Combustion Characteristics of a High Pressure Fuel Injected Single Cylinder Compression-Ignition Engine, Fuelled With Diesel–Ester Blends under Various Fuel Injection Advance Angles

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Abstract- In Diesel engines quality of combustion is depending on the formation fuel-air mixture. A high-quality of formation for combustion is achieved by mixing of pulverized fuel drops and the air inside the cylinder. In this matter, injection parameters such as timing and period of injection, injection pressure and the number of the injection beams affect quality of combustion and mixture formation. The main purpose of this work is to find the optimum injection advance angle for traditional diesel and diesel-ester blends in a direct injection (DI) compression ignition engine. Tests are conducted on an air cooled single cylinder, high pressured (600-1600 bar), plc controlled research engine. Engine torque, brake power and brake specific fuel consumption values associated with each of these fuel blends are collected under certain operating points. A piezo transducer is utilized to detect in-cylinder pressure and an incremental encoder for the relative position of the piston top to the dead center location. In the light of the obtained values, no negative impact was observed on the performance with the addition of ester up to 20% by volume and these results are concordant to the results of the other researches. It is seen that at suitable injection advance ester blended fuels capture the peak pressure value in less time for engine as given in the literature. Similar to the prior studies, biodiesel addition to diesel fuel raises heat output at premixed combustion phase, reduces the combustion at diffusion phase. On the other hand, when the injection advance had been closer to TDC, it caused a decrease in pre-phase peak value and an increase at the values of diffusion phase.

Keywords Alternative fuel, diesel engine, pressure, ester, HRR

1. Introduction

In recent years, the petroleum price is increasing rapidly; therefore the researchers are seeking alternative fuel sources. They produced different kinds of vegetable oil based fuels as an alternative fuel for compression ignition engines. Currently, researchers are focused on producing reliable and viable fuel from vegetable oil, bio-diesel (transesterified vegetable oil-methyl esters of vegetable oils, biogas for diesel-engines. Vegetable oils are widely available in rural areas and can be easily blended with diesel in the neat and esterified (biodiesel) forms.

In diesel engines, combustion efficiency depends on the mixture formation. The injection parameters such as the timing and the period of the injection, the pressure and the number of the injection beams affect the quality of combustion and the mixture formation (Bauer, 1999a, 1999b; Desantes et al., 2004b). In alternative fuel studies, the injection system parameters like pressure, injection advance, and injection character must be controllable. In general, single cylinder diesel test engines have mechanical unit pump systems and these systems have no changeable parameters. From this point of view, the mechanic injector must be changed with an electromagnetic injector to control parameters.

In order to investigate the optimal operation zones of an engine running on alternative fuels such as esters, a single-cylinder conventional diesel engine was set up with an electromagnetic injector, attached to a common-rail pressure mechanism. In this setup, the injector has to be controlled depending on the engine's operational parameters. Also, the injection characteristics have to be tuned online.

The application of the high-pressure injection system increases the amount of fuel injection per crankshaft angle and it also shortens the ignition delay. Naturally, this delay has a minimum value that cannot be breached. In these systems, the amount of the fuel injected into cylinder increases with the pressure until the ignition starts, which causes higher levels of NOx and mechanical noises. In order to compensate for these problems, a pre-injection technique is utilized. The pre-injection technique provides lower NOx and noise levels (Denso Corporation, 2003; Desantes et al., 2004a; Ghaffarpour and Baranescu, 1996; Heywood, 1988; Ogawa et al., 2000). Additionally, high-pressure injection improves specific fuel consumption (SFC) and particle emission levels (Desantes et al., 2004a; Reddy and Ramesh, 2006).

In direct injection Diesel engines, changes of injection timing have a significant impact on NOx emissions. In Uchida et al. study; the increase of injection advance resulted higher NOx emissions and lower particulate emissions. In this work, they determined that the increase of fuel injection rate provides of the more fuel get into the pre-combustion phase and a higher heat output. He and Bao (2003) have tested canola oil as an alternative fuel in a single-cylinder engine. To give the best results for specific fuel consumption and thermal efficiency, fuel distribution angle should be 20o and it is required to give 2-3o advance in diesel fuel. Selim (2003) examined the effects of jojoba oil methyl ester to the diesel engines performance. Pure JME fuel at low loads exhibited a slightly higher pressure rate rise than diesel and its blends. Change of spraying advance has usually increased the maximum pressure and maximum pressure rate rise. Maximum pressure rise rate and maximum pressure standard deviation of JME fuel is as fewer as diesel fuel which has periodic variation in engine.

Injection pressure of diesel engines has important effects on engine performance and emissions. Cinar et al. (2005) study, observed the decline in torque caused by the increasing pressure in 4-stroke 4-cylinder indirect injection diesel engine. Reddy and Ramesh (2006) observed fine atomization with the increased injection pressure and this situation increased the heat output per crank angle in a single-cylinder direct injection engine however, increasing injection pressure improves the performance and emissions. Soybean oil methyl ester and tallow oil methyl ester are used as fuel on John Deere tractor engine at Yahya's study. These fuels were compared with Diesel fuel at different injection advances and pressures. When spray pressure was increased, it was noted that the fuel consumption decreased around % 6.4-7.

Desantes et al. (2004) investigated the effects of injection rate structure and pressure over combustion process and exhaust emissions in direct injection diesel engine. Low injection pressure was found to reduce the formation rate of blend. Huang et al. (2004) used methanol-diesel fuel blends as fuel in a diesel engine and they observed an increase at the rate of heat output in the pre-combustion phase with increasing the amount of methanol, combustion delay was shortened at diffusion phase.

In a study conducted by Scholl and Sorenson (1992), the vegetable oil (soy) methyl esters were proposed as an alternative fuel in diesel engines. In this study, engine performance, exhaust emissions and heat losses were studied and the effects of different injection timing performance with different nozzle diameters were investigated. In terms of the HC emissions and black smoke, the methyl ester was better than diesel fuel.

2. Experimental Setup

A high pressure (2000 bar of injection pressure) common-rail traditional fuel injection system has adopted to the test engine. Fuel injection systems were controlled from an external Programmable logic control unit (PLC). In cylinder pressure measurement system equipments are given in table-1. Injection, pressure and incremental encoder signals recorded simultaneously with 0.1 °CA intervals. Temperature values were measured by using K-type thermocouples. The schematic description of experimental apparatus is shown in figure-1. A single cylinder, DI (direct injection), naturally aspirated, air cooled diesel engine has been modified for CR application. The technical specifications of test engine are given in table-2. The control algorithm is explained in figure-2

Table 1. In cylinder pressure measurement system equipments

Brand Name	Lecroy	Kistler	Kistler
Model	24Xs	5011 B	6052 B
Range	200 ps/div–1000 s/div	±10…999000 pC	0–150 bar
Sensitivity	2 mV/div–10 V/div (1 MΩ); 2 mV/div–1 V/div (50 Ω)	0,01…9990 pC/bar	-19.92 pC/bar

Table 2. Technical specifications of test engine

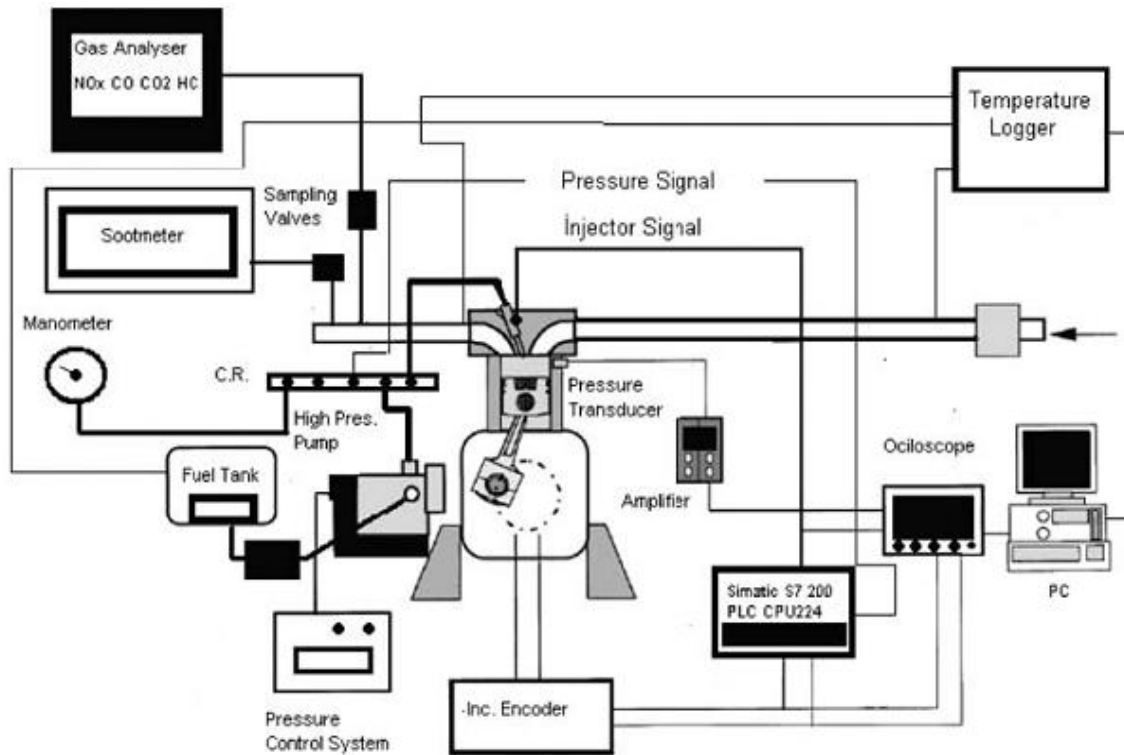|	
Total displacement	454 cm^3
Number of cylinders	Single
Stroke	80 mm
Bore	85 mm
Compression Ratio	17.5/1
Max. torque at 2000 rpm	28.5 Nm
Max. Power at 3000 rpm	7.5 kW

Fig. 1. Scheme of test bench

Fig. 2. Diesel engine control algorithm

Experiments are conducted based on the procedure explained below:

(1) Common-rail pressure and advance angle were set.

(2) A speed value was determined and engine speed controller was set to operate the engine at constant speed.

(3) The engine was loaded with the DC motor until the speed has decreased. This point is the operating condition where the engine can generate its maximum torque level for that speed. If the load is increased, the speed of the engine decreases even the fuel consumption increases.

(4) Torque, speed and pressure of the cylinder are recorded. Pressure is observed to determine the beginning of knocking. The number and the duration of the injections are used to compute the amount of the fuel consumed.

(5) Throughout all tests, the injection timing varied to 25°, 20°, 17° and 15° before top dead center.

3. Results &Discussion

Firstly, 100% diesel fuel used to obtain the reference values at the experiments. Before testing, fuel injection duration is determined to give the same amount of injection for the value of each pressure. Spraying advance before the TDC modified to 25-20-17-15°CA, the effects have been observed in experiments. The specifications of the test fuels and the abbreviations of fuels are given in table-3 and table-4 respectively.
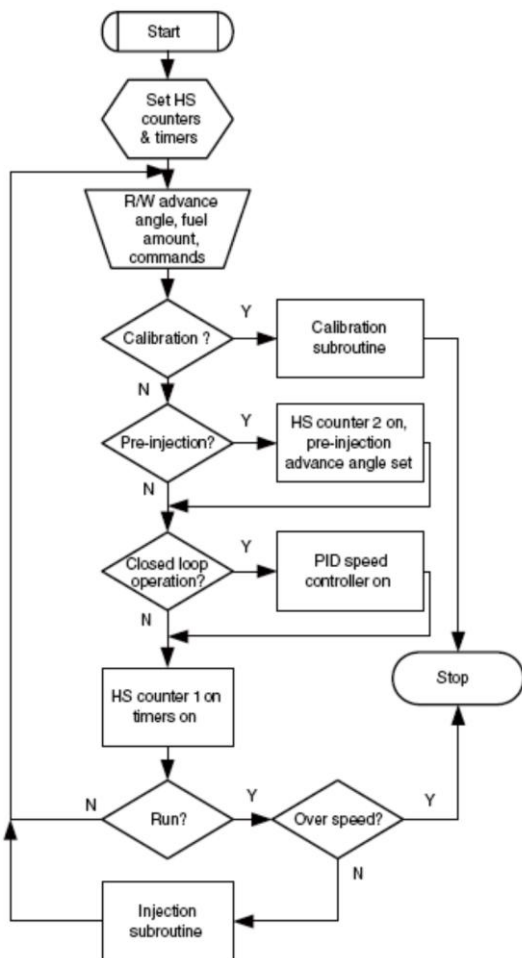
Table 3. Test fuels specifications

Parameter	Result		Unit
	Biodiesel	Diesel	
Ester content	98.4	-	% (m/m)
Density 15 oC	882.1	838	kg/m^3
Viscosity 40 oC	4.38	2,317	mm^2/s
Carbon residue (10%)	0.26	0.12	%(m/m)
Flash point	125	64	^{o}C
CFPP	-15	-	^{o}C
Sulfur content	6.8	2117	mg/kg
Water content	433	83	mg/kg
Oxidation stability	5.6	14	h
Acid Value	0.385	-	mgKOH/g
Total contamination	12	8	mg/kg
Iodine value	121	-	g ıodine/100g
Free glycerol	0.01	-	% (m/m)
Monoglyceride content	0.72	-	% (m/m)
Diglyceride content	0,17	-	% (m/m)
Triglyceride content	0,14	-	% (m/m)
Pourpoint	-35	-	^{o}C
Calorific value	37.35	40.20	MJ/kg
Polycyclic Aromatic Hydrocarbons	-	7	% (m/m)
Ester content	98.4	-	% (m/m)

Table 4. The abbreviations of fuels

Parameter	Fuel Type	Injection Advance ^{o} CA
DADV15 - DADV17- DADV20	Diesel	15-17-20
E5ADV15- E5ADV17- E5ADV20	%5 Ester+%95Diesel	15-17-20
E10ADV15- E10ADV17- E10ADV20	%10 Ester+%90Diesel	15-17-20
E20ADV15- E20ADV17- E20ADV20	%20 Ester+%80Diesel	15-17-20

At the beginning of the experiment; the DC motor was used to give the first movement to the diesel engine. Before each experiment; externally driven engine was heated for 5 minutes out of fuel spraying. After this time, the engine idled for 5 minutes with a minimum fuel delivery and the subsequent measurements were started. Firstly; engine fuel injection pressure and injection advances were set to 1100, 25°CA (BTDC) respectively. The amount of fuel was set by the PLC for the maximum power speed of 3000 rpm. In the meantime, the engine torque, in-cylinder pressure change and exhaust emissions were measured and recorded. Following this procedure; the injected fuel and the engine load was increased after the first stage, the injection pressure changed to 1200 and 1300 bar, the amount of sprayed fuel were determined for the new conditions. The experimental procedure as described at above was repeated for all advances and pressure values and the results were recorded. During the experiments, injection signal with TDC signal was recorded by oscilloscope. Fuel, exhaust outlet, the ambient and intake temperatures were identified with the placed thermocouples at different locations.

According to the analysis of the obtained experimental results, it is found that an increase at performance levels was caused by the increase of injection pressure. In general, the maximum power values are obtained at an injection timing of BTDC 17°. In the experiments with diesel fuel, 7.27 kW power was obtained for the 1300-bar injection pressure value at the 3000 rpm engine speed. At the same engine speed and injection pressure conditions, 7.34 kW for B5 fuel, 7.14 kW for B10 fuel and 7.15 kW power for B20 fuel was obtained. An increase at spraying advance has been observed which caused the decline in the observed maximum power value. On the other hand; the power was reduced with decreased advance (BTDC). The addition of the biodiesel didn't reduce the engine's maximum power value at the proper injection advance value.

Examined the obtained results, the maximum torque was observed when the injection advance was decreased. The maximum torque showed differences at some points depending on the spraying pressure.. In the experiments; at 1300 bar injection pressure value with diesel fuel, 26.77 Nm maximum torque value was observed at 2200 rpm engine speed condition at a spraying angle of 15° CA before the TDC. The experiments with the mixture of fuels, the maximum torque; 26.84 Nm for B5 fuel, 26.93 Nm for B10 fuel and 26.96 Nm for B20 fuel were measured at the 1300 bar pressure at 2200 rpm engine speed value. In the light of these obtained values, no negative impact was observed on the performance with the addition of biodiesel up to 20% by volume and these results are concordant to the results of the other researches (Antolin et al. (2001), Çanakcı et al.(2006), Çanakcı et al.(2009).
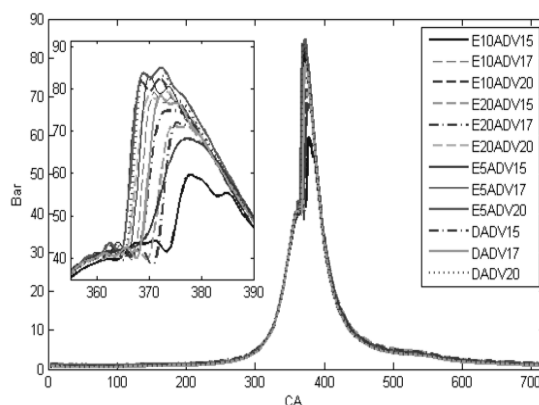

Fig. 3. In-cylinder pressure variation is given for different advance values. (Engine speed 3000 rpm)
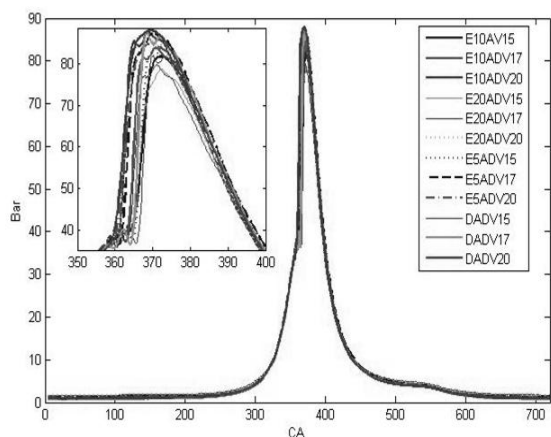
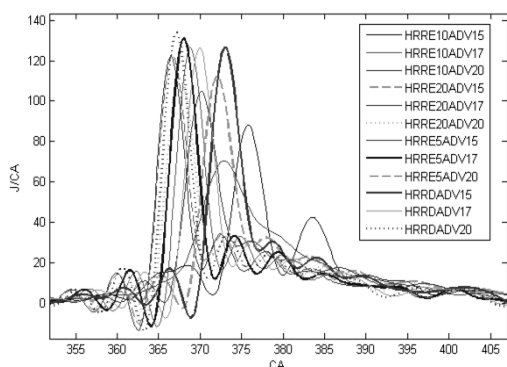**Fig. 4.** In-cylinder pressure variation is given for different advance values(Engine speed 2200 rpm)

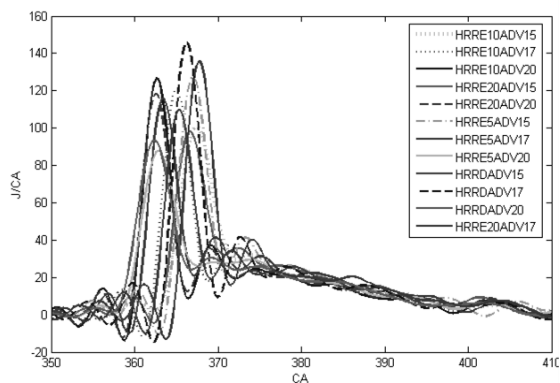**Fig. 5.** HRR is given for different advance values. (Engine speed 3000 rpm)

Fig. 6. HRR is given for different advance values. (Engine speed 2200 rpm)

In Figure 3 in-cylinder pressure variation is given for different advance values. The injection started at 15-17-20° CA before TDC at 1300 bar injection pressure value under 3000 rpm engine speed maximum power condition for diesel and mixture fuels. It is seen that biodiesel blended fuels capture the peak pressure value in less time at suitable injection advance for engine as given in the literature. However, as highlighted in the studies of Yanagihara et al. (1997), reduction of injection advance lead to decline in peak pressure value.

Though Carraretto et al. (2004) observed torque and power decrease with the addition of biodiesel. In the study,

the combustion rate increased with the pure biodiesel and to optimize the combustion, they concluded that there should be a reduction of spray advance while they are using the biodiesel as a fuel. In addition, Banapurmath et al. (2008) observed the obtained maximum power with 23° CA injection advance and diesel fuel was obtained by 27° CA with sesame oil and Jatropha oil methyl ester, 19° CA advance with hong oil methyl ester. Ignition delay time increased with biodiesel fuels, at the pre-mixed phase combustion heat output decreased.

Hountalas (2004) observed that increasing boost pressure (400-1600 bar) increases the end of the combustion cylinder pressure, the combustion rate and exhaust temperature, reduces the specific fuel consumption. Positive effect on the threshold value for each operating condition began to deteriorate. On the other hand, increasing injection pressure has opportunity to shrink the spray pressure advance.

Laforgia and Ardito (1994) and Kumar et al. (2006) observed in their studies that biodiesel addition to the fuel reduces the value of peak pressure. In the study of Kumar, mixture with up to % 20 biodiesel also demonstrated close values with diesel fuel as in the study ours.

When heat output curves are analyzed in Figure 5, similar to the prior studies, biodiesel addition to diesel fuel raises the heat output at premixed combustion phase, reduces the combustion at diffusion phase. On the other hand, when the injection advance had been closer to TDC, it caused a decrease in pre-phase peak value and an increase in the values at diffusion phase. Similar to these results in the study of Huang et al. (2004), biodiesel fuels raises the pre-mixed combustion phase peak value, downsizing of injection advance affects heat output phase structure, being closer to the TDC reduces the pre-mixed peak value. Similar results were also observed by Rakopoulos et al. (2007a). In the study, although peak pressure values remain the same in usage of biodiesel, heat output structure in usage of biodiesel is pre-mixed combustion which has high peak value. In another study of Rakopoulos et al. (2007b), it was observed that being participation in fuel for ethanol which is the basic contribution to convert the oil to biodiesel raises the pre-combustion phase peak value accordingly. Having low cetane number for ethanol extends ignition delay time and leads to an increase in amount of prepared fuel to burn. This situation provides that rapid combustion occurs just after the ignition, so pre-mixed combustion phase becomes higher and sharper. Main biodiesel additives alcohols (methanol-ethanol) can be given as the main reason for pre-mixed phase peak values in biodiesel-diesel blends. In the study of Çanakcı (2006), it was found that % 20 biodiesel-diesel blend shows heat output behavior close to the diesel fuel and % 100 biodiesel has lower pre-mixed peak value with an early ignition. Similarly, in the study of Kumar et al. (2006), they observed that the heat output behavior is close to the diesel with B20 fuel.

In Figure 4 in-cylinder pressure variation is given for different advance values at the maximum torque speed of 2200 rpm. It is seen that biodiesel blended fuels capture the peak pressure value in less time at suitable injection advance for this engine as given before the maximum power results.

When heat output curves are analyzed in Figure 6, opposite to the maximum power results, it's seen that, biodiesel addition to diesel fuel raises heat output at premixed combustion phase, when the injection advance had been closer to TDC. It caused an increase in pre-phase peak value and a decrease in the values of diffusion phase.

4. Conclusion

The purpose of this work was to investigate the effect of the various fuel injection advance angles on the combustion characteristics of biodiesel-diesel blends. From these, conclusions of this work are derived as follows.

In the combustion from single-high pressure injection, the combustion pressure and rate of heat release at an injection timing of BTDC 25 dramatically decreased because the most of the injected spray was distributed in the squish and crevice regions as well as in the piston bowl area. These characteristics influenced the decrease of the IMEP due to the incomplete combustion. That's way these results couldn't mention in the text.

In the analysis of the spray targeting points, the injection advance must be changeable in the operating regime. Biodiesel addition to diesel fuel raises heat output at premixed combustion phase, reduces the combustion at diffusion phase. When the injection advance had been closer to TDC, it caused a decrease in pre-phase peak value and an increase in values in diffusion phase.

In the light of obtained values, no negative impact observed on performance with the addition of ester up to 20% by volume and these results are concordant to the results of the other researches. It is seen that ester blended fuels capture the peak pressure value in less time at suitable injection advance for engine as given in the literature. Similar to the prior studies, biodiesel addition to diesel fuel raises heat output at premixed combustion phase, reduces the combustion at diffusion phase. On the other hand, when the injection advance had been closer to TDC, it caused a decrease in pre-phase peak value and an increase in values in diffusion phase.

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