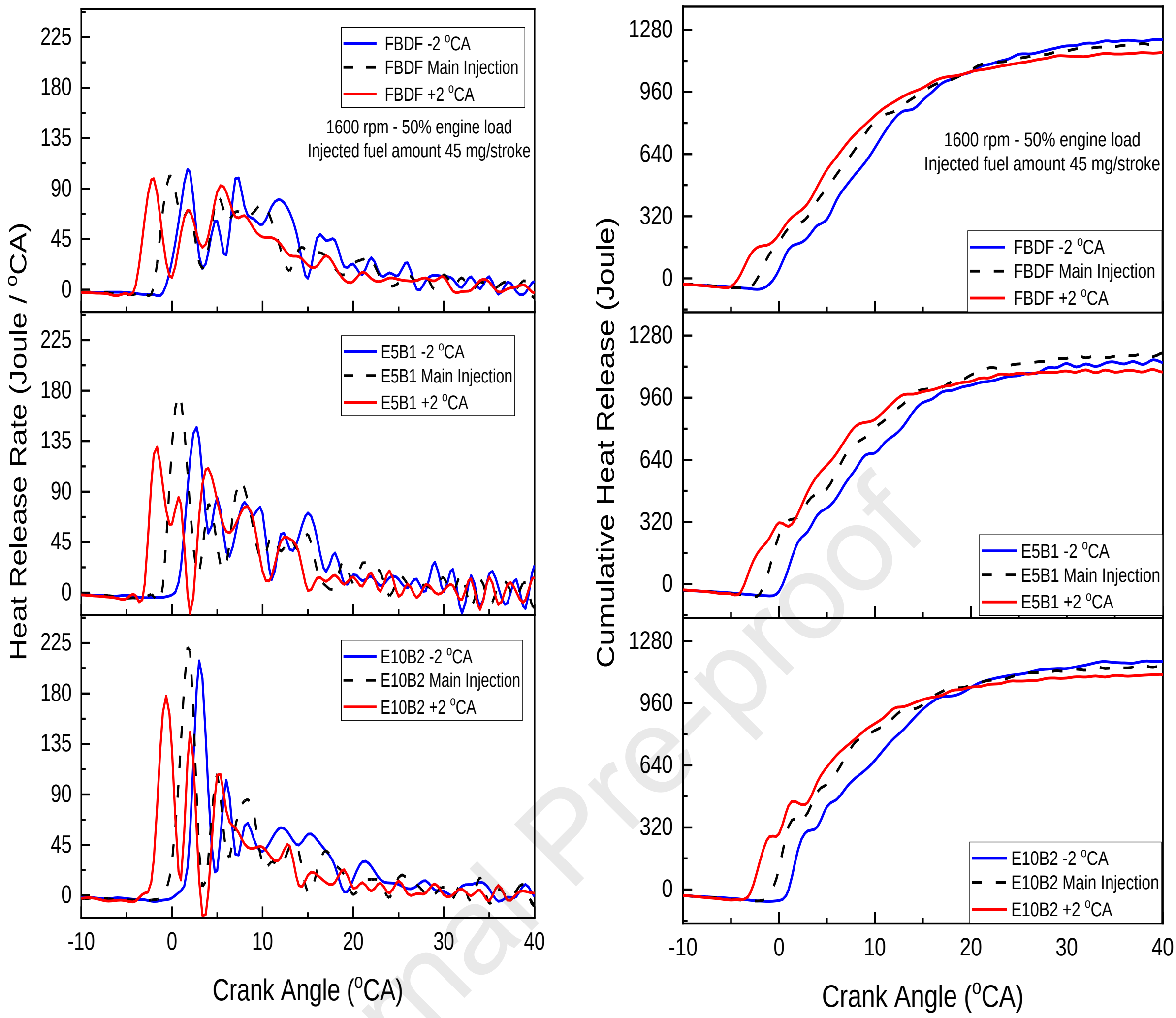
SOI Timing	Crank Angle °CA ATDC	Max Cylinder Gas Pressure (bar)
-2 °CA	6.4	75.34
Main	9	80.66
+2 °CA	7.1	88.02

Fig.8. The effect of the fuel injection phase on cylinder gas pressure

At the main SOI timing, the cylinder gas pressure values obtained using blends were 81 bar for E5B1 at ATDC 9 ^{o}CA and 80.6 bar for E10B2 at ATDC 9 ^{o}CA while it was 80 bar for FBDF at ATDC 9.8 ^{o}CA. It can be expressed that having earlier and higher maximum cylinder gas pressure with blended fuels is because of the OH group that alcohol fuels have. OH-group in alcohols provides faster combustion and decreases DOC so that heat losses from the cylinder wall decrease [56]. By retarding of the SOI timing 2^{o} CA to TDC according to the main SOI timing, cylinder gas pressure tended to decrease with using E5B1, E10B2 and FBDF fuels. When the fuels were injected at 8.4 ^{o}CA BTDC, the cylinder gas pressure was obtained as 77.7 bar, 75.3 bar, and 74.7 for E5B1, E10B2, and FBDF, respectively. In addition, compared to main SOI, when fuels were injected at 8.4 ^{o}CA BTDC, it was seen that there was a decrease for E5B1, E10B2, and FBDF, 3.3 bar, 5.3 bar, and 5.1 bar, respectively. For all the fuel types and all the SOI timing, the lowest cylinder gas pressure value was 74.7 bar at 8.4 ^{o}CA BTDC. The advanced SOI timing and addition of the alcohol fuel to FBDF affected cylinder gas pressure positively. Since the advanced SOI timing allows fuels to mix more homogenous and more fuels burn BTDC, higher maximum cylinder gas pressure can be obtained around the TDC.

Fig. 9(a) shows the amount of energy released in the cylinder at each crank angle using E5B1, E10B2, and FBDF. In addition, the cumulative heat release rates in each fuel use are given in Fig.9(b) to show the total energy released in the cylinder sourced from combustion. In tests, the maximum heat release rate was calculated as 218 joules (J) at the time of main injection with E10B2 fuel, while the minimum heat release rate was as 99 J at 12.4 °CA BTDC with FBDF. At the fuel injection time of 8.4 ^{o}CA BTDC, while the heat release rate for FBDF was obtained as 104.8 J, it increased approximately 36% with E5B1 and 100% increase with the use of E10B2.

The joint use of the fuel injection phase and the alcohol-diesel blends significantly affect the heat release rate. Although alcohol fuels have a higher oxygen content than that of FBDF, this fuel feature of alcohols does not mean that they generate more energy output in cylinder than the use of FBDF. This study observed that the high oxygen content in alcohols caused a sudden increase in the heat release rate. However, the rate of heat release of FBDF was found to be wider than that of alcohol-FBDF blends since alcohols have less calorific value than FBDF. In literature, while Zhang et al. [57] observed similar results, Prabakaran et al. [58] obtained different values in the cylinder gas pressure and the heat release rate. They explained as increase in the rate of combustion with FBDF. It can be interpreted that blend fuels have lower cetane number and longer ignition delay so fast combustion of fuel in the combustion chamber and oxygen content of the blend fuels lead higher value of cylinder gas pressure and heat release rate.



a) Heat Release Rate *b) Cumulative Heat Release*

Fig.9. The effect of the fuel injection phase on heat release rate

3.3. Emission Characteristics

3.3.1. Carbon monoxide (CO) emission

CO emission is a toxic exhaust emission resulting from the incomplete combustion of the fuel in the cylinder as a product of incomplete combustion or its combustion at low temperatures [59], [60]. Fig. 10 shows the effect of the fuel injection phase and fuel type on CO emission. With the use of alcohol-diesel mixtures, significant reductions in CO emissions were observed in all injection phases. At the same SOI, increase in alcohols rate in blend fuels decreased CO emission. This can be explained by oxygen content of alcohol fuels that provides better combustion and high temperature in the cylinder. Changing the injection phase resulted in a reduction in CO emissions with alcohol-diesel fuel mixtures, while delaying the injection phase with the use of FBDF resulted in a reduction in CO emissions. The maximum CO emission was determined with FBDF by advancing the SOI timing as 303 ppm, while the maximum CO emission was monitored at the main SOI timing with alcohol-diesel fuel mixtures as 275 ppm and 271 ppm (E5B1 and E10B2, respectively).

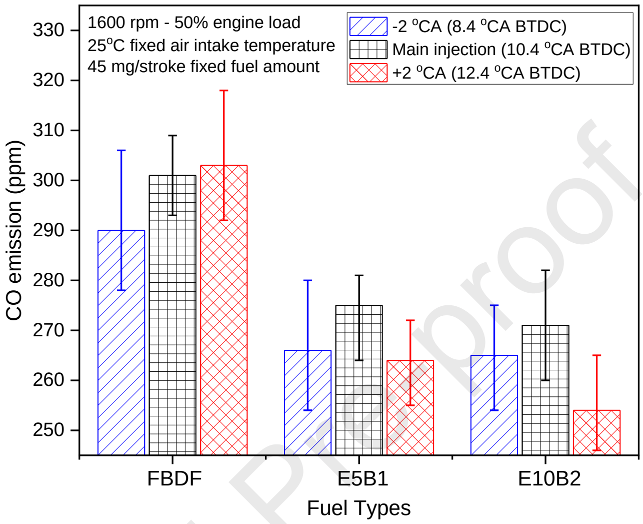


Fig.10. The effect of the fuel injection phase on CO emission

By retarding the SOI timing, a decrease in CO emission was observed for blends compared to the main SOI timing. However, when the error variation in CO emissions were examined, it was seen that the error values were stable at the main SOI timing for each fuel type.

3.3.2. Carbon dioxide (CO_2) emission

It is a natural combustion product formed by the reaction of carbon and oxygen molecules during the combustion of the fuel-air mixture in the cylinder [59]. Fig. 11 shows the effect of the fuel injection phase and fuel type on CO_2 emission. The change of injection phase for all fuels showed a stable variation in CO_2 emission formation. The use of alcohol-diesel mixtures caused in a 4% reduction in CO_2 emissions. It can be said that at the same SOI, a decrease trend was seen with increasing amount of alcohol fuels in blend fuel. At the retarded SOI, CO_2 emission values were as 4.88% for FBDF, 4.8% for E5B1, and 4.79% for E10B2.

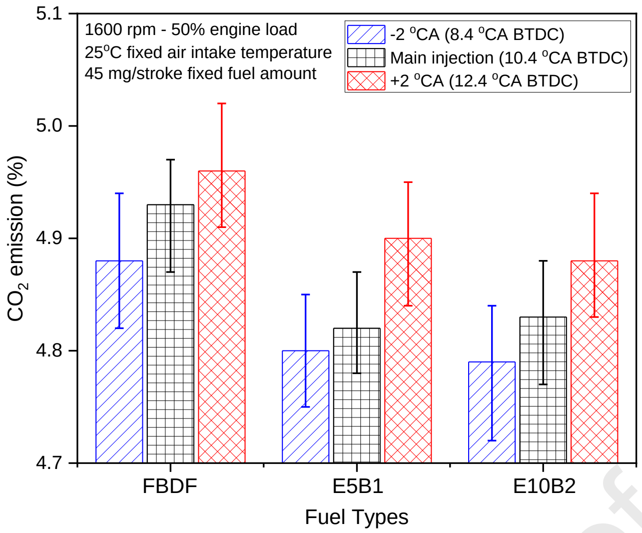


Fig.11. The effect of the fuel injection phase on CO_2 emission

When the SOI timing is retarded, the lowest CO_2 emission value was obtained for all test fuels. On the other hand, the highest CO_2 emission value for all fuels was obtained by advanced SOI timing. Maximum CO_2 emission was caused by FBDF at 12.4°CA BTDC as 4.96% and also at the same SOI, 4.9% of CO_2 emission and 4.88% of CO_2 emission with E5B1 and E10B2, respectively. Having maximum CO_2 emission at advanced SOI is because of air-fuel can be mixed more homogenous better combustion phenomenon is obtained. In literature, He et al. [61] and Chauhan et al. [62] observed a similar trend in CO_2 emission to our study and explained their result as an increased rate of ethanol in blend fuel decreases C/H rates of fuels producing a decrease in CO_2 emission. It was determined that the error range of CO and CO_2 emissions for alcohol-FBDF fuel blends was slightly wider than that of neat FBDF. Similar to the error variance of CO, the error variations of CO_2 are quite stable for all test conditions and fuel types.

3.3.3. Ammonia (NH_3) emission

Fig. 12 shows the fuel injection phase and fuel type effect on NH_3 emission. It has been determined that the use of alcohol-diesel mixture significantly reduces NH_3 emissions. At the main SOI timing, the maximum NH_3 emission was produced by FBDF, while NH_3 emission was reduced by approximately 6.5 times in the use of E5B1 and was reduced by around 13 times in the use of E10B2. By retarding the fuel injection time, the lowest NH_3 emission values were measured for all test fuels.

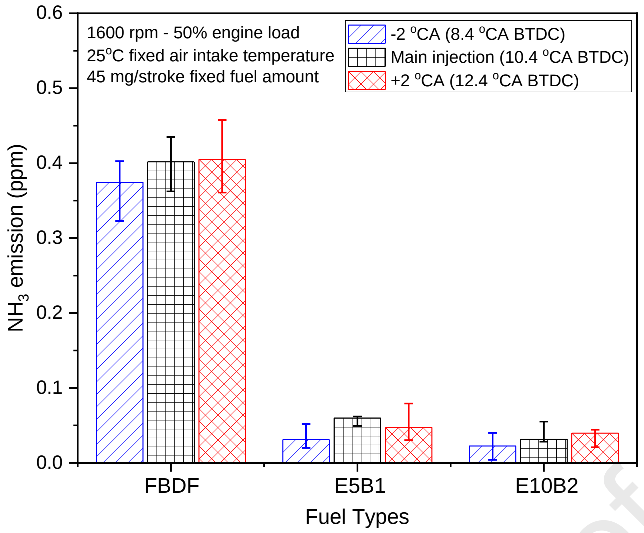


Fig.12. The effect of the fuel injection phase on NH_3 emission

Huai et al. [63] monitored the NH_3 emission from light commercial vehicles operating on fossil fuels for different driving cycles. They reported that NH_3 emissions vary from near zero to 0.144 g/km over all vehicles and cycles. It was determined from the NH_3 emission error analysis values in our study that the error ranges of NH_3 are not stable in the use of alcohol-FBDF fuel blends. It was thought that the changes in the error values were unstable because the values measured in ppm were too small. It was concluded that detailed comments are needed about the instability in NH_3 emissions by conducting studies with a sudden increase in engine speed, enrichment of air-fuel ratio, the use of different biofuel-fossil diesel fuel blends, and sudden change of engine operating parameters.

3.3.4. Nitrogen oxide (NO_x) emission

Toxic and reactive NO_x emissions result from the combustion of the fuel-air mixture in the cylinder and reaching high temperatures [64]. Fig. 13 shows the effect of the fuel injection phase and fuel type on NO_x emission. Table 7 gives exhaust gas temperature and pressures in all test conditions. In experiments, minimum NO_x emission was monitored 463 ppm with FBDF at 8.4 °CA BTDC, while maximum NO_x emission was observed with using E5B1 (700 ppm) fuel was obtained by advancing the injection timing 2 °CA from TDC, according to the main injection period. It is thought that this is because of advanced SOI led improvement in combustion and higher temperature in cylinder obtains so that an increase was seen in NO_x emission.

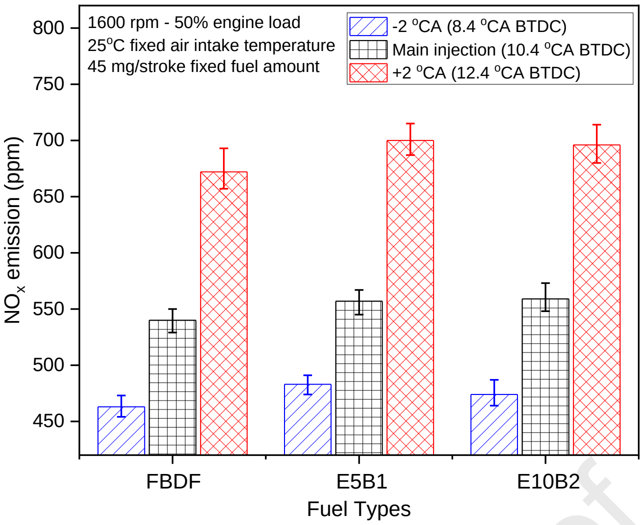


Fig.13. The effect of SOI timings on NOx emission

Table 7. Exhaust gas temperatures and pressures in all test condition

Injection Start Time	Fuel Type	Exhaust Temperature (°C)	Exhaust Pressure (mbar)
(-2 °CA)	FBDF	320.5	11.5
	E5B1	314.7	11.5
	E10B2	313.7	11.9
(Main)	FBDF	324.5	11.8
	E5B1	317.3	11.4
	E10B2	317.9	11.7
(+2 °CA)	FBDF	328.8	12.4
	E5B1	322.1	12.2
	E10B2	320.5	12.1

NO_x emissions caused by using FBDF were lower than those of E5B1 and E10B2 at all SOI timing. In the main SOI timing (10.4 °CA BTDC), NO_x emission was determined as 540 ppm with FBDF, while an increase of approximately 3.2% was observed in the use of E5B1 (557 ppm) and E10B2 (559 ppm). With the use of blended fuels, obtained increase in NO_x can be explained by the oxygen content that alcohol fuels improve combustion and lead to higher temperatures in the cylinder.

In the tests performed, it was observed that NO_x emission at the SOI timing of 8.4 °CA BTDC was at the minimum level for E5B1 (483 ppm), E10B2 (474 ppm) and FBDF (463 ppm). The minimum NO_x emission amount for each fuel was obtained by retarding the injection time 2 °CA to TDC according to the main SOI timing. The maximum NO_x emission values were determined by advancing the injection time 2 °CA from TDC according to the main SOI timing; it was observed with

E5B1 (700 ppm), E10B2 (696 ppm), and FBDF (672 ppm). The error rates of NO_x emission values were found to be close and stable for all fuel types.

Advancing injection timing leads to lower soot formation, to higher NO_x emissions [65]. By advancing fuel injection time, the air-fuel reaction time is increased so that a more homogenous mixture is obtained due to an increase in the temperature of the combustion chamber. It is seen from Table 7 that there is an increase in the exhaust gas temperature throughout the exhaust line with the advancing fuel injection timing. In this study, it was seen that an increase in NO_x emissions was observed by advancing the fuel injection time regardless of the fuel type. It can be said with certainty that the effect of fuel injection time on NO_x emissions is much more effective than the fuel type.

It is thought that the increasing rate of ethanol in a mixture leads to an improved combustion process since ethanol contains oxygen, consequently, CO emission decreases. Increasing the ethanol rate in blended fuels leads to rapid combustion in the cylinder, which increases the maximum cylinder pressure. Therefore, a higher maximum cylinder temperature is obtained as a result of NO_x emission increases. Park et al. [66] observed opposite results for CO but found similar results for NO_x emissions values to this study. They expressed that the high heat of evaporation of ethanol fuel caused lowered combustion temperature and increased CO emission. The rate of NO_x emission is mainly related to the cylinder temperature.

4. Conclusions

This study investigated the effects of ethanol-butan-2-ol-FBDF blends and the fuel injection timings on combustion parameters in a single-cylinder diesel engine with common rail fuel injection system at 1600 rpm constant engine speed and 50% constant engine load.

It was monitored that the minimum *BSFC* values were obtained with pure FBDF by advancing the fuel injection time according to the main injection time. However, it is noticed that the change in the fuel injection time (±2 ^{o}CA) not have a crucial effect on *BSFC*.

At all injection timings, it was seen that the use of the blended fuels increased the ID. At the same SOI, more than 10% ID was prolonged using blends. Compared to neat FBDF, as the rate of alcohol fuels increased in the blends, the chemical energy of fuels was converted 25% earlier to heat energy. DOC was not affected by a change of SOI however significant reduction of DOC was determined with use of alcohol fuels. At the same SOI, up to 15% period of DOC was shortened with the use of blended fuels.

PRR was increased by more than an acceptable point with E5B1 and E10B2. Compared to FBDF, the use of E10B2 increased PRR up to %90. This situation increases the tendency of the engine to work knocking. However, retarding the injection start timing was beneficial in controlling the PRR to some extent. When the blends were compared to pure FBDF, the maximum cylinder gas pressure increased with the use of the blends for all fuel injection timings. Moreover, advanced SOI led to better combustion phenomena and higher maximum cylinder gas pressure. The heat release rate rose as the ethanol ratio in alcohol-diesel mixtures increased. The minimum heat release rate for each fuel was observed at the advanced fuel injection timing.

The maximum CO emission values were achieved at main injection time, CO emissions decreased by approximately 10% for E5B1 and about 15% for E10B2, compared to FBDF. When the ethanol amount in blended fuels increased, CO emissions decreased.

CO_2 emission was higher with FBDF at all fuel injection timings compared to E5B1 and E10B2. The maximum CO_2 emission value was measured with pure FBDF when the injection time was close to TDC. With the fuel injection timing change, the decrease in CO_2 emissions was on average 2.1%.

NO_x emission values obtained with blended fuels increased by approximately 5% compared with neat FBDF. These values showed that the change in the fuel injection timing have an important effect on NO_x emissions. NO_x emissions decreased by approximately 15% with the use of E5B1, E10B2 and FBDF by the retarded fuel injection timing.

Ethanol is a fuel with a high potential for blending with FBDF to control NH_3 emissions. Compared to neat FBDF at all fuel injection timings, the blended fuels significantly reduce NH_3 emissions. An average of 8 times reduction in NH_3 emission was calculated with E5B1, while an average of 12 times reduction in NH_3 emission was calculated with E10B2.

In general, it was seen that the results obtained for the parameters examined in the test conditions as a result of the use of E5B1 fuel and E10B2 fuel were close to each other. However, when the PRR values were examined, it was seen that the use of E10B2 removed the PRR from the acceptable value and increased the knocking tendency of the engine. On the other hand, it was determined that E5B1 improves combustion and reduces exhaust emissions at certain points. In addition, when the SOI in the experiments were examined, it was determined that +2 ^{o}CA SOI significantly improved the cylinder gas pressure. As a result of the study, the use of E5B1 at +2 ^{o}CA SOI will be the best configuration under the experimental conditions.

In the literature, the general drawback of using ethanol-FBDF blends in diesel engines is having phase separation of ethanol-FBDF mixtures. The experiments in this study indicated that use of 2-butanol is an effective stabilizer to prevent phase separation at low scale ethanol-FBDF fuel blends. It was observed that 2-butanol inhibited the phase separation significantly and for a long time in the tests performed at ambient temperature conditions. The use of 2-butanol will be an essential option for researchers to prevent phase separation in future studies. In addition, the researchers should study not only higher blending ratio of ethanol-diesel fuel blends with the use of 2-butanol as stabilizer, but also the methods for diesel-methanol blends with the use of 2-butanol as stabilizer.

ABBREVIATION

ABE : Acetone-butanol-ethanol
ATDC : After the top dead center
BSFC : Brake specific fuel consumption
BTDC : Before the top dead center
CA : Crank angle
CA10 : The crank angle point of 10% fuel mass burned
CA50 : The crank angle point of 50% fuel mass burned
CA90 : The crank angle point of 90% fuel mass burned
CO : Carbon monoxide
CO$_2$: Carbon dioxide
DOC : Duration of combustion
E5B1 : 5% ethanol + 1% butan-2-ol + 94% FBDF (vol.%)
E10B2 : 10% ethanol + 2% butan-2-ol + 88% FBDF (vol.%)
FBDF : Fossil-based diesel fuel
IBE : Isopropanol-butanol-ethanol

ID : Ignition delay
MFB : Mass Fraction Burned
NH_3 : Ammonia
NO_x : Nitrogen Oxides
PRR : Pressure Rise Rate
SOI : Start of injection
SOC : Start of combustion
TDC : The top dead center
UHC : Unburned hydrocarbon
m_b : the mass of fuel burned
m_f : the amount of fuel in the cylinder.
S_x : the standard deviation
X : the measured variable
$\bar{X}$: the mean value
θ : the instantaneous crank angles

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Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Mustafa Vargün: Investigation, Methodology, Data processing, Writing – original draft.
Ahmet Necati Özsezen: Writing – review & editing, Conceptualization, Visualization, Supervision, Project administration.

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Highlights

- In this study, ethanol-butan2ol-diesel fuel blends were used.
- It was determined that alcohol blended fuels caused a significant increase in PRR.
- As a result of the advancing SOI, an improvement was observed in the maximum cylinder gas pressure.
- The use of blended fuels caused the ID to prolong while the DOC to shorten.
- For all test fuels, reductions in NO_x, NH_3 and CO_2 emissions were determined with the retarded injection start timing.

Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: