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# A comprehensive study on the effect of pilot injection, EGR rate, IMEP and biodiesel characteristics on a CRDI diesel engine

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ABSTRACT

Although many studies have concerned effect of different kind of biodiesel fuel on engine, there are no information about the comparison between different biodiesels in a comprehensive study and with consideration of pilot injection and EGR system. Therefore, the aim of this study is to have a comprehensive investigation of the effect of pilot injection timing and EGR system, as common ways to reduce engine emissions, on engine combustion, emissions and performance while using of different kind of the biodiesel. The brassica, cardoon, coffee, waste cooking oil biodiesels and standard diesel fuels were evaluated fuels. However, the results of the study depicted that different characteristics of the considered fuels had changed the engine response to variation of injection strategy and EGR application. The maximum reduction of combustion duration compare to diesel fuel (17.7%) was related to coffee biodiesel. Moreover, Coffee biodiesel has lowest pressure rise rate. On the other hand, cardoon had shortest ignition delay and highest combustion temperature. In addition, maximum retardation of combustion position was for brassica biodiesel fuel (19.07%). Although the $NO_x$ emission has decreased due to application of EGR (up to 86%) and pilot injection (up to 29.3%), high EGR rate in high IMEP has changed the combustion quality due to sewer changes in the combustion quality. In this condition, CO and THC emission increased severely. Higher viscosity and lower oxygen content of the coffee and cardoon biodiesel than diesel fuel decreased combustion quality and caused the higher THC, CO and soot emissions and lower $NO_x$ emissions than brassica and WCO biodiesel fuels in higher EGR rates and IMEPs. It can be stated that pilot injection and EGR are two parameters which are effective significantly on the engine characteristics and the adjusting of these parameters should be done properly specially according to the used fuel properties.



## 1. Introduction

In recent years, the increase of energy demand and the oil field depletion have increased the research towards new energy sources such as biofuels. However, their utilization has led to either advantages or drawbacks in engine combustion characteristics and consequently performance and emissions. Concerning the engine management, a proper calibration is therefore required in order to enhance the advantages and compensate disadvantages of the biodiesel fuel application such as increase in the amount of $NO_x$ emissions due to its excess oxygen content compare to diesel fuel.

Changes in the emissions, performance and combustion characteristics of the engine due to application of biodiesel fuel in diesel engine is reported by many researchers and generally these variations are being related to the characteristics of these fuels. For instance, higher CN of biodiesel fuel is introduced as a reason for the shorter ignition delay of the biodiesel fuel compare to diesel fuel. This cause lower amount of fuel injection before combustion and then causes lower MAXPR and MAXHRR [1]. This is also a reason, not the main reason, for increase in the amount of the $NO_x$

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**Nomenclature**

| | |
|---|---|
| BSFC | Brake specific fuel consumption (g/kWh) |
| CI | Compression ignition |
| $CO_2$ | Carbon dioxide (%) |
| $CO_{2(amb)}$ | $CO_2$ measured in ambient (%) |
| $CO_{2(exh)}$ | $CO_2$ measured at engine exhaust (%) |
| $CO_{2(int)}$ | $CO_2$ measured at engine cylinder intake (%) |
| CN | Cetane number |
| EGR | Exhaust gas recirculation |
| SPI | Start of pilot injection |
| °bMI | Crank angle degree before main injection |
| bTDC | Before top dead center |
| CAD | Crank angle degree |
| ICE | Internal combustion engine |
| LHV | Lower heating value |
| $NO_x$ | Nitrogen oxides (ppm) |
| Co | Coffee biodiesel |
| Ca | Cardoon biodiesel |
| Br | Brassica biodiesel |
| WCO | Waste cocking oil biodiesel |
| $H_2O$ | Hydrogen dioxide |
| THC | Total hydrocarbon |
| HRR | Heat release rate |
| MAXPR | maximum pressure rise |
| MAXHR | Maximum heat release |
| NHR | Net heat release |
| Tmax | Maximum combustion temperature |
| ID | Ignition delay |
| FSN | Filter smoke number |
| WP | Without pilot injection |
| PMII | Pilot-main injection interval |

emissions [2]. However, opposite trend is also reported by some other researchers [3]. These two different trends can be seen for the EGT of the engine fueled with biodiesel fuel. Increase in the heat release rate, which is due to lower LHV of the biodiesel fuel compare to diesel fuel, is introduced as a reason for increase in the EGT of the engine fueled by biodiesel fuel [3]. The other characteristics of the biodiesel fuel is its inherent oxygen content. Generally, biodiesel contains about 10–12% (by weight) oxygen in its chemical structure. Although, this help toward more complete combustion and lower HC, CO and soot emissions, it causes increase in the formation of the $NO_x$ emissions [4,5]. In addition, it is reported that the surface tension and density of the biodiesel fuel are mainly higher than diesel fuel which alter the fuel injection characteristics and then deteriorate the combustion quality [6]. The other difference between diesel and biodiesel fuels is the lower LHV of the biodiesel fuel compare to diesel fuel. This means that the higher amount of the fuel should be burnt to produce same amount of the engine power. In other words, BSFC and BTE of the engine while fueling by biodiesel fuels is higher than that when is fueled by diesel fuel [2,7]. Finally, however biodiesel fuel changes the engine combustion, performance and emissions, increase of $NO_x$ emissions has been the most challenging issue related to these kind of fuel.

One of the ways to reduce $NO_x$ emissions of the IC engines is to use the EGR (exhaust gas recirculation) system. This system recirculates a portion of exhaust gases into the combustion chamber [8], which their effects is dependent on the engine working conditions (IMEP and speed), the fraction and the temperature of recirculated gases [8]. However, the reduction of $NO_x$ emissions increases CO, UHC and PM [9,10].

Another technology, initially proposed for reducing combustion noise emissions in compression ignition engines is performing a primer injection (so-called pilot injection) before the main injection [11]. In this way, the reduction of the main injection ignition delay, and then the reduction of the premixed combustion burned fuel and peak combustion temperature are observed. In addition, it decreases $NO_x$ emission of the engine [11,12].

Yasin et al. [13], conducted a research on effect of the EGR and palm biodiesel application in a DI diesel engine. They found that engine torque, engine power and $NO_x$ emissions decreased and fuel consumption, CO, particulate matters and $CO_2$ increased while application of the palm biodiesel and EGR. Solaimuthu et al. [14], studied effect of the EGR and Mahua biodiesel fuel on engine combustion, performance and emissions. They stated application of the EGR with Mahua biodiesel can leads to a trade-off problem about the increase of particulate matters and $NO_x$ emissions reduction.

Effect of the pilot injection strategy on the diesel engine characteristics have been investigated by different researchers. They found that $NO_x$ emission is decreased while using of the pilot injection. The opposite trend has been found for the soot formation [11,12]. Particulate matter and soot have increased while using pilot injection. But some researchers stated that using of small amount of pilot injection and closer to the main injection is not effective on the soot formation [12,15]. It is found that THC emission increases due to using of pilot injection while in high load the variation in THC emission is negligible [15,16].

According to the above mentioned studies and literature review, it would be a good idea to investigate the effect of the EGR and pilot injection simultaneously on the emission, combustion and performance of CRDI engine while using of the different biofuel sources. Then, the aim of this study is to consideration of the effect of the different EGR rate (0, 10 and 20%) and pilot injection timing (10 and 5 °bMI) in different IMEPs (4, 6 and 800 kPa) while using 5 different fuels (brassica, cardoon, coffee and waste cooking oil biodiesel and standard diesel). Due to different characteristics of the biodiesels, it is expected to reveal different behavior to the applied engine management strategies. In term of the literature review done by the authors, this is first comprehensive study on the simultaneously effects of these engine management strategies on the engine parameters while fueling by such different type of biodiesel fuels.

## 2. Materials and methods

### 2.1. Experimental setup

The experiments have conducted on a four stroke, common rail AVL single cylinder research engine model 5402. The technical main features of the engine are reported in Table 1. The engine shaft was coupled to an eddy current dynamometer (SYSTEM ANTRIEBSTECHNIK), which can either dissipate the output power of the engine. The control unit (AVL EMCON series 300) allows to set two of the following three variables: engine speed, braking torque and fueling.

### 2.2. Instrumentation

Fig. 1 shows a schematic diagram of engine setup and its instrumentation. ETK interface manages, through a dedicated PC (personal computer), the engine control unit (BOSCH EDC15C7); in

**Table 1**
Specifications of AVL single cylinder research engine 5402.

| | |
|---|---|
| Engine type | 4-stroke water cooled Diesel |
| Manufacturer | AVL |
| Model | 5402 |
| Number of cilynders | 1 |
| Maximum power | 18 kW |
| Bore | 85 mm |
| Stroke | 90 mm |
| Connecting rod | 138 mm |
| Displacement | 510 $cm^3$ |
| Compression ratio | 17.1:1 |
| Combustion chamber | Bowl with valve pockets and flat head |
| Injection system | Common rail |
| Max. injection pressure | 1300 bar |
| Number of nozzles | 5 |
| Nozzle diameter | 170 μm |
| Spray angle | 142° |

this way it is possible to monitor, as well as to set to defined values for the fuel injection parameters such as injection pressure, injection duration and start of the injection.

A piezoelectric sensor (AVL QC33C), equipped with an amplifier (AVL 3066A01), was used to measure inside cylinder pressure. The pressure inside the cylinder was measured during 10 consecutive cycle and the average of them reported as the cylinder pressure of the engine. Two piezoresistive sensors are used to measure the absolute pressure in the piping connecting the high pressure pump with the solenoid injector (KISTLER 4067A2000) and along the intake duct (KISTLER 4045A2). Both sensors mentioned above are connected to a voltage amplifier (respectively, KISTLER 4618A2 and 4643). The sampling of the pressure signals takes place on an angular basis, provided by an encoder AVL 364C, which trigger the acquisition and storage of the signals every 0.2 CAD (Crank angle degree). Thermocouples have been used to measure the engine intake and exhaust temperature as well as coolant water and lubricating oil temperature, these last two in order to monitor the correct operation of the engine. The engine fuel consumption has been measured through an AVL Fuel Balance 733S with an accuracy of 0.12%.

In-cylinder pressure measurements allowed to estimate the heat release rate as suggested in Ref. [17]:

$$\frac{d\dot{Q}}{d\theta} = \frac{\gamma - 1}{\gamma} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta} \tag{1}$$

where θ is the crank angle degree and γ is the specific heat ratio of the in cylinder mixture gases fixed equal to 1.35, V and p are the instantaneous values of cylinder volume and pressure.

To calculate the EGR ratio, the following formula was used:

$$\%EGR = \frac{CO_{2(int)} - CO_{2(amb)}}{CO_{2(exh)} - CO_{2(amb)}} \times 100 \tag{2}$$

where.

$CO_{2(exh)}$ is $CO_2$ gas amount in tailpipe (ppm)
$CO_{2(int)}$ = amount of $CO_2$ gas in cylinder inlet (ppm)
$CO_{2(amb)}$ = amount of $CO_2$ gas in Air (ppm)

The measurements of the temperatures of the coolant and exhaust gases which took place by means of thermocouples, have allowed to ascertain the correct operation of the engine. Thermocouples of the same type have been used for the purpose of measuring the temperature of the intake and the lubricating oil temperature. The test set up was conducted by LabVIEW software, a development environment for applications oriented to the

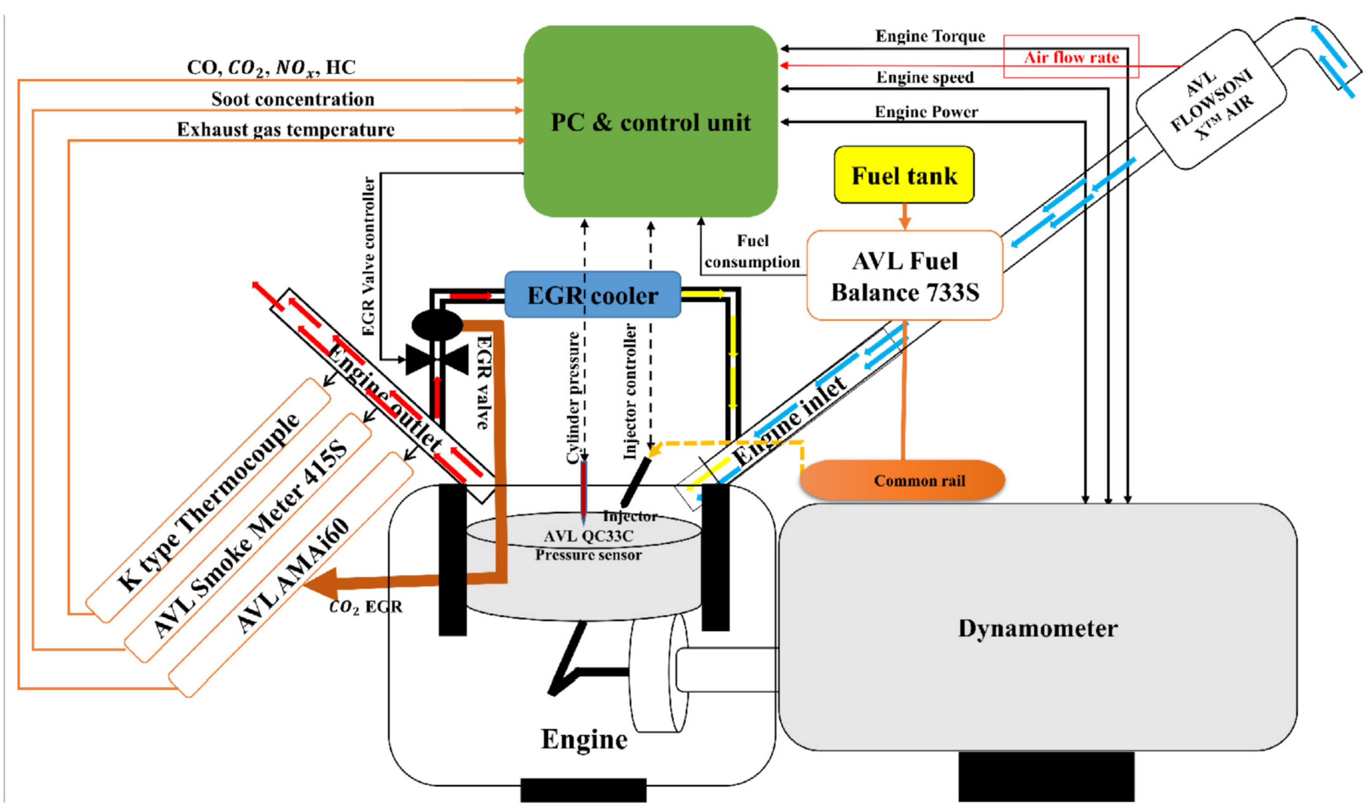


**Fig. 1.** Schematic of the experimental layout.

Table 2
Technical specification of measuring equipment.

| Parameter | Measurement range | Accuracy | Measurement device |
|---|---|---|---|
| $NO_x$ | 0 … 10/10,000 ppm | ±10% | AVL AMAi60 |
| CO | 0 … 0.5/10 vol% | ±0.03% | AVL AMAi60 |
| $CO_2$ | 0 … 0.5/10 vol% | ±0.5% | AVL AMAi60 |
| THC | 0 … 10/20,000 ppm C3 | ±10 ppm | AVL AMAi60 |
| Intake air mass flow | 0 (±20) … ± 1400 kg/h | < ± 1% of reading | AVL FLOWSONIX™ AIR |
| Intake air temperature | −200 up to 1100 °C | −40 − 375: ±1.5<br>375−1000: ±0.004 × T | K-type thermocouple |
| Soot concentration | 0 to 10 FSN | 0.002 FSN | AVL smoke meter 415SE |
| Fuel consumption | 0−150 kg/h | ≤0.12% (acc. to DIN 1319) | AVL fuel balance 733S |
| Exhaust gas temperature | −200 up to 1100 °C | −40 − 375: ±1.5<br>375−1000: ±0.004 × T | K-type thermocouple |

acquisition of data, the management of electronic devices and signal processing. This allows real-time display and generation of a report of the variables values. The consumption of the engine have been recorded with the aid of the balance AVL Fuel Balance 733S, which enables the sampling of the signal corresponding to the fuel consumption at intervals of a tenth of a second, with an accuracy of 0.12% and AVL FLOWSONIXTM AIR were used to measure the intake air flow rate. In addition, CO, $CO_2$, $NO_x$ and THC exhaust emissions were measured by AVL AMA i60, while AVL Smoke Meter 415S provided for the measurement of particulate concentration. Specification of the measuring equipment are shown in Table 2.

### 2.3. Tested parameters and experimental procedure

Engine tests were conducted by fueling the engine with B20 (20% biodiesel and 80% conventional diesel fuel, volume based) mixtures obtained from the four biodiesels, at 1500 rpm engine speed. Two different pilot injection timings (5 and 10° crank angle before main injection (bMI) (in the other words, pilot-main injection interval were 5 and 10 CAD)) and three different EGR rate (0, 10 and 20%) were tested at three different IMEPs (400, 600 and 800 kPa). Main injection was set at 6° before top dead center in all test points. Injection pressure was always set equal to 50 MPa. The test matrix for each fuel blend is summarized in Table 3.

### 2.4. Biodiesel production

In this research, three biodiesels derived from three oleaginous species of great interest, brassica and cardoon seeds and waste coffee, have been characterized in order to assess their potential for biodiesel production. Waste cooking oil as a common biodiesel fuel source was used to have more comprehensive study. The biodiesels were provided by the Institute of Food Production (ISPA-CNR Sciences) and the methodology followed to extract them which is described in Ref. [6].

Table 3
Test matrix for each fuel blend.

| Factor | Unit | Levels |
|---|---|---|
| IMEP | kPa | 400-600-800 |
| EGR rate | % | 0-10-20 |
| Pilot injection | °bMI | 5−10 |

## 3. Results and discussion

### 3.1. Test fuel standardization

The properties of biodiesels and their blends are compared to ASTM biodiesel standards. The tested properties of methyl esters of brassica, cardoon and coffee oil are found to be reasonable agreement with ASTM 6751. It is observed from Table 4 that the typical characteristics of brassica, cardoon and coffee biodiesels are in the range of the requirement of the engine.

### 3.2. Pressure rise rate

Maximum pressure rise (MAXPR) rate is a measure of the combustion noise [18]. As it can be seen in Fig. 2, MAXPR of biodiesel fuels were lower than diesel fuel when pilot injection was not applied. This is in accordance with the results of the research conducted by Islam et al., [19]. Qi et al. [20], found that MAXPR of biodiesel compared to diesel fuel depends on engine load: higher at lower engine load and vice versa. They stated that the pilot injected fuel and longer ID are the reasons for higher MAXPR of biodiesel fuel than diesel fuel.

MAXPR were decreased due to application of EGR in most of the test conditions. One reason for the reduction of the MAXPR due to application of the EGR is its prolongation of the ignition delay due to application of the EGR. This is in accordance with the results of Huang et al., [21].The maximum reduction of the MAXPR due to application of the EGR rate for brassica, cardoon, coffee, WCO and diesel fuels were 27.1, 28.9, 13.2, 19.6 and 17.2%, respectively.

It seems that the effect of the pilot injection to reduce MAXPR

Table 4
Characteristics of produced biodiesels.

| Parameter | Standard | Unit | Limits | Cardoon | Coffee | Brassica | WCO | Diesel |
|---|---|---|---|---|---|---|---|---|
| Flash point | ASTM D93 | °C | 93 min | 309 | 292 | 296 | 302 | 78 |
| Methanol content | EN14110 | % m/m | 0.2 max | <0.01 | <0.01 | <0.01 | <0.01 | – |
| Water and sediment content | ASTMD2709 | % v/v | 0.05 max | <0.01 | <0.01 | <0.01 | <0.01 | – |
| Dynamic viscosity at 40 C | ASTM D445 | cSt | 1.9−6.0 | 9.5 | 5.7 | 6 | 6.1 | 3.5 |
| Cetane number | ASTM D 613 | | 47 min | 57.44 | 56.11 | 56.44 | 57.12 | 48 |
| oxidation stability | EN 15751 | h | 3 min | >12 | 9 | >12 | >12 | – |
| Lower heating value | – | MJ/kg | – | 40.69 | 39.18 | 40.10 | 39.6 | 43.8 |
| Oxygen content | – | % | – | 10.91 | 7.77 | 13.44 | 9.45 | 0 |
| Surface tension | Drop shape method | mN/m | – | 40.99 | 37.62 | 42.05 | 40.52 | 34.1 |

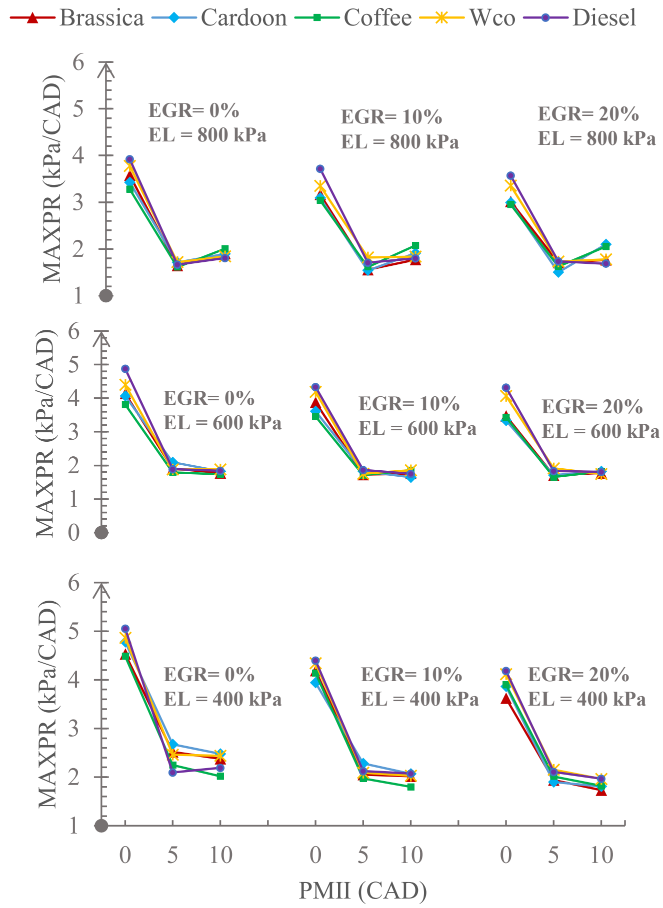


**Fig. 2.** Effect of the using of different fuels, EGR rates and injection strategy on combustion pressure rise in different engine load.

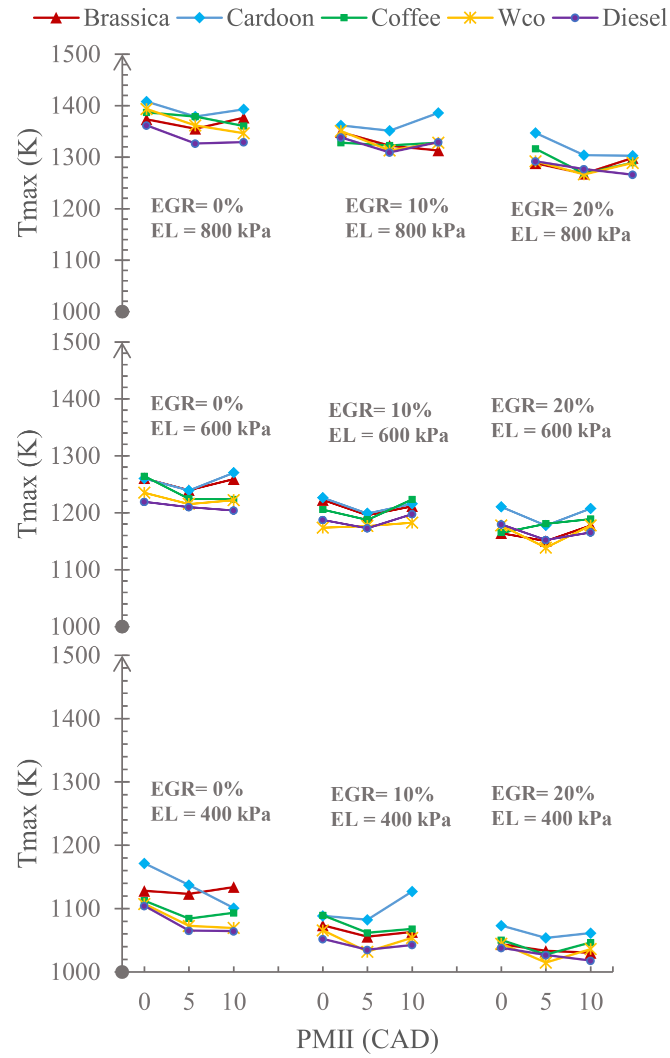


**Fig. 3.** Effect of the using of different fuels, EGR rates and injection strategy on maximum combustion temperature (K) in different engine load.

for diesel fuel was higher than that for biodiesel fuels. This can be due to this fact that ID which has the main role in the amount of the peak heat release and MAXPR, of the diesel fuel was longer than biodiesel fuel. Then, effect of pilot injection to reduce ID and MAXPR was higher than that for biodiesel fuel. The maximum reduction of the MAXPR due to application of the pilot injection for brassica, cardoon, coffee, WCO and diesel fuels were 57.1, 55.2, 56.5, 58.2 and 62.3% respectively.

### 3.3. Combustion temperature

Maximum in-cylinder bulk temperature (Tmax) is important given that strongly influences production of the $NO_x$ [22].

Higher combustion temperature of biodiesel fuel compare to diesel fuel is a point which can be seen in Fig. 3. This is due to higher CN and then lower ID of the biodiesel fuel which has changed the heat release rate and premix combustion phase [23].

Tmax of the cardoon biodiesel fuels is higher than other fuels in most of the IMEPs, EGR rates and injection strategies. This is due to this fact that the CN of cardoon biodiesel is higher than other fuels (57.44). Oxygen content of the biodiesel fuel provides the possibility of the combustion with lower air requirement. This is a reason for the increase of the combustion temperature of biodiesel fuel combustion [24]. The maximum increase in the Tmax is 8.09% and it is for cardoon biodiesel in 400 kPa IMEP, 10% EGR rate, 5°bMI SPI. Some other researchers stated that the peak combustion of biodiesel fuel is lower than diesel fuel [25] which can also be seen for some test point. This can be due to lower burn rate of the biodiesel fuel which cause low acceleration of fuel burning rate during diffusion combustion and then lower peak temperature. This is in agreement with the result of research conducted by Ooi et al., [25].

Reduction of the Tmax with increase in EGR rate is due to higher specific heat capacity of the recirculated gas such as $CO_2$ and $H_2O$ than fresh air molecules [24]. The maximum reduction of the Tmax is 9.14% which is for brassica biodiesel in 400 kPa IMEP, without pilot injection and 20% EGR rate. This reduction is calculated regard to Tmax for diesel fuel without EGR in same test condition.

Application of the pilot injection has reduced the Tmax slightly. This can be due to lower NHR and also reduction of the maximum of HRR. Maximum reduction of the Tmax due to using of the pilot injection is 6.03% and it is equal to 1101.1 °C. This is for cardoon biodiesel in 400 kPa IMEP, 10 °bMI and without EGR. Except this test point, the reduction for the Tmax due to application of pilot injection is lower than 4%.

### 3.4. Heat release rate

At high IMEP and without pilot injection, heat release rate behavior exhibited two separated peak (Fig. 4), the first one associated to the premixed combustion followed by a second one associated to the diffusive combustion [26]. Generally, this is more

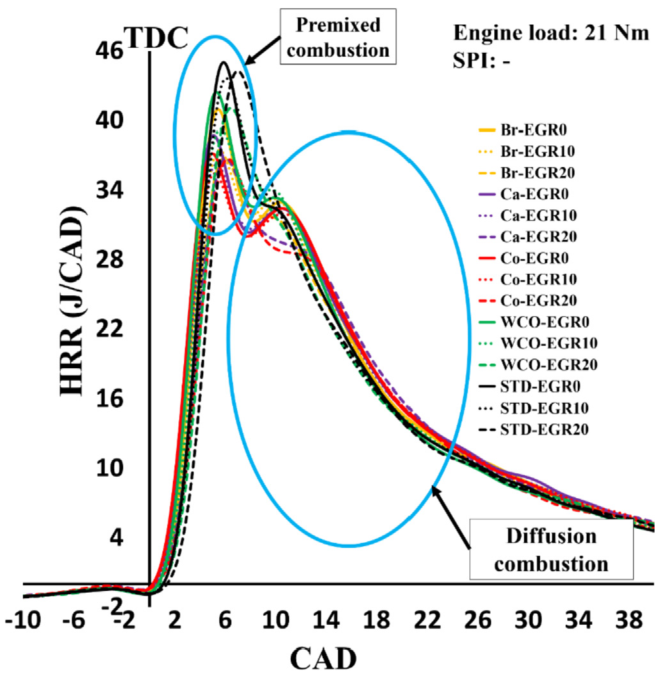


**Fig. 4.** HRR of the different fuel combustion and EGR rates for 800 kPa IMEP without pilot injection.

significant for biodiesel fuels due to oxygen bound which has improved combustion quality in diffusion combustion phase [27]. This lower premixed combustion leads to lower $NO_x$ and noise of the engine [25].

The initial impression from Fig. 5 is the growth of the NHR with rise of the IMEP. It is notable that the NHR of the biodiesel diesel fuel blends are higher than NHR of the pure diesel. This is more significant for coffee and cardoon biodiesel fuel. This can be due to lower surface tension and dynamic viscosity of coffee biodiesel and higher LHV of cardoon biodiesel fuel compare to other biodiesel fuels. In addition, NHR is decreased due to application of the EGR in most of the operational test point and fuels. Reduction of the in cylinder temperature due to application of the EGR is stated as the reason for decrease in the NHR and MAXHR [27].

A noticeable feature is the different trend of the NHR vitiation due to application of the pilot injection. In lower IMEP (400 kPa) NHR of the cardoon, coffee and diesel fuel experienced maximum reduction which is for 10 °bMI SPI and without EGR. The maximum reduction of the NHR is 5.8%. However there it is important to note that the NHR is increased in some test points and fuel types. The maximum increase of the NHR in 400 kPa IMEP is 1.3%. Increase of the NHR in 400 kPa IMEP is occurred mainly in high EGR rate (20%). In 600 kPa IMEP the maximum increase and decrease of the NHR due to application of the pilot injection are 2.6 and 3.6%. In 800 kPa IMEP variation of the NHR is reduced specially for brassica and diesel fuel. However the changes of NHR due to application of the pilot injection for coffee and cardoon biodiesel is still significant. The highest reduction and increase of the NHR in 800 kPa IMEP are 5.2 and 3.2%, accordingly. Another distinguishing feature is higher effect of the advanced SPI on NHR for all kind of the fuels. The rise of the NHR with advanced of SPI is stated by other researchers [28].

In addition, maximum heat release (MAXHR) is decreased due to application of the EGR. Generally, this decline is more pronounced for biodiesel fuel than diesel fuel. A noticeable feature is similar trend for various fuel rate when only main injection is applied and various trend of MAXHR variation when pilot injection is applied. The maximum reduction of MAXHR is 25%. In most of the test points, application of the pilot injection has intensified effect of the EGR rate on reduction of MAXHR. It is important to note that effect of EGR rates on reduction of MAXHR of brassica which has lower LHV is higher than other biodiesel fuel. Furthermore, MAXHR is decreased due to application of pilot injection.

The reduction of the MAXHR in 400 kPa is mostly higher than 40% and maximum and average of this reduction is 56 and 46.2%,

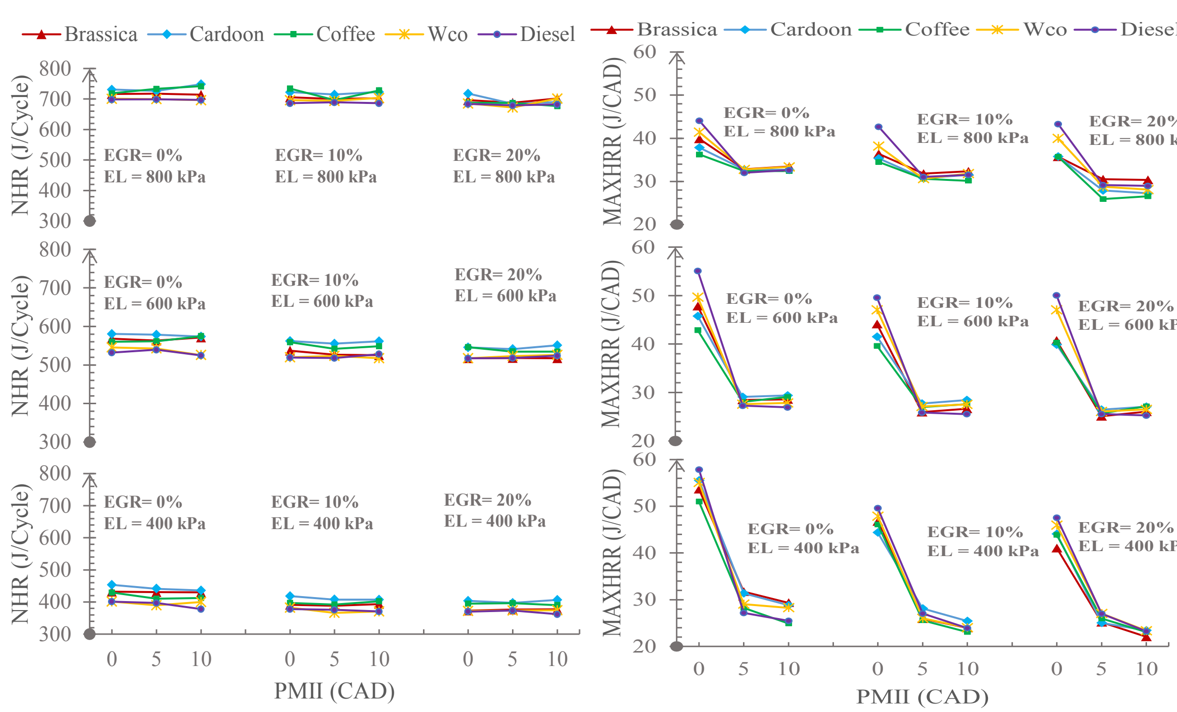


**Fig. 5.** Effect of the using of different fuels, EGR rates and injection strategy on net heat release rate (J/Cycle) and maximum heat release in different engine load.

respectively. This reduction of the MAXHR in 800 kPa IMEP is more decreased such that the average and maximum of it are 19.6 and 33.1%, respectively. It is important to notice that the reduction of the MAXHR for biodiesel fuel specially in lower EGR rate is lower than diesel fuel in 800 kPa IMEP. Reduction of the MAXHR is also reported by Ryu [28]. This can be due to oxygen content of the biodiesel fuel which had improved oxygen availability in high engine load.

### 3.5. *Ignition delay (ID)*

Time interval between the start of the fuel injection and start of the combustion is defined as the ignition delay. One of the most effective parameter on the engine heat release rate and its emission is the ignition delay [29,30].

Fig. 6 shows the effect of fuel type, engine load and injection strategy on the ignition delay for different IMEP, EGR rate and SPI.

The main effective parameter on the ID is the CN of the fuel and it is known that ID is shortened with increase in the CN. As it can be seen in Table 4 the CN of all of the biodiesel is higher than the diesel fuel. Therefore, their ID is shorter than diesel fuel. The other parameters which are effective on ID are those parameters which may deteriorate the combustion quality. This can cause increase ID. The differences of the CN for biodiesel fuels is in the range of 1.33. Therefore, however in most of the engine working mode the lowest ID is for cardoon biodiesel fuel which has lowest CN, the differences in the ID for different biodiesel fuel can be attributed to their surface tension and oxygen contents which are two effective parameters on combustion quality. There is an interesting feature about the ID of different fuels in the various EGR rate. ID of the cardoon and coffee is closer to ID of diesel fuel with increase in EGR rate while this is in opposite trend for brassica and WCO biodiesel. This is due to different surface tension of the biodiesel fuels which is effective on atomization quality. Since the design of the injection system and engine is according to the pure diesel fuel, then the fuel which has similar characteristics to diesel fuel will show same characteristics. Surface tension of the coffee is 37.62 which is the minimum among the four biodiesel fuels and it is closer to surface tension of diesel fuel (34.1) while the maximum surface tension is 40.99 for cardoon biodiesel fuel. Therefore, as it can be seen in Fig. 6 in some data points coffee biodiesel fuel has lowest ID. Furthermore, oxygen content of the brassica and WCO (13.44% and 12.01%) are higher than that for cardoon and coffee (10.91% and 7.77%) biodiesel. Then, this higher oxygen content can be a reason for sooner start of the combustion and shorter ID in higher EGR rate and especially higher IMEP which oxygen inside the cylinder is

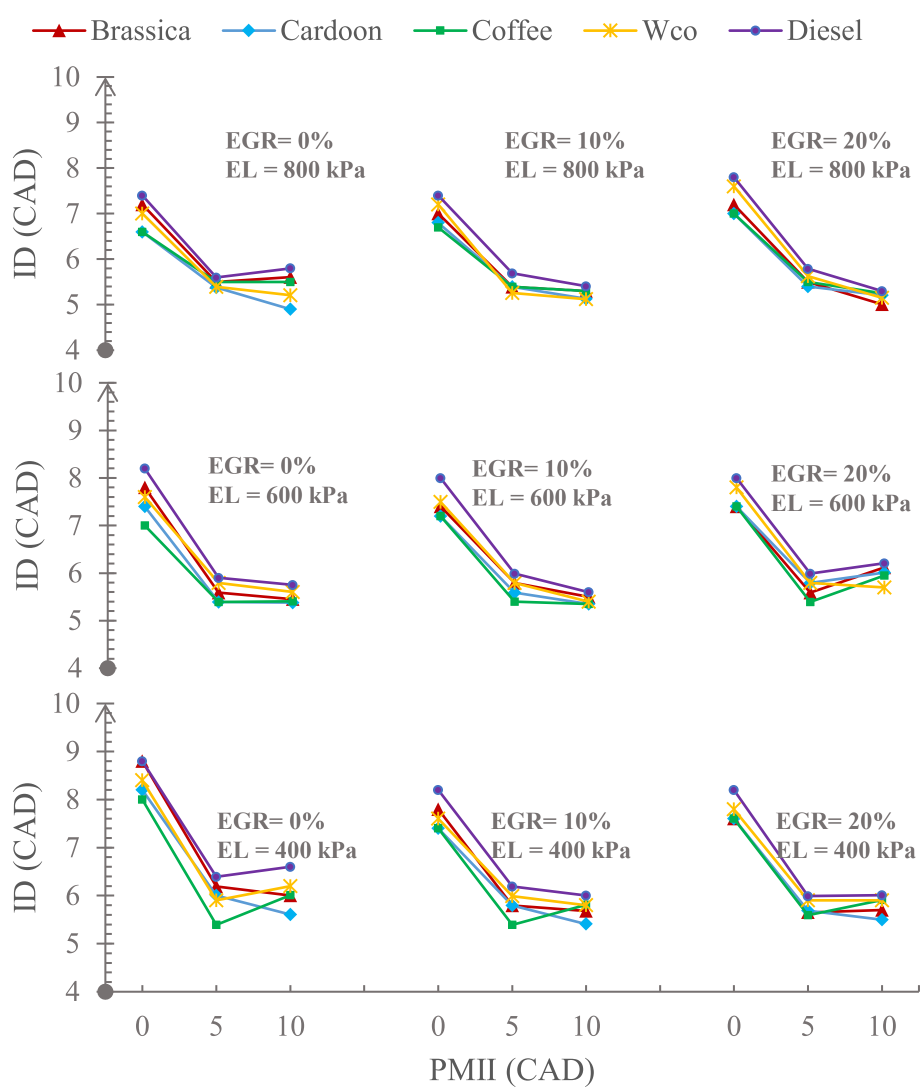


**Fig. 6.** Effect of the using of different fuels, EGR rates and injection strategy on ignition delay (CAD) in different engine load.

minimum value. Maximum reduction of the ID due to using of the cardoon, coffee, brassica and WCO fuel compare to diesel fuel are 15.6%, 15.6, 7.7 and 10.2%, respectively.

ID is decreased with combustion without pilot injection due to application of the EGR. This can be seen obviously in 4 kPa IMEP. The maximum reduction of ID in 10 and 20% EGR rate in 4 kPa IMEP without pilot injection are 11.4 and 13.6%, respectively. Application of EGR in higher IMEPs (6 and 8 kPa) cause just a low reduction in ID or even increase of it. Maximum increase of the ID is in 20% EGR rate and 800 kPa IMEP which is 8.6%. Changing of the injection strategy and using of the pilot injection in 5 °bMI has changed the effect of the EGR rate on the ID. The ignition delay in this condition has increased and as it can be seen in the 20 EGR rate and 800 kPa IMEP is the maximum value which is 7.5% higher than that without EGR for cardoon biodiesel. Application of the advanced SPI (10 °bMI) is increased the ID especially in 20 EGR rate and 8 kPa IMEP and the highest increase in ID due to application of the EGR rate is 12.3%. Despite this increase of the ID for this test point, ID is decreased due to application of the EGR rate while using of the advanced pilot injection. Reduction of the ID due to application of the EGR is also reported by other researchers [31]. Other researchers stated that the EGR will increase the ID. Larger premix combustion fraction due to application of the EGR is reported as the reason for this increase [26]. Retardation of the start of combustion and longer ID due to application of the EGR is also reported by Tsolakis et al., [32].

Totally, it can be stated that although ID of all of the biodiesel fuels were shorter than diesel fuel due to their higher CN compare to diesel fuel, the parameters such as surface tension and oxygen content of the biodiesel fuel were effective parameters cause different ID for different biodiesel fuels which have approximately same CN.

## 4. Performance analysis

### 4.1. Brake thermal efficiency

Brake thermal efficiency (BTE) is a measure of the fuel conversion efficiency which shows the derived power from chemical energy of the fuel [31].

BTE of the engine for various fuels in different EGR rates, injection strategies and IMEPs are shown in Fig. 7.

As it can be obviously seen in this figure BTE of all biodiesel fuels are lower than diesel fuel in most of the test points. This is mainly due to lower LHV of the biodiesel fuels than diesel fuel [31,33].

In addition, low quality of the atomization and combustion due to higher viscosity of the biodiesel are stated as the reasons for the lower BTE of the biodiesel than diesel fuel [31,33,34]. This can be the reason of the reduction of the BTE in lower IMEP of the brassica and cardoon in lower IMEPs since the surface tension of the brassica (42.05 mN/m) is the highest surface tension among all of the fuels and the dynamic viscosity of the cardoon biodiesel fuel (9.5 cSt) is the highest value among all of the fuels.

In the other hand, the oxygen content had played more significant role in higher IMEP (8 kPa) and the BTE of the brassica which has higher oxygen content was higher than other fuels which had lower oxygen content. The other important feature is increase of the BTE for all kind of the fuels with increase of the IMEP. Maximum reduction of the BTE were related to the cardoon and coffee biodiesel in 800 kPa IMEP, 20% EGR rate and without pilot injection strategy and they were 24.8 and 27.6% which is due to severe deterioration in the combustion quality in these test points for these fuels.

Low oxygen content, low temperature inside the cylinder and combustion deficiency due to application of high EGR rate are

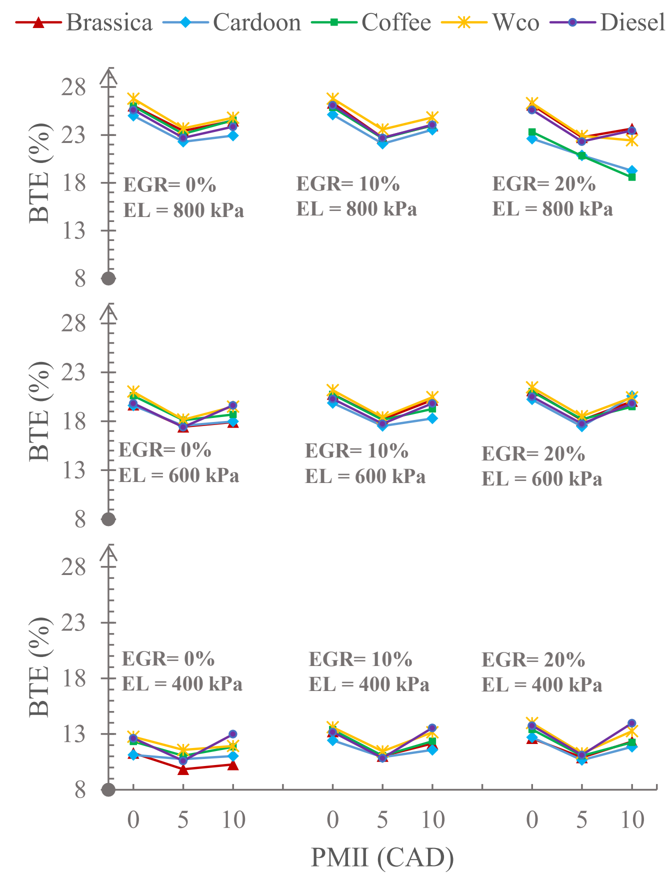


**Fig. 7.** Effect of the using of different fuels, EGR rates and injection strategy on brake thermal efficiency in different engine load.

stated as the reasons for the reduction of the BTE in higher EGR rate [31]. It is important to note that highest reduction of the BTE are for coffee and cardoon biodiesel fuels (24.4% and 16%) which have lowest oxygen content (7.77 and 10.91%, respectively) in all injection strategies. It is noticeable that BTE of the brassica and WCO which have highest amount of the oxygen content are higher than other fuels. It can be stated that in low and medium engine loads oxygen content of the brassica and WCO has decreased effect of the EGR in reduction of the oxygen inside the cylinder. Maximum increase of the BTE due to application of the EGR while using of the biodiesel fuel is for brassica biodiesel (18.4%).

Application of the pilot injection has decreased BTE of the biodiesel fuels in all of the operational test points. BTE of the various fuels in 10 °bMI SPI is lower than it in 5 °bMI SPI for 400 kPa engine load. Higher BTE of the pure diesel fuel is due to higher LHV of the diesel fuel than biodiesel diesel blend fuels. It can be stated that advanced SPI has controlled heat release rate of the combustion better than SPI closer to main injection and has increased BTE of the engine [35].

### 4.2. Brake specific fuel consumption (BSFC)

The BSFC of the engine in different IMEPs, EGR rate and pilot injection for various fuels are shown in Fig. 8.

As it can be seen in this figure the BSFC for all of the biodiesel-diesel blends is higher than pure diesel fuel and this is more significant in lower IMEP (400 kPa). This is due to lower LHV of biodiesels than diesel fuel which means higher amount of biodiesel

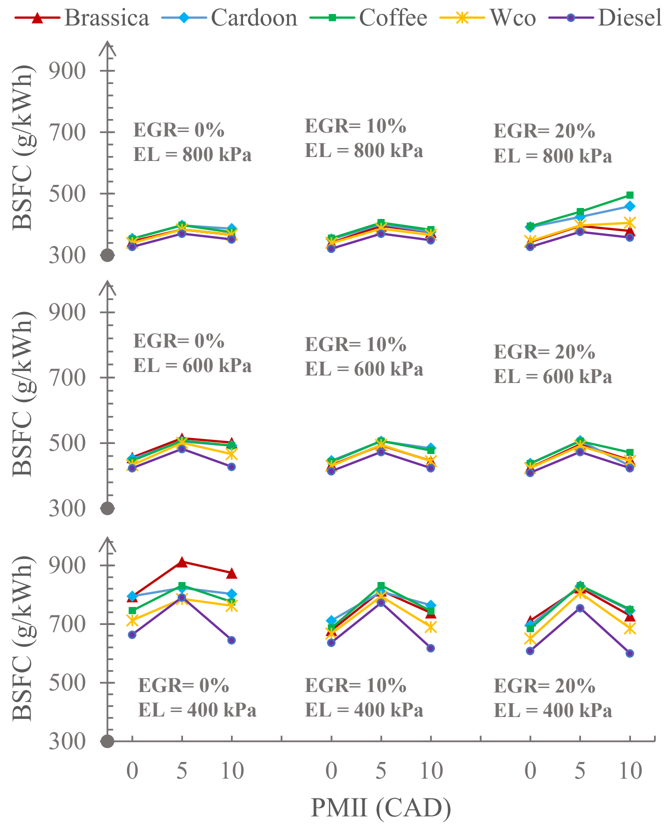


**Fig. 8.** Effect of the using of different fuels, EGR rates and injection strategy on brake specific fuel consumption in different engine load.

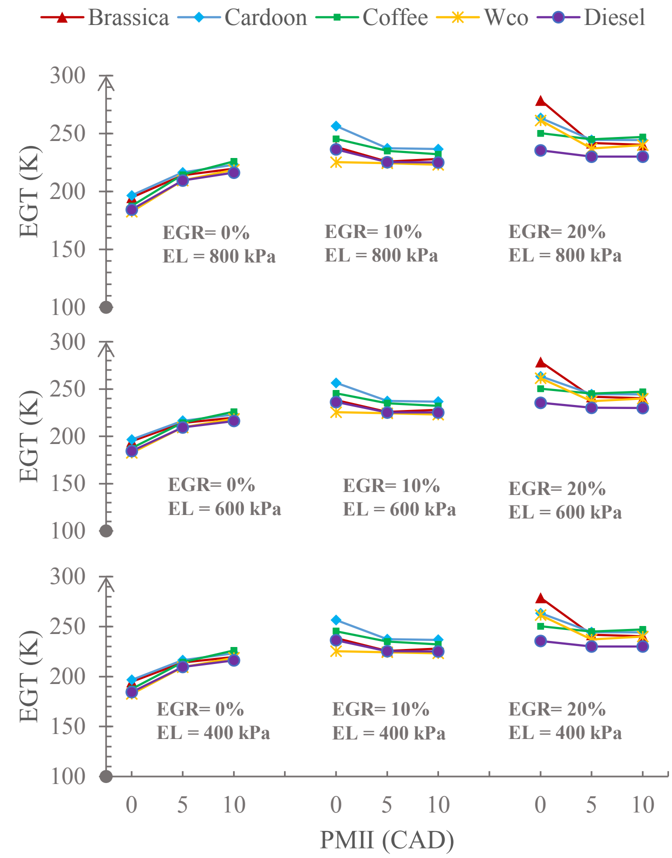


**Fig. 9.** Effect of the using of different fuels, EGR rates and injection strategy on exhaust gas temperature in different engine load.

fuel is required to produce same thermal power as diesel fuel [36–38].

Increase in BSFC with increase in EGR rate is due to reduction of the combustion quality which comes from the chemical effect of EGR and reduction of the oxygen content inside the cylinder [27]. This can be seen obviously for the coffee and cardoon biodiesels. In high IMEP (800 kPa) the role of the biodiesel oxygen content is more important, especially in higher EGR rate. Then, the BSFC for coffee and cardoon fuels which have lower oxygen content (10.91 and 7.77%, respectively) in 800 kPa and 20% EGR rate is higher than other fuels. In addition, advanced SPI reduced BSFC. This is due to increase of the combustion quality which improves the thermal efficiency of the combustion. In addition, BSFC is decreased with increase in IMEP. This is due to lower frictional power in higher engine load [39]. The maximum BSFC is related to low IMEP (400 kPa) and 5°bMI pilot injection which is 912.05 (g/kWh) for brassica biodiesel without EGR. This is also highest increase of BSFC regard to diesel fuel (103.17%). The maximum BSFC of other biodiesels is appeared in same condition but with 20% EGR rate which are 829, 831 and 806 (g/kWh) for cardoon, coffee and WCO biodiesels, respectively.

Maximum increase and decrease of BSFC due to using of EGR are 32.2% and 16.6% respectively, and it is for brassica biodiesel. Increase of the BSFC due to application of the EGR is result of deterioration of combustion. It is came from higher specific heat of recirculated gases and reduced oxygen in cylinder [27]. BSFC is increased while using of the pilot injection in most of the test conditions. Rise of the BSFC due to advanced SPI is also reported by other researchers [40].

### 4.3. Exhaust gas temperature

Exhaust gas temperature is important because it is effective on the after treatment devices and catalytic converters [41]. Fig. 9 compares exhaust gas temperature of engine while using different biodiesel in various IMEPs, EGR rate and start of pilot injection.

As it can be seen in this figure, exhaust gas temperature of all kind of fuels is increased with increase in IMEP. Lee et al., stated that this is due to extension of the combustion duration and shifting of combustion to the end of the expansion stroke [41]. In addition, exhaust gas temperature of different biodiesel blend fuels are higher than pure diesel fuel. This is more significant for coffee and cardoon biodiesel. The highest exhaust gas temperature for coffee, cardoon, brassica and WCO biodiesel diesel fuels are 442.76 (800 kPa IMEP, 5 °bMI SPI and 20% EGR rate), 441.09 (800 kPa IMEP, 5 °bMI SPI and 20% EGR rate), 426.28 (800 kPa IMEP, 5 °bMI SPI and 20% EGR rate) and 44.90 °C (800 kPa IMEP and 20% EGR rate), respectively. Higher exhaust gas temperature of the biodiesel fuels can be understood by considering of heat release rate graph. As it can be seen in the HRR graph, higher fraction of the combustion and heat release is shifted to the end of the combustion stroke [24].

Although there is two test point which exhaust gas temperature is decreased due to application of EGR, in all of other operational test point EGT is increased by application of the EGR. This can be seen clearly in lower IMEP (400 kPa). The maximum increase in exhaust gas temperature is 43.2% and it is for WCO. In addition, the rate of the growth in EGT due to application of the EGR rate is lower in advanced SPI. The heat release graphs should be considered in order to have more specific study of the EGT. This is in contrary with the result of the Agrawal et al., research [42]. Application of the EGR decreases EGT and introduced lower oxygen availability and higher specific of the recirculated gas as the reason for this reduction. Hawi et al., found that the reduction of the EGT due to application of the EGR and the reasons stated by Agrawal et al., has a limitation. They indicated the high EGR rate can increase EGT by increasing the heat of the cylinder than reducing it [43]. Although the EGT is increased in most of the operational point, it is reduced in lower IMEP (4 and 600 kPa) and advanced SPI (10 °bMI). As stated before, extension of the combustion duration and shifting of combustion to the end of the expansion stroke is a reason of the increase in EGT. This expansion can be seen for tests with pilot injection. Application of the pilot injection has shifted the peak HRR to the end of the expansion stroke as it can be seen in the HRR graphs (Fig. 4). One interesting point is the maximum increase of the EGT is in these IMEPs condition and without EGR. Maximum increase of the EGT due to application of the pilot injection is 20.5%.

## 5. Engine exhaust emissions

In the following sections emissions of the engine for different engine working mode and fuels are presented. The value of the THC, CO and $NO_x$ are converted from ppm to g/kWh by using of the method which is proposed by Pilusa, Mollagee and Muzenda [44] and Ağbulut, Sarıdemir and Albayrak [45].

### 5.1. THC emission

Fig. 10 compares THC emission of engine while using different biodiesel in various IMEPs, EGR rate and start of pilot injection. In general point of view, THC emission in 800 kPa IMEP and 20% EGR rate of coffee biodiesel is much higher than other fuels and test conditions. In 800 kPa IMEP and 20% EGR rate the THC value for

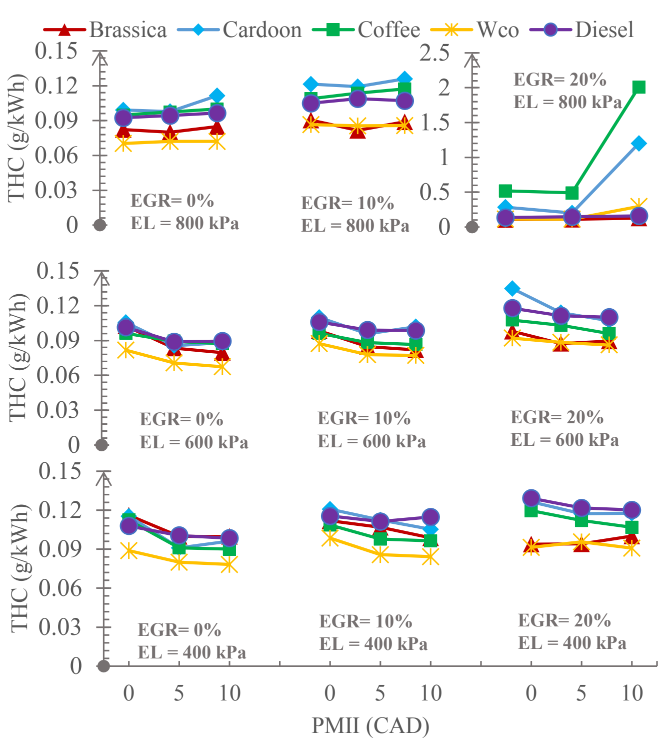


**Fig. 10.** Effect of the using of different fuels, EGR rates and injection strategy on THC emission in different engine load.

coffee biodiesel fuel increased significantly. The THC for this fuel in 0, 10, 15 °bMI SPI were 0.52, 0.49 and 2.01 g/kWh, respectively. This can be seen for cardoon biodiesel but not at that intensity.

In other test conditions the value of the THC emission is lower than that for diesel fuel. The maximum reduction of the THC emission is in 400 kPa IMEP, 20% EGR rate and without pilot injection. It is 29.196% and for WCO biodiesel fuel. Totally, the THC for the WCO is lower than all of the fuel in all of the test conditions. This is due to its higher oxygen (12.02 wt%) content and lower dynamic viscosity (6.1 cSt). Similar effect can be seen for the brassica biodiesel but with lower percentage of the THC reduction. This may be due to higher surface tension of the brassica biodiesel (42.05 mN/m) than WCO biodiesel fuel (40.52 mN/m) which decreases the quality of the atomization and then combustion quality.

THC emission is increased with increase in the EGR rate and generally the highest THC emission is related to the 20% EGR rate except in the 400 kPa IMEP and without pilot injection for brassica and WCO (0.09 g/kWh) biodiesel fuels. This is may be due to the compensation of the lower oxygen availability arising from high EGR rate by the high oxygen content of these biodiesel fuels [46,47]. In addition, high EGR rate has increased the temperature of the charge and enhance the quality of the combustion. Another reason for rapid growth of the THC emission for coffee and cardoon biodiesel fuels can be the shifting of the combustion to the end of the expansion stroke and lower time for the reaction of the carbon with oxygen. The most interesting behavior of the THC emission while using of the EGR and biodiesel simultaneously, has been the reduction of this emission. The oxygen content of the biodiesel has been decreased the HC emission of the engine and it compensate the increase of this emission due to using of the EGR [47].

THC emission is reduced due to application of the pilot injection in lower IMEPs (4 and 600 kPa). The maximum reduction of THC emission due to application of the pilot injection is 22.4%. Another distinguishing feature is high THC emission in high IMEP and EGR rate especially for advanced SPI (10 °bMI). This is also reported by Ref. [35]. They found that the too much advanced pilot injection increases THC emission. They introduce over-mixing due to too much advanced injection as the responsible for creation of fuel lean zones and THC emission.

### 5.2. $NO_x$ emissions

The initial impression from Fig. 11 is the reduction of the $NO_x$ emissions with increase in EGR rate in all tests and fuels. Another interesting point is the lower $NO_x$ value of the biodiesel blends than diesel fuel in most of the tests. This is more evident in higher IMEP (800 kPa). In addition, only in one test point with 10 °bMI SPI $NO_x$ emissions of the biodiesel is higher than diesel fuel and generally it can be stated that this start of the pilot injection has more positive effect on reduction of the $NO_x$ emissions [48]. The reduction of the $NO_x$ emissions is due to using of the pilot injection is reported [12,49]. The reduction of peak temperature and better distribution of the low temperature inside the cylinder may be the reason for the reduction of the $NO_x$ emissions while using of the pilot injection strategy. Although, with advanced SPI amount of the $NO_x$ emission is increased. This is due to higher combustion temperature in flame zone and longer duration of the high temperature combustion around the TDC caused by advanced ignition [28,50].

As it can be seen in Fig. 11 the $NO_x$ emission of the cardoon biodiesel is lower than other biodiesel fuels in most of the tests. This can be due to its higher viscosity than other fuels. The viscosity of the cardoon is 9.5 cSt while it is 5.7, 6, 6.1 and 3.5 for coffee, brassica, cardoon and diesel fuel, respectively. The second lowest amount of the $NO_x$ emission is for coffee biodiesel. Although dynamic viscosity of the coffee is lower than cardoon biodiesel and

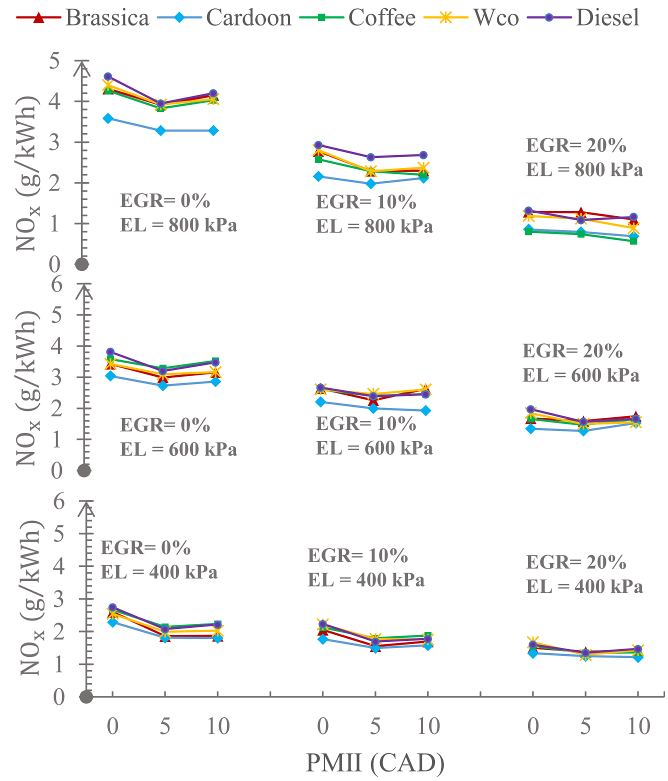


**Fig. 11.** Effect of the using of different fuels, EGR rates and injection strategy on $NO_x$ emission in different engine load.

approximately equal to other biodiesel fuel, its oxygen content is lower than other biodiesel fuels. The oxygen content of the coffee biodiesel is 7.77% while it is 10.91, 13.44 and 12.01% for cardoon, brassica and WCO biodiesels fuel, respectively.

Maximum reduction of the $NO_x$ emission is 51.32% for coffee biodiesel in 20% EGR rate, 800 kPa IMEP and without pilot injection. However, this decrease was accompanied by an increase of 1231.4% in the amount of CO, 1153.14% in THC. The same condition can be seen for cardoon and coffee biodiesel in other test condition with 20% EGR rate and 800 kPa IMEP. This is due to incomplete combustion for cardoon and coffee biodiesels fuel in these test conditions which can be seen in the cylinder pressure, heat release rate and combustion temperature graphs. In the high IMEP and EGR rate, oxygen availability inside the cylinder is lower. Then, the effect of the fuel oxygen content is more crucial. An interesting feature is the effect of brassica and WCO oxygen content on the quality of the combustion in these test conditions. The $NO_x$ emission of brassica is 5.26% lower than diesel fuel in 20% EGR rate and 800 kPa IMEP and in the same condition, CO and THC emission are 14.69 and 20.04% lower than diesel fuel, respectively. Then, it can be stated that for biodiesel fuels with higher value of the oxygen content (such as brassica and cardoon) higher value of the EGR rate in the higher IMEP can be applied.

In other hand, for biodiesel with low oxygen content (such as coffee) or high dynamic viscosity (such as cardoon), lower amount of the EGR rate (10%) is recommended in order to reduction of the $NO_x$ emissions without negative effect on the other emissions or combustion quality.

Maximum decrease in $NO_x$ emission due to application of EGR is 86%. Although, Tsolakis et al., found that effect of the EGR on reduction of the $NO_x$ emission is more significant for rapeseed methyl ester biodiesel fuel than diesel fuel [32], it can be seen in Fig. 10 which this is not true for all of the biodiesel fuel and it is dependent on the biodiesel fuel characteristics.

Application of the pilot injection has decreased the $NO_x$ emission in most of the operational test points. Maximum reduction of the $NO_x$ due to application of the pilot injection is 29.3%. Reduction of the $NO_x$ emission is also reported by other researchers [35]. They introduced reduction of the combustion temperature while using of the pilot injection as main reason for this reduction.

### 5.3. CO emission

Looking to Fig. 12, it is clearly evident that in 800 kPa IMEP and higher EGR rate (20%), amount of the CO emission for coffee and cardoon fuels is by far higher than other fuels and test conditions, although in this IMEP and without EGR CO emission is remarkably low. In addition, CO emission increases with increase in EGR rate. Another distinguishing feature is the different trend of brassica biodiesel emission with increase in EGR rate compared to other fuels.

The CO emission has been increased in high EGR rate especially in high IMEP which is significantly increased. Same trend has been reported by the other researchers [9]. These is due to the reduction of the temperature and oxygen availability inside the cylinder and lower homogeneity in fuel air mixture while using of the EGR. Another interesting feature is the reduction of the CO emission while using of the EGR system in low IMEP (400 kPa) especially for biodiesel diesel blend fuels. Totally, the growth of the CO emission due to EGR application can be compensated by using of the biodiesel fuel due to its oxygen content.

Application of the pilot injection causes CO emission reduction in 4 and 600 kPa IMEPs, it has increased CO emission of the various fuels in 800 kPa IMEP. The higher temperature inside the cylinder before the main combustion and higher oxidation value of the carbon is the reason for reduction of the CO emission in 4 and 600 kPa IMEPs [50]. Increase of the CO emission specially in

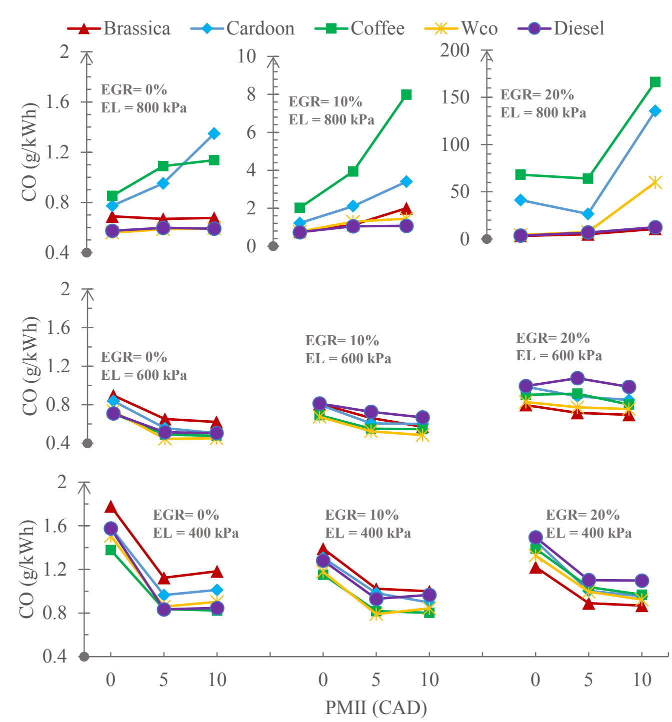


**Fig. 12.** Effect of the using of different fuels, EGR rates and injection strategy on CO emission in different engine load.

advanced SPI is due to lower temperature in cylinder before the combustion and incomplete combustion of the carbon cause by longer ignition delay with advanced SPI [28]. In addition, as it can be obviously seen there is approximately same trend for different fuels to the effect of the pilot injection on CO emission.

### 5.4. Soot

Formation of the soot is the result of the incomplete combustion of the liquid fuel and partially reacted of carbon of the fuel hydrocarbon [51].

The graph in Fig. 13 concern how the soot emission of the considered engine changes in different IMEPs, EGR rate, SPI and fuel types. The unit of the soot measurement is FSN (Filter Smoke Number) which is a number in the range of 1–10. Reduction of the soot emission while using of the biodiesel is due to its oxygen content and also reduction of the carbon in the molecular structure of the biodiesel than diesel fuel [51]. It is interesting to note that amount of the soot emission while using 10 °bMI SPI has decreased the production of this emission in 400 and 600 kPa IMEPs for all kind of the fuels. Different behavior is reported by previous researches [28]. Furthermore, the soot emission of the coffee and cardoon is by far higher than that for other fuels. An important reason for increase of the soot emission is reach mixture inside the cylinder. For instance, the highest FSN of biodiesel fuels is for coffee biodiesel in 800 kPa IMEP and 20% EGR rate (9.643) which has the lowest λ value (0.8) among all of the fuels and operational test points. This has led to rich mixture formation inside the cylinder [52].

Using of the high EGR rate (20%) for coffee and cardoon biodiesels fuels has increased the soot emission considerably. In 400 and 600 kPa IMEPs, soot emission of the biodiesels are lower than diesel fuel, although the EGR has increased the amount of this emission. Using of the EGR has been decreased the combustion temperature due to the decrease and dilution of the oxygen content with increase of specific heat capacity of the in-cylinder charge. The decrease in the temperature of the combustion and lower oxygen

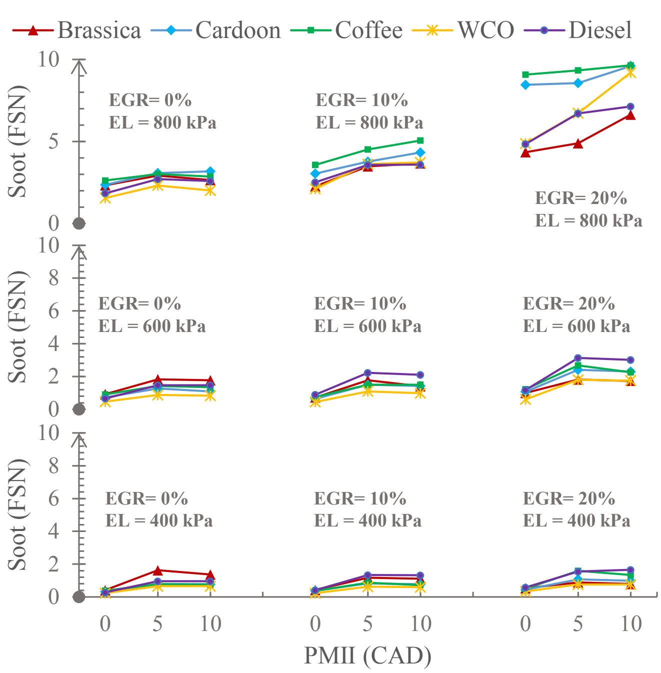


**Fig. 13.** Effect of the using of different fuels, EGR rates and injection strategy on soot emission in different engine load.

content with EGR cause a rising in the formation rate of carbon nuclei from unsaturated smoke forerunners such as acetylene and ethylene and decrease in the smoke oxidation level [53]. Although there is different trends and response of the fuels in various IMEP to the changing of the injection strategy, soot emission is increased while using of the pilot injection for all of the test points and fuels. The soot emission is increased as the SPI is closer to the main injection. This is due to rise of the diffusion combustion during main combustion which is the result of the poor mixture of the air and fuel [12]. One noticeable point is extreme increase of the soot emission in advanced SPI, IMEP and EGR rate even up to 754%.

## 6. Conclusions

Following conclusions can be drawn according to the results of the study:

- The changes in emission, performance and combustion properties of the engine due to application of the EGR and pilot injection are extremely related to the characteristics of the used biodiesel and a general statement for all of the biodiesel fuels cannot be proposed.
- MAXPR were decreased due to application of EGR in most of the test conditions due to prolongation of the ignition delay. Pilot injection causes reduction of MAXPR by far higher than effect of EGR and effect of the pilot injection to reduce MAXPR was higher than that for biodiesel fuels, however differences between two different pilot injections on MAXPR were not too much.
- BSFC of all of the biodiesel fuel were higher than that for diesel fuel. BTE of different fuels had opposite trend compare to BSFC and it has mostly decreased with while using of the biodiesel fuel except in high EGR rate and IMEP. The maximum reduction in BTE was 27.6% and for coffee biodiesel compare to diesel fuel.
- The $NO_x$ emissions for biodiesel with low oxygen content or high dynamic viscosity, lower amount of the EGR rate (10%) is recommended in order to reduction of the $NO_x$ emissions without negative effect on the other emissions or combustion quality.

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