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Influence of lean premixed ratio of PCCI-DI engine fueled by diesel/biodiesel blends on combustion, performance, and emission attributes; a comparison study

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ABSTRACT

The traditional combustion mode which utilized in the DI diesel engine has high and excessive emissions so the most wanted combustion is creating new modes which produce low combustion temperatures and low emissions. The main objective of the research is executing combustion, performance, and emissions attributes for PCCI-DI engine using blends of biodiesel and commercial diesel fuel blends for reducing the reactivity of the waste cooked oil and fossil diesel fuel mixtures. In this investigation, the waste cooked oil biodiesel is mixed with pure diesel fuel to formulate two blends by volume are 20% biodiesel 80% diesel (B20D80) and the other is 40% biodiesel 60% diesel (B40D60). The PCCI-DI engine methodology is activated after running the engine traditionally with direct injection for keeping stable running and prevents cold starting. The PCCI-DI operation insures that the charged mixture of a certain fraction of the supplied fuel is vaporized outside the engine manifold and the rested fuel quantity is conventionally burned before the TDC. However, the fuel blends that vaporized are adjusted at different premixed ratios at 20%, 25% and 30%, in that orders. The present investigation shows upgrades in all engine attributes. The obtained results of PCCI-DI technique at different premixed ratios shows a certain reduction for the peaks of the in-cylinder pressure, reduction in apparent heat release, rising in average brake thermal efficiency from 19.34% at conventional direct injection to 29.91% at PR_3. In addition, reduction in average CO emission from 0.324% to 0.083% and reduction in average NO_x from 559.3 PPM to 150.5 PPM.

1. Introduction

The HCCI combustion methodology is a developed lean burn diesel engine technique which assures efficient combustion, minimizing emissions and engine performance attributes are acceptable [1,2]. LTC of the premixed charge of air and fuel is ignited by compression through raising the engine piston during the compression stroke. HCCI technique has the ability to NO_x and soot emissions reduction in addition to perfection in BTE [3,4]. However, HCCI has unique of the deficiencies like the limiting the operating ranges, the difficulty of combustion phasing control, cycle to cycle variation, the cold starting, high load operation causes knocking phenomena, high CO and UHC emissions [5,6].

According to the previous investigations on the HCCI combustion fueled by biofuel the diesel fuel was added as blends in order to maintaining the combustion like fossil diesel fuel. As a difference between the DI and HCCI combustion, it was noticed low amounts of nitric oxides (NO_x), carbon monoxide (CO) and smoke emissions [2,7]. The

Abbreviations: B20-D80, 20% biodiesel and 80% diesel; B40-D60, 40% biodiesel and 60% diesel; BSEC, Brake specific energy consumption; BTE, Brake thermal efficiency; CO, Carbon monoxide; DI, Direct injection; EGR, Exhaust gas recirculation; HCCI, Homogenous charge compression ignition; H_2, Hydrogen; KOH, Potassium hydroxide; LTC, Low temperature combustion; Na OH, Sodium hydroxide; NO_X, Nitrogen oxides; NG, Natural gas; PCCI-DI, remixed charge compression ignition-Direct injection; PPM, Particles per millions; PM, Particulate matters; PR, Premixed ratio; RPM, Revolution per minute; T_{ex}, Exhaust temperature; TDC, Top dead center; UHC, Unburned hydrocarbon; WCO, Waste cooked oil.

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simulation and experimental analysis have been used to investigate a new and alternative fuel such as compressed natural gas has been applied to operate a single cylinder engine [8]. The diesel fuel was fumigated and injected inside the intake manifold to enhance the mixture preparation of the air and fuel inside the engine cylinder [9]. HCCI technique fuel injection was attempted through inlet manifold or inside the engine cylinder during the suction and/or the compression stroke. The emissions were affected by the method of injection, injection timing and duration, total fuel splitting and other injection parameters [10]. The impacts of the charge equivalence ratio and EGR were studied on the polyoxymethylene dimethyl ethers (PODE) for HCCI combustion. It was noticed decreasing in CO emissions with a slight effect on the UHC at the condition of increasing the charge equivalence ratio and decreasing EGR rate [11]. The effect of double fuel of gasoline and natural gas (NG) mixtures in HCCI combustion technique was particularly studied. The obtained results show a higher BTE and lowering in NOx emissions compared with the conventional spark ignition engine [12]. Advanced combustion techniques like HCCI, PCCI and dual fuel premixed charge compression ignition (DF-PCCI) were executed in single cylinder engine at fixed load. It was observed that all emission attributes of advanced combustion techniques were reduced like PM and NO_x then the BTE had higher values compared with the conventional combustion technique [13]

The PCCI-DI combustion technique is kind of HCCI techniques. PCCI-DI is an advanced method that used to improve the internal combustion engine characteristics like lowering the temperature of combustion by using ultra-lean air–fuel mixture. The fuel injection can be attempted by two stages are the external and internal injection. The external injection is attempted by using fuel injection system which includes intake manifold, electronic injector and fuel vaporizer. The rest of fuel is injected internally by original injector of the engine at the end of compression stroke [14]. The main problems of PCCI combustion are the hard control on combustion and the limited ranges of operation due to knocking phenomenon [15]. The results obtained from the previous research activity concerning this combustion method has a remarkable lower combustion temperature which produces less NOx, PM emissions and also increases the engine brake thermal efficiency (BTE).

Dimethyl ether-diesel fuels mixture was used in PCCI combustion at high premixed ratio and cooled EGR. It was observed low NO_x emissions but high UHC and CO emissions in addition to the peak of the in-cylinder pressure were reduced with lagging crank angles [16,17].PCCI combustion was executed by using bioethanol injected in the intake manifold and wheat germ oil was directly injected at 30% premixed ratio. it was observed improvement in all attributes like BTE which increased to 29.14% and the NO_x emissions reduced to 756 PPM compared to 813 PPM using diesel fuel only [18]. The spray formation of the diesel/DME fuel blends have been investigated to study the in-cylinder mixture formation and the engine combustion and emission characteristics [19]. The comparisons between the different strategies of LTC performed for both the HCCI, PCCI, and reactivity controlled compression ignition (RCCI). The points of comparison were studied like operating and emissions attributes. From the obtained statistics, the engine might be operating with RCCI technique at the condition of engine full load with 16.3% higher BTE, lower NOx and smoke emissions. However, the PCCI and HCCI techniques are expanded to run at 40–60% of engine full load [20].The analyses of in-cylinder pressure and rate of heat release data for PCCI-DI technique using lemon grass oil were studied. The results showed successful combustion results using lemon grass oil comparing with using pure fossil diesel [21]. Cottonseed biodiesel used in DI combustion and n-butanol was injected inside the intake manifold in order to achieve PCCI technique. The engine operated at constant speed with 20% EGR. The obtained results were compared with commercial diesel fuel. The soot and NOx emissions were reduced if the PCCI combustion was accomplished to be 84% and 17% respectively. The CO and UHC emissions were also reduced while the engine was running with PCCI combustion concept. PCCI-DI was operated using water-diesel emulsion at different concentrations of water like 3%, 6% and 9% as a fuel. It was found that at 9% of water tends to enhancement in BTE and CO, NO_x and the UHC emissions lack [22,23]. A simulation research was achieved to forecast the influence of the premixed ratio and the equivalence ratio on the attributes of PCCI engine. The fuel used was mixtures of diesel and ethanol at different premixed ratios (0, 10, 20, 30, 40 and 50%) [24]. The attributes of combustion technique were compared with DI diesel combustion and PCCI-DI combustion using pure fossil diesel fuel at different premixed ratio were 20%, 25% and 30%. The results showed enhancements in all characteristics at PCCI-DI combustion compared with DI combustion [25]. Experimental study used PCCI technique to analysis combustion and emission attributes by ethanol and diesel fuel. Ethanol was preheated by air to 40 °C and injected to the intake manifold at various premixed ratio and engine loads. It was found at low brake mean effective pressure the NO_x emission lowered and also the smoke opacity. The heat release rate and the in-cylinder pressure were increased [26].

Alternative fuels are any kind of fuel beyond fossil diesel and gasoline fuels. The alternative fuels have different manufacturing resources, processes and final forms. The alternative fuels include alcohols, hydrogen (H2), algae oil, biodiesel, and others [27]. The alternative fuels have many advantages that make them more important in combustion than fossil diesel like energy sustainability, engine performance improvements also reductions in all emissions [28].

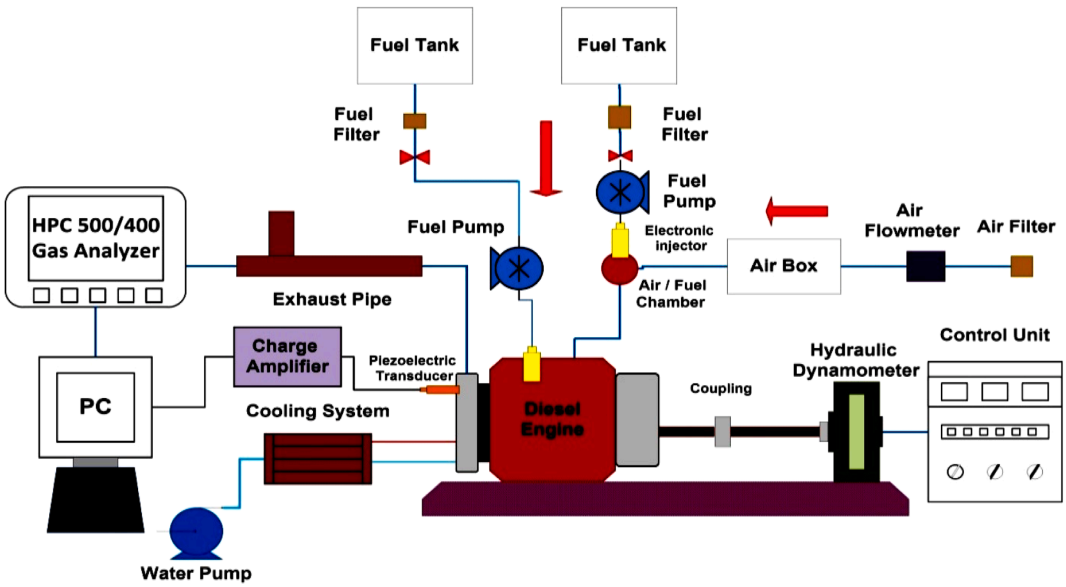
Biodiesel production has multiple routines like pyrolysis, dilution with diesel fuel, micro emulsion and transesterification [29]. Different types of biodiesel were investigated in the previous researches such as waste cooked oil (WCO) biodiesel. Transesterification process is a chemical reaction that converts the triglyceride oil like waste cooked oil feedstock using alcohol and a catalyst like (K OH) or (Na OH) which are fast and more economy in addition to enhance the reaction rate to form esters and glycerol. The produced waste cooked oil biodiesel is purified and washed using pure water [30,31]. It is noticed from the standard data of the diesel fuel and biodiesel that the biodiesel is denser, has higher flash point, modulus of elasticity and cetane number compared with fossil diesel fuel. Biodiesel has lower heating value that needs more volume of biodiesel to get the same power comparing with fossil diesel. However, biodiesel has higher viscosity that causes bad atomization [32,33]. The majority of the researches reported that the diesel engine attributes improved by using mixtures of fossil diesel and biodiesel

Table 1
The specifications of the tested diesel engine.

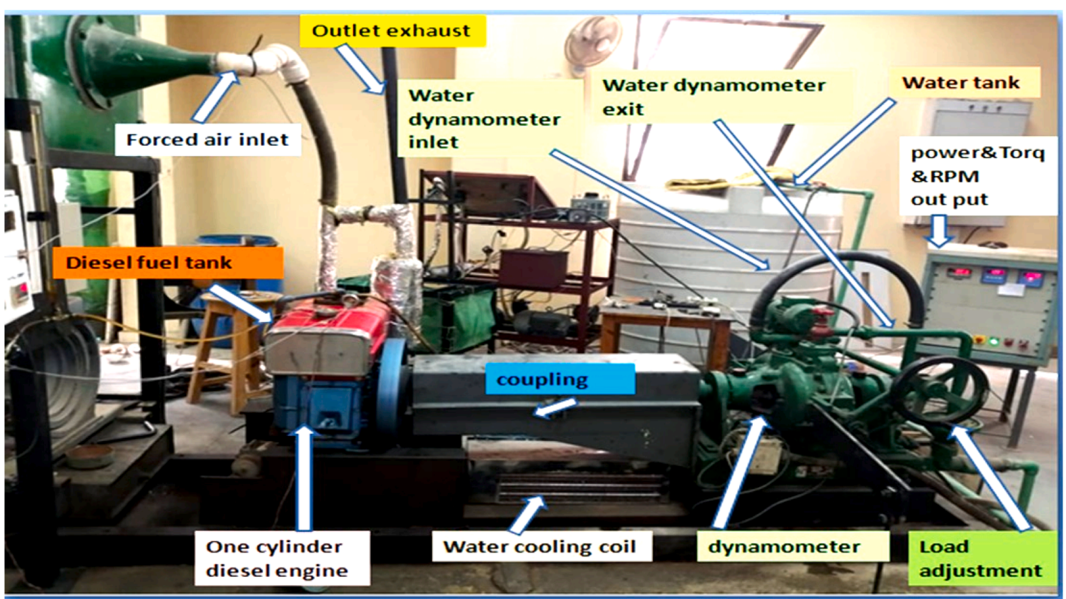
Engine brand	DEUTZ FL 511/W
Bore- Stroke	100 mm-105 mm
Compression ratio	17
Cooling type	Water cooling
crown clearance	1–1.2 mm
Weight	116 kg
Power	7.7Hp = 5.7 kW
Displacement	825 cm^3
Inlet valve opens	32° before TDC
Inlet valve closes	59° after BDC
Exhaust valve opens	71° before BDC
Exhaust valve closes	32° after TDC
Injection pressure	115 bar
No. of cylinder	One cylinder

Table 2
Fossil diesel fuel and WCO specifications [25].

Property	Property unit	Fossil diesel fuel	Waste cooked oil
Density	(kg/m^3)	830	875
Calorific value	(MJ/kg)	42.10	39.51
Kinematic viscosity	(mm^2/s)	2.38	3.54
Flash point	(°C)	45	158
Auto ignition temperature	(°C)	263	273
Cloud point	(°C)	0	6



(a)



(b)

Fig. 1. a) The schematic diagram of the experimental apparatus. b) Image of the engine with the hydraulic dynamometer connection.

Table 3
Smoke and gas analyzer resolution and ranges

Emission type	Limit of resolution	Emission ranges	Uncertainty percentage
CO	0.01×10^{-2} (VOL %)	$0–10 \times 10^{-2}$ (VOL %)	$\pm 0.03 \times 10^{-2}$ (%)
NO_x	1×10^{-6} (PPM)	0–5000	$\pm 25 \times 10^{-6}$ (PPM)
UHC	1×10^{-6} (PPM)	0–10,000	$\pm 10 \times 10^{-6}$ (PPM)

compared with pure fossil diesel [34–37]. The brake thermal efficiency and emissions attributes of single cylinder diesel engine were studied using five blends of diesel fuel, linseed and rubber seed oil. It was observed that the BTE of blend 1 which consisted of 5% linseed, 5% rubber seed, 90% diesel and the second blend which consisted of 10% linseed, 10% rubber seed, 80% diesel were the optimum BTE[38].

The major objective of this study is to solve a problem which hasn't any previous available data about comparison between DI combustion and PCCI-DI combustion at different premixed ratios using two blends are B20D80 and B40D60 of waste cooked oil biodiesel and fossil diesel fuel by volume at different operating loads and fixed engine speed. The reasons of using (B40-D60) in PCCI-DI combustion is to reduce the reactivity of the mixture, expand the operating loads without knocking and reduce fuel consumption [39]. The experiments achieved by using water cooled single cylinder CI diesel engine and the PCCI-DI engine at different Premixed Ratios (PR) were 20%, 25% and 30% at different ranges of the engine loads. The premixed ratio defined as the ratio between injected fuel quantities inside the intake manifold to the whole engine injection.

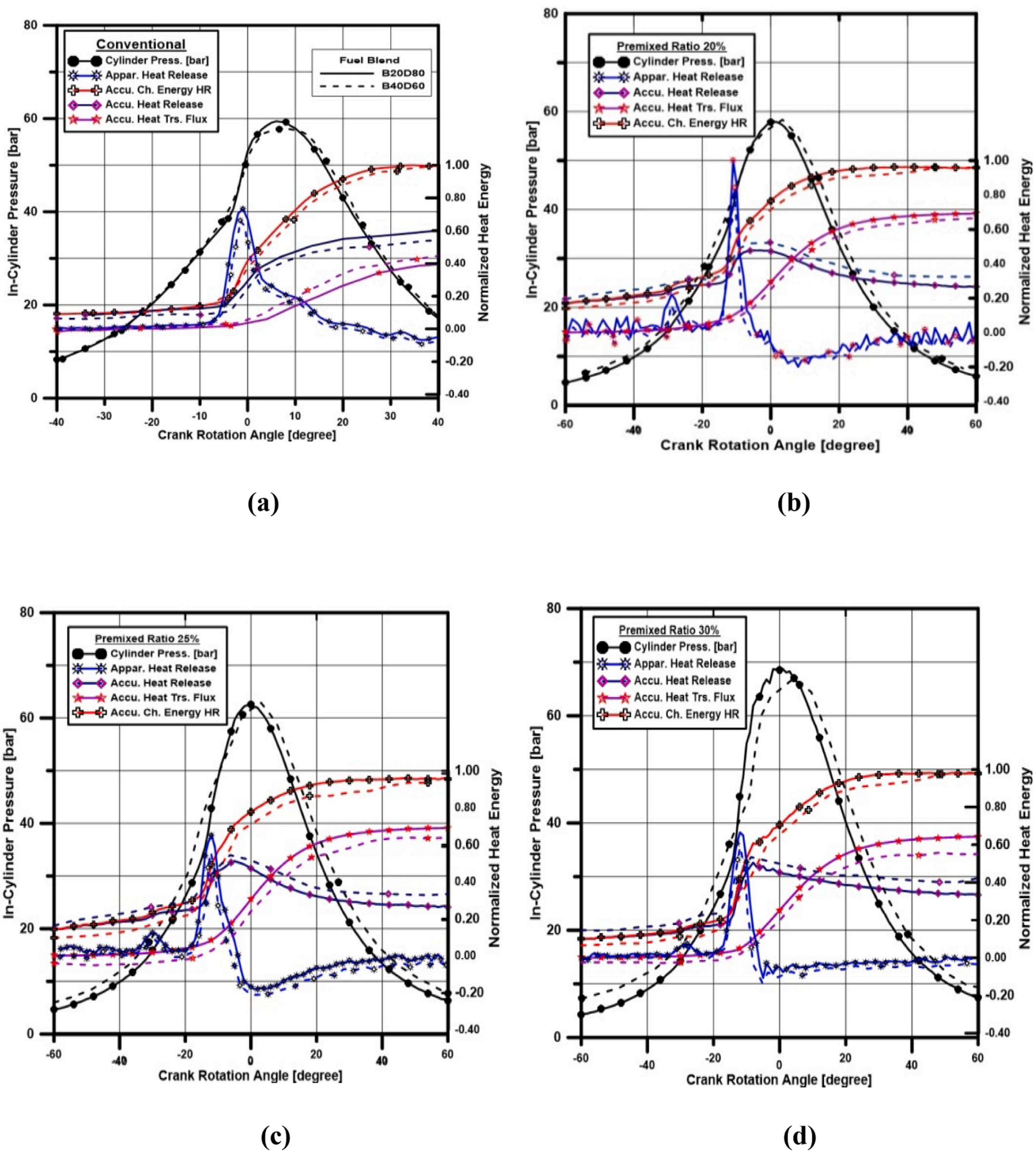
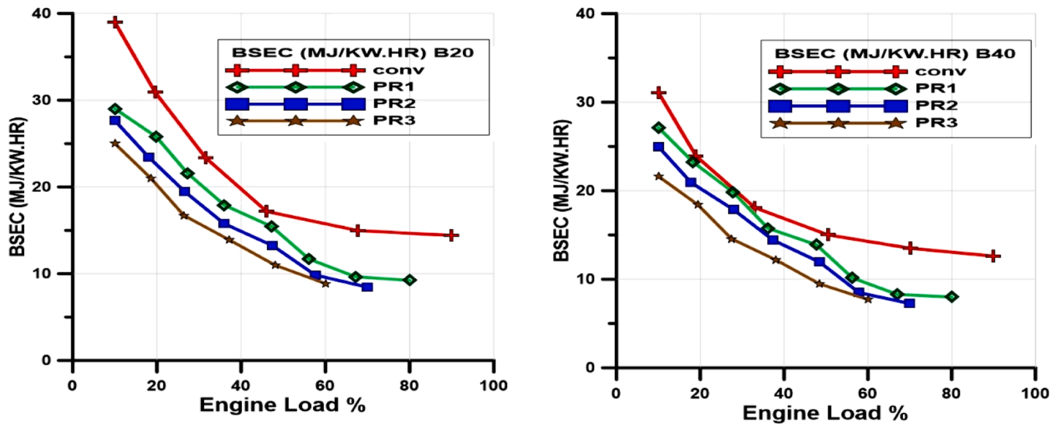
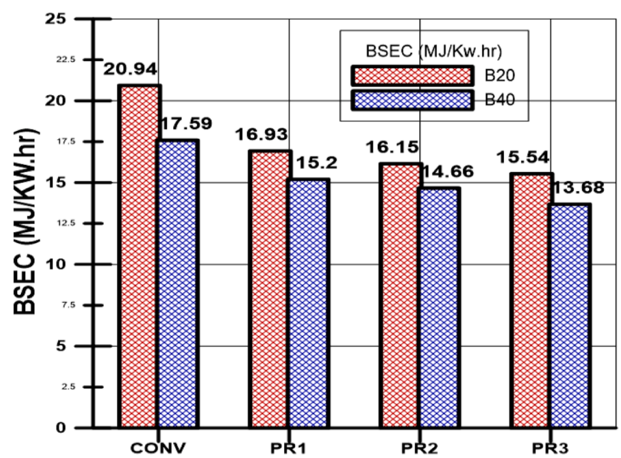


Fig. 2. Combustion attributes at varied crank rotation angle using B20-D80 and B40-D60 at 1500 rpm speed and 40% of the maximum load; a) DI combustion, b) PCCI-DI at PR_1, c) PCCI-DI at PR_2, and d) PCCI-DI at PR_3.



a) BSEC with load percentage at B20-D80 **b) BSEC with load percentage at B40-D60**



c) The mean of BSEC at B20 and B40

Fig. 3. The BSEC variation with load percentage and their mean values using B20-D80 and B40-D60 at DI and PCCI-DI combustion modes.

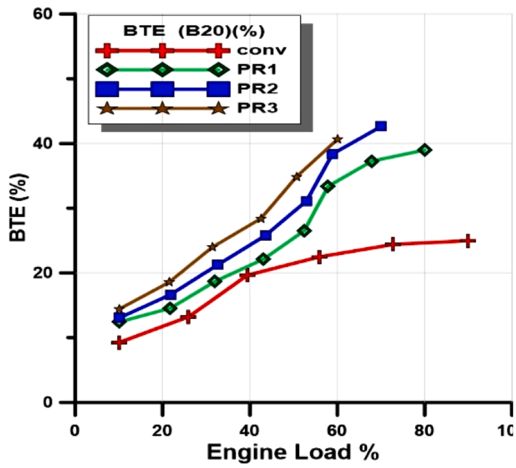
2. The experimental setup and procedure

To discuss the attributes of DI and PCCI-DI combustions by mixtures of fossil diesel and WCO biodiesel blends. The experiments are performed using "DEUTZ FL 511/W" water cooled diesel engine has 1500 RPM base speed connected with dynamometer using coupling. The dynamometer is a device used to determine torque, rotational speed and the power of the engine which has a rotor coupled with the crankshaft by coupling. The motion of the rotor runs against the magnetic field produced by the electromagnets creating resistance to the rotor and therefore apply load to engine. The force generated on dynamometer is determined according the change in strain gauge according the torque which is determined by the product of the R-distance between the center of the pivotal point (strain gauge) and the varying force extracted by the hydraulic pump. However, the output brake power can be calculated for the engine at the specified speed and can be recorded by the dynamometer control panel.

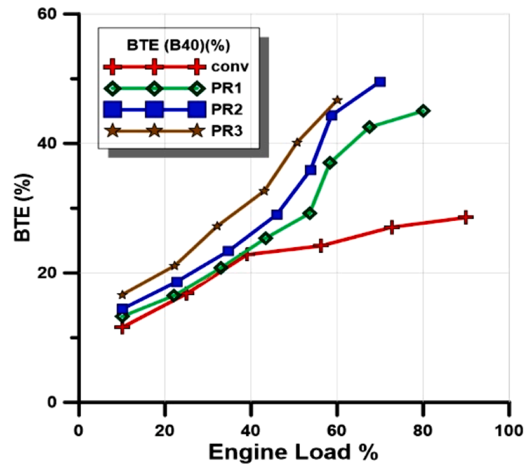
The technical specifications of the "DEUTZ FL 511/W" engine are tabulated in Table 1. There are two fuel tanks one of them is the original tank linked with graduated burette for measuring the consumed fuel per second. The other is the intake manifold tank fixed on a mass scale to determine the injected fuel per second. The fossil diesel fuel and WCO biodiesel properties were inspected in official laboratories [25] and tabulated in Table 2. The test rig is indicated in Fig. 1a and b with the intake manifold system, which consists of a pump, fuel tank, accumulator, mass scale and electronic injector with fuel vaporizer.

The fuel injection timing process performed by using fuel injection timing software developed by LAB view, motor driver for giving suitable voltage to the data acquisition related to the charge of the electrical solenoid injector. For monitoring, the motion of the crankshaft there is "AUTONICS E50S-8-360-6-L-5" which is an optical rotary encoder connected with the crankshaft of the engine. Rota meter is used for measuring the air flow rate consumption.

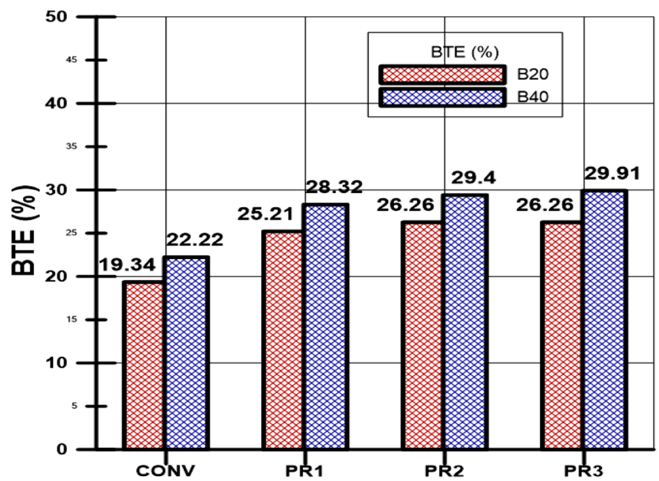
The "HPC 500/400" exhaust and smoke analyzer used for analyzing all emissions such as CO, CO_2, UHC, NOx, unused oxygen and smoke opacity. It is observed from Table 3 the CO emission is characterized by percentage of volume, NOx emission is characterized by particle per million and the un burned hydrocarbon is characterized by particle per



a) **BTE using B20-D80**



b) **BTE using B40-D60**



c) **The mean values of BTE using B20 and B40**

Fig. 4. The BTE variation with load percentage and average values by B20 and B40 at DI and PCCI-DI combustion modes.

million. The measurement of the smoke attempted visually by putting the probe at the exhaust breather. The ranges of the smoke and exhaust analyzer are in Table 3.

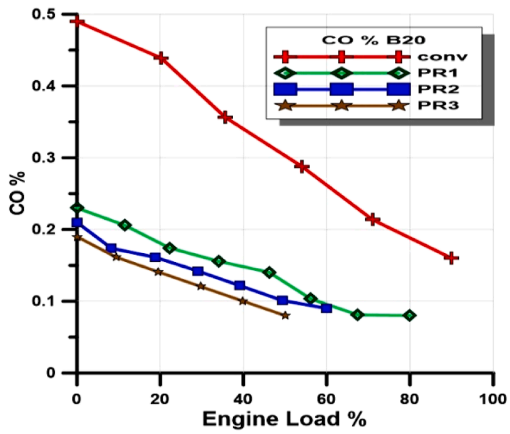
In this paper, the trials done for comparing between the DI combustion and PCCI-DI combustion using two blends are B20-D80 and B40-D60. The engine operates firstly in DI combustion mode using B20-D80 and B40-D60 with recording the attributes results. Then the engine converted to PCCI-DI combustion using also B20-D80 and B40-D60 at different loads avoiding knocking phenomenon with recording all attributes. The performance, emissions and combustion attributes are measured and compared using B20-D80 and B40-D60 at the DI combustion mode and then at the PCCI-DI combustion mode with different three premixed ratios are 20%, 25% and 30. Average or the arithmetic mean for each case of combustion is taken for comparing between the cases of emissions and performance attributes. The average or the arithmetic mean defined as the total of all values divided by the numbers of them.

The trials are attempted according to the following modes. The first mode the engine operated at the DI mode using B20-D80 and B40-D60 respectively. In this mode the intake manifold system is always closed. The attributes of combustion are measured as possible at various loads with smooth operation. The second mode is the PCCI-DI combustion that operated using both the intake manifold and DI fuelled with B20-D80 and B40-D60 respectively. At the second mode, the fuel blends directly injected also injected into the intake manifold at different premixed ratios are 20%, 25% and 30%. The attributes of combustion are measured at various loads avoiding knocking.

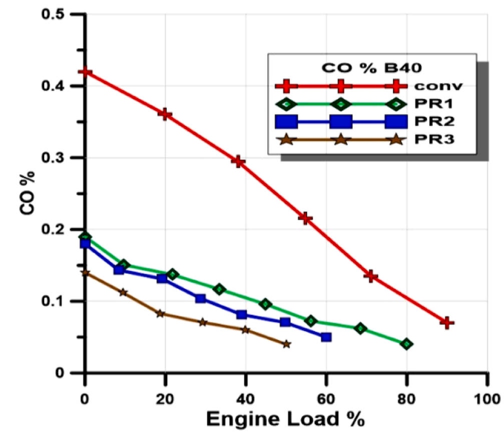
3. Results and discussions

3.1. Combustion attributes

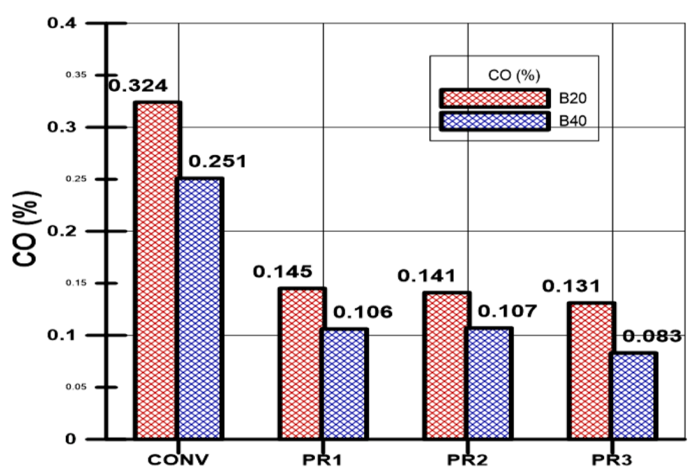
The combustion data have measured experimentally by collecting the in-cylinder pressure simultaneously. Conversely, by using the cylinder pressure profile we can detect whether the engine has to work in abnormal combustion or engine component malfunction. The engine pressure data for the studied cases of different premixed ratio were existed in Fig. 2 at constant load of 40% from the engine power. The stated figures illustrate the in-cylinder pressure data changes at various crank angles. The apparent heat release rate has been calculated by estimating the amount chemical energy release for the fuel that important to obtain the pressure, while the combustion reaction extent is calculated through the released fraction of the total fuel chemical energy.



a) CO using B20-D80



b) CO using B40-D60



c) The mean values of CO using B20 and B40

Fig. 5. The CO percentage variation with load percentage and average values using B20-D80 and B40-D60 at DI and PCCI-DI combustion modes.

The accumulated chemical energy is defining as the total stored combustion energy during the engine thermal cycle. Accumulated chemical energy is producing through reactions that occur during the chemical compounds transforming of the combusted fuel inside the engine cylinder. Fig. 2 shows the measured in-cylinder pressure also the rate of heat release at various crank angles under three values of the premixed charge at selected engine speed of 1500 rpm and 40% from the maximum load of the engine. It is observed that by increasing the premixed charge ratio, the peak value of the in-cylinder pressure becomes higher, and the crank angle (CA) at the maximum pressure becomes earlier. The DI combustion shows a single stage of apparent heat release while show a two stages with increasing the premixed ratio of the charged fuel inside the engine cylinder. By increasing the premixed ratio it is observed that the maximum rate of the heat release increased and the start of the two combustion stages is increased. This feature can be observed obviously in the rate of heat release curve. These notes indicate that the auto-ignition timing and combustion duration of PCCI-DI Engine combustion depend on chemical kinetics and the piston compression for fuel–air mixture. At higher premixed ratio conditions, the PCCI-DI combustion occurs very rapidly with high rate of heat release and in-cylinder pressure leading to noise and vibration.

3.2. Performance attributes

The brake specific energy consumption (BSEC) variation with the percentage of load is indicated at Fig. 3. Using B20-D80 and B40-D60 blends indicated at Fig. 3a and b consequently. The engine was operated at two types of operation are DI combustion and PCCI-DI combustion at the three premixed ratios. The graphs indicated that the BSEC decreases at PCCI-DI combustion comparing with DI combustion. The BSEC has minimum values by increasing the premixed ratio because lean mixture which reduces the fuel consumption. The increasing in the premixed ratio is limited for controlling the loading range of operation. The lowest value of BSEC is at PCCI-DI combustion with PR_3 and B40-D60. The best case of combustion is at PCCI-DI with PR_2 at B40-D60 due to the low BSEC value and the high load operating ranges. As shown in Fig. 3c the average values of BSEC decrease at PCCI-DI from 20.94 (MJ/kW.hr) at DI combustion and B20-D80 to 13.68 (MJ/kW.hr) by using PCCI-DI combustion at PR_3 and B40-D60.

The brake thermal efficiency (BTE) variation with load percentage is indicated in Fig. 4. The combustion done using B20-D80 and B40-D60 are indicated in Fig. 4a and b consequently. The engine operated at DI combustion and PCCI-DI combustion at PR 20%, 25% and 30%

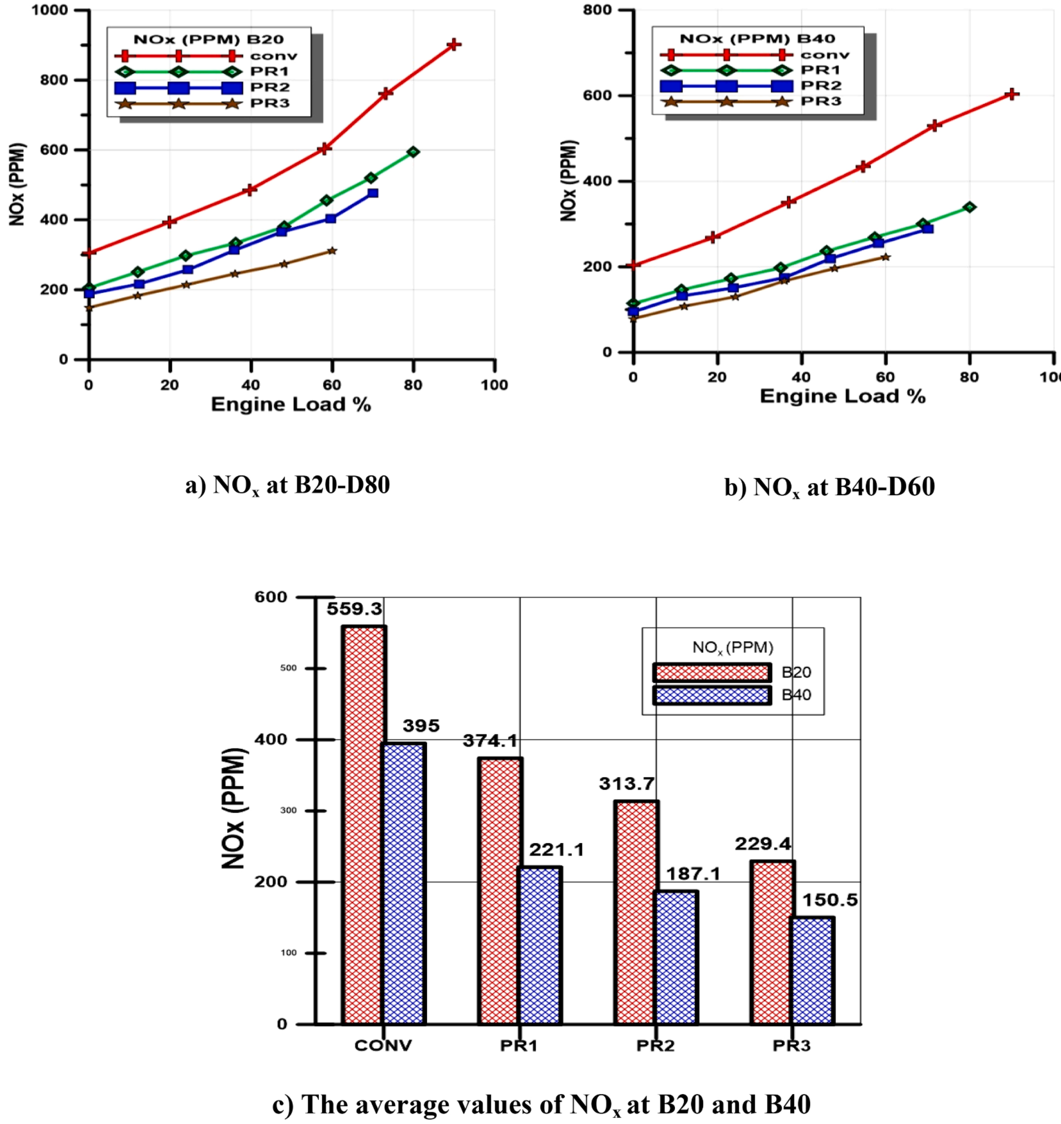


Fig. 6. NO_x variations with load percentage and their average values using B20-D80 and B40-D60 at DI and PCCI-DI combustion modes.

respectively. The BTE rises with rising the load percentage and its upper value at the maximum load at each case because the capability of converting the fuel energy into mechanical work and also the reduction in fuel consumption. The maximum value of BTE is at PCCI-DI combustion with PR_3 and B40-D60 due to the lean mixture formation and the low fuel consumption. The best case of combustion is PCCI-DI with PR2 at B40-D60 due to the high value of BTE and high load percentage.

As indicated in Fig. 4c the average value for BTE rises by using PCCI-DI combustion with B20-D80 and B40-D60. The maximum average value of BTE increases from 19.34% to 29.91% by using PCCI-DI combustion at PR_3 and B40-D60.

3.3. Emissions attributes

The variation of CO emissions with load percentage is indicated in Fig. 5. Using B20-D80 and B40-D60 is indicated in Fig. 5a and b consequently. The engine operated at DI combustion and PCCI-DI combustion at PR 20%, 25% and 30% respectively. At PCCI-DI combustion, CO emissions rise because of decreasing in the temperature of the combustion and CO is not oxidized completely to form CO_2. By increasing load percentage, the combustion temperature rises and so on CO emissions decrease. The CO emissions have the lowest values using PCCI-DI combustion at PR_3 and B40-D60 due to the adjustable timing of injection for the intake manifold charge and the high oxygen content for B40-D60. The best case of combustion for CO emissions is PCCI-DI with PR_2 at B40-D60 because the minimal value of CO emission and high load percentage.

As indicated in Fig. 5c the average percentage of CO reduces by using PCCI-DI at B20-D80 and B40-D60. The minimum average percentage decreased from 0.324% to 0.083% by using PCCI-DI combustion at PR_3 and B40-D60.

The variation of NOx emissions with load percentage is indicated in Fig. 6. Using B20-D80 and B40-D60 indicated in Fig. 6a and b consequently. The engine operated at DI combustion and PCCI-DI combustion

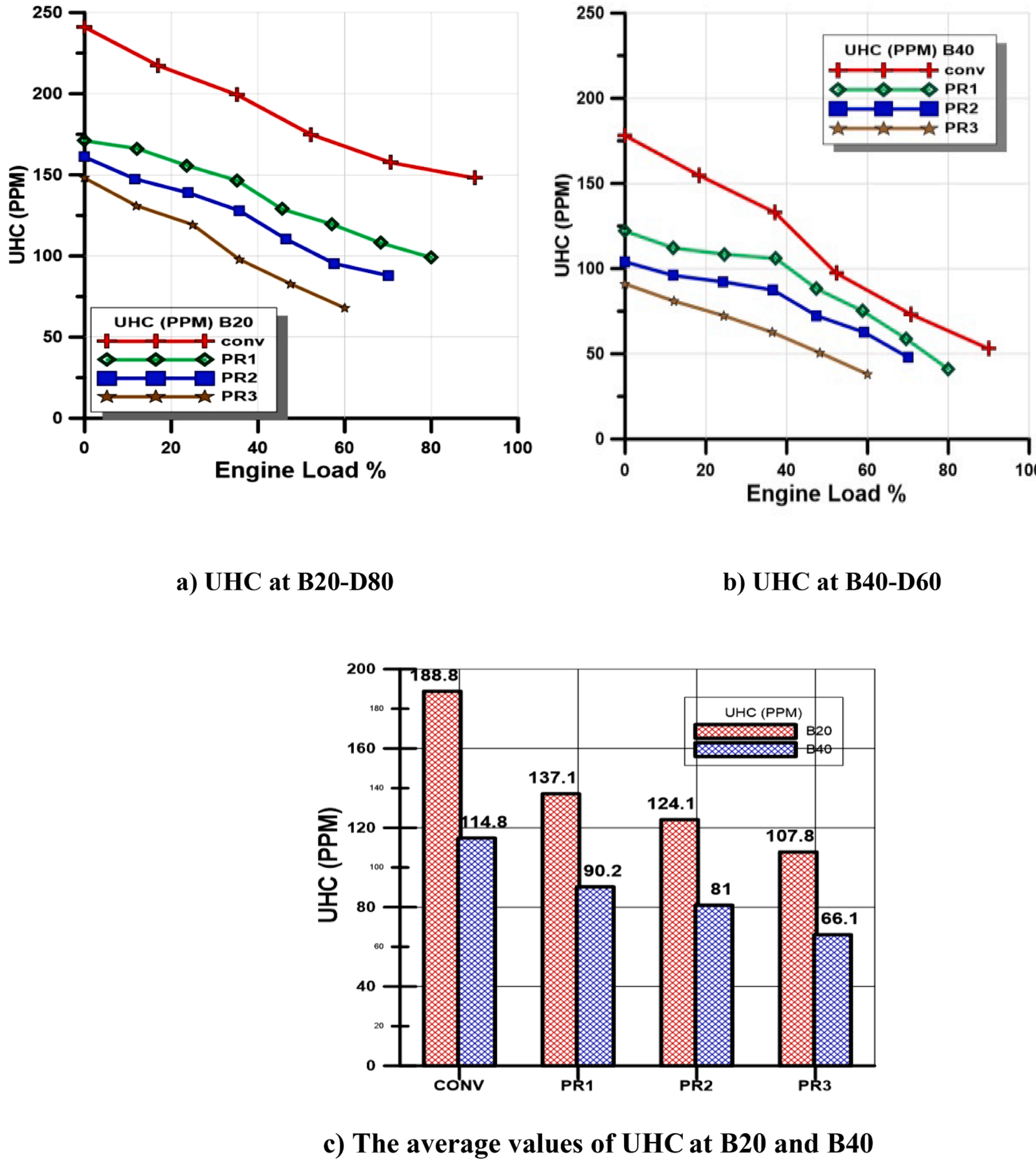
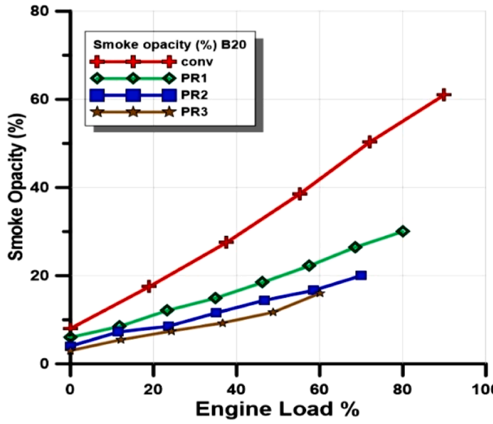


Fig. 7. The UHC variations with load percentage and their average values using B20-D80 and B40-D60 at DI and PCCI-DI combustion modes.

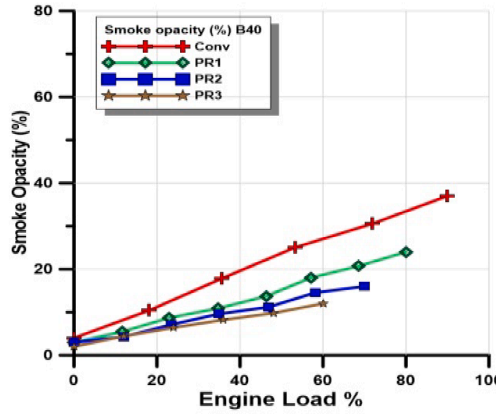
at PR 20%, 25% and 30% respectively. The figures show that NO_x emissions increase with increasing load percentage because of rising temperatures of combustion. NO_x emissions have lowest values using PCCI-DI at PR_3 and B40-D60. The main causes of reducing NOx emissions using PCCI-DI combustion is the low temperature of combustion and the good formation of mixture before injection compared with DI combustion. The best case of combustion related to NO_x emissions is at PCCI-DI with PR_2 and B40-D60 because of the low value of NO_x emissions and the high load percentage which is 70%. As indicated in Fig. 6c the average values of NO_x emissions decrease at PCCI-DI combustion with B20-D80 and B40-D60. The lowest average value reduces from 559.3 PPM to 150.5 PPM by PCCI-DI combustion at PR_3 and B40-D60 but with low load percentage.

The variation of UHC emissions variation with load percentage is indicated in Fig. 7. Using B20-D80 and B40-D60 indicated in Fig. 7a and b consequently. The engine operated at DI combustion and PCCI-DI combustion at PR 20%, 25% and 30% respectively. PCCI-DI combustion has low temperature compared with DI combustion. The UHC for PCCI-DI combustion modes have lower values than DI combustion. The UHC values decrease by load percentage increasing which increases the combustion temperature. The UHC has the lowest values using PCCI-DI combustion using PR_3 and B40-D60 due to the adjustable timing of injection, the fully premixed for the fuel with air and the high oxygen content for the fuel used. The best case of combustion for the UHC emission results is at PCCI-DI with PR_2 and B40-D60 due to the reduced values of UHC emissions at high percentage of loads, which is 70% of the engine power. As indicated in Fig. 7c the average values of the UHC reduces by using PCCI-DI combustion with B20-D80 and B40-D60 while decreased from 188.8 PPM to 66.1 PPM at PR_3 and B40-D60.

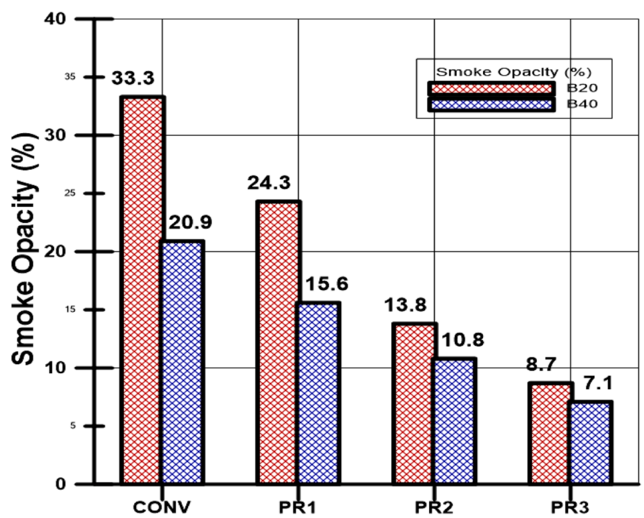
The variation of smoke opacity percentage with load percentage is indicated in Fig. 8. Using B20-D80 and B40-D60 indicated in Fig. 8a and b consequently. The engine operated at DI and PCCI-DI combustion at PR 20%, 25% and 30% respectively. By rising the load percentage the smoke opacity percentages rise. PCCI-DI combustion reduces smoke opacity percentage because of good mixing process comparing DI combustion. The smoke opacity lowest percentages are using PCCI-DI combustion at PR_3 and B40-D60 but with low load percentages. The best case of combustion related to the smoke opacity percentage is at



a) The smoke opacity percentage at B20



b) The smoke opacity percentage at B40



c) The average values of the smoke opacity at B20 and B40

Fig. 8. Smoke opacity variation with load percentage and their average values using B20-D80 and B40-D60 at DI and PCCI-DI combustion modes.

PCCI-DI with PR_2 and B40-D60 due to the low percentage of smoke opacity and the high load percentage that is 70% of the maximum.

As indicated in Fig. 8c the smoke opacity percentage average value reduces by using PCCI-DI combustion whereas the smoke opacity percentage reduced from 33.3% at DI combustion with B20-D80 to 7.1% at PCCI-DI combustion with PR3 and B40-D60.

The variation of exhaust temperature (T_{ex}) with load percentage is shown in Fig. 9. Using B20-D80 and B40-D60 indicated in Fig. 9a and b consequently. The engine operated at DI and PCCI-DI combustions at PR 20%, 25% and 30% respectively. From all graphs, due to the increasing in the temperature of the combustion the exhaust temperature increases. The T_{ex} using PCCI-DI combustion is lower than using DI combustion because of the low temperature of combustion. The lowest recorded values of T_{ex} occurred by using PCCI-DI combustion at PR_3 and B40-D60 but with low load operating range. The best case of combustion for the T_{ex} results is at PCCI-DI with PR_2 and B40-D60 because of the low value of the exhaust temperature and the high load operating ranges that is 70% of the total load of the engine.

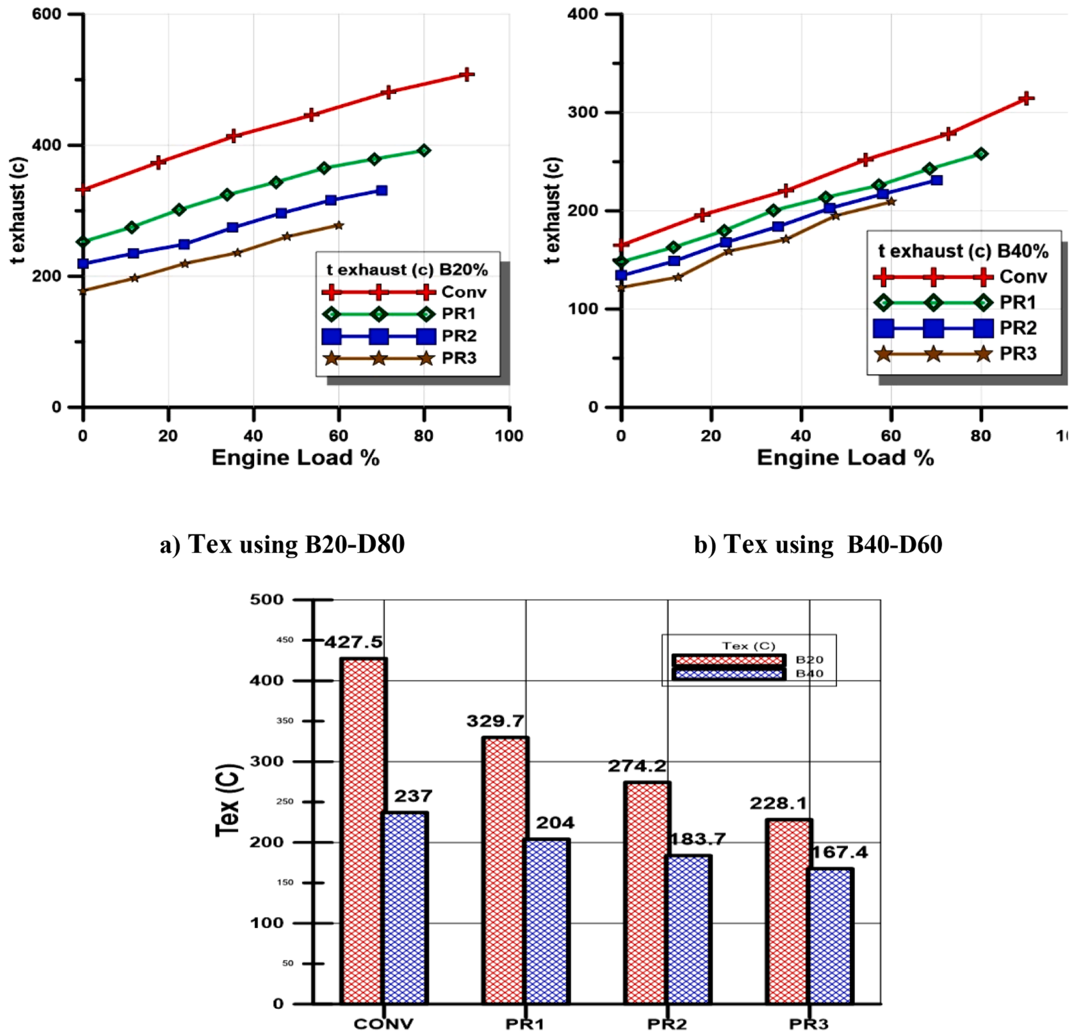
As shown in Fig. 9c the T_{ex} average value decreases at PCCI-DI combustion using different premixed ratios compared with DI combustion. The T_{ex} decreased from 427.5 $^{\circ}$C at DI combustion with B20-D80 to 167.4 $^{\circ}$C at PCCI-DI combustion with PR_3 and B40-D60.

4. Conclusions

Two blends of waste cooked oil and fossil diesel fuel are used to investigate the emissions, performance and combustion attributes for premixed charge compression ignition –direct injection combustion and direct injection combustions. The PCCI-DI combustion was at three premixed ratios are 20%, 25% and 30%.

The importance of PPCCI-DI combustion is showing and compared with the DI combustion, and the conclusion summarized that:

- The peak value of in-cylinder pressure increases with earlier crank angle by increasing the premixed ratio of PCCI-DI combustion at constant load which is 40% of total load
- The PCCI-DI combustion is complicated to control at high load operating ranges because of knocking and loss of maintaining for the premixed ratio.
- Significant improvement in the average value of BTE by using PCCI-DI combustion with B40-D60 at PR_3 from 19.34% at DI combustion to 29.91%.
- Reduction in the BSEC with PCCI-DI combustion using blends of diesel and WCO biodiesel at PR_3 and B40-D60 compared with the conventional DI combustion by a range of 22.22%.



a) Tex using B20-D80

b) Tex using B40-D60

c) The average values of Tex at B20 and B40

Fig. 9. The exhaust temperature variations with load percentage and their average values using B20-D80 and B40-D60 at DI and PCCI-DI combustion modes.

- Reduction in CO emission by 66.93%, NO_x emissions by 61.89%, UHC emissions by 42.42%, smoke opacity emissions by 66% and T_{ex} by 29.36% at PCCI-DI combustion at PR_3 and B40-D60 compared with DI combustion.

CRediT authorship contribution statement

Medhat Elkelawy: Experiment. **Hagar Alm-Eldin Bastawissi:** Experiment. **E.A. El Shenawy:** Experiment. **Mahmoud M. Shams:** Experiment. **Hitesh Panchal:** Supervision. **Kishor Kumar Sadasivuni:** Supervision. **Akhilesh Kumar Choudhary:** Supervision.

Declaration of Competing Interest

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

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