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Experimental Investigation of the Biodiesel Direct Injection and Diesel Fuel as Premixed Charge on CI-Engine Emissions, Performance, and Combustion Characteristics

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***Abstract*: This study aims to investigate the use of waste cooking oil biodiesel blend (B30D70) in CDC mode and the use of different premixing ratios of diesel vapor (15%, 20%, 25% and 30%) through manifold injection at a manifold premixed temperature of 110 ^{0} C in PCCI mode when using biodiesel blend (B30D70) as the main fuel and diesel as the premixed fuel. The experiments were carried out on 4-stroke, single-cylinder, air cooled, DI diesel engine which was modified to run in PCCI mode with adding a fuel vaporizer to create the external homogeneous mixture. The engine combustion parameters, performance, and emissions characteristics were fully discussed, and the results were compared with these of CDC mode fueled by diesel. The obtained results for the use of B30D70 fuel indicates a certain decrement for exhaust gas temperature, HC, and CO emissions, but with a penalty in brake thermal efficiency, NOx, and smoke opacity. The experiments revealed that the best results were indicated for 20% diesel vapor in PCCI mode as CO, HC, NOx, and EGT reduced by 34.62%, 43.75%, 2.65% and 8.53% respectively and almost has the same BTE compared to CDC mode fueled by diesel. While increasing PR to 25% and 30% decrease the volumetric efficiency leads to rich mixture and deterioration of combustion and increase CO, HC and smoke emissions.**

***Keywords*: Engine emissions; engine performance; Biodiesel/diesel blends; PCCI engine; Low temperature combustion; external mixture formation; fuel vaporizer; Fossil diesel fuel; Brake thermal efficiency**

I. INTRODUCTION

The better thermal efficiency, reliability, and durability of diesel engines (compression ignition-CI) making it more widely used in transportation sector and a variety of industry applications [1-3]. However, it suffers from higher emissions of oxides of nitrogen (NOx) and soot emissions and excessive noise due to it has high diffusion combustion ratios and improper fuel mixing which are challenges with its combustion process [4-7]. Additionally, the energy demand is increasing, fuel supplies is depleting and large amount of harmful emissions to human health and environment with the use of fossil fuels [8-11]. Owing to these adverse effects of the CI engines, a lot of stringent politics have been lunched on the emissions limitation that made researchers looking for developing an efficient technology that produce low exhaust emissions with high combustion efficiency in addition to a flexibility in utilization of fuels[12-15]. There are many methods were developed to improve engine performance and decrease exhaust emissions produced from the engines such as low temperature combustion technology, after-treatment devices, and renewable fuel sources [16]. The two distinct methods for the improvement of engine performance and emissions were discussed below.

First method, using of renewable sources of energy alternative to diesel such as alcohols, algae oil, hydrogen, biofuel, and others have been applied [17-19]. Biodiesel is gaining more attention globally as the best choice for replacement of fossil fuels in CI engines as its properties are almost the same of the diesel fuel[20, 21]. Additionally, the use of biodiesel enhances the performance of combustion and emissions as it has a ratio of O_2 with no sulfur content[22-25]. However, the main problem of using biodiesel is its higher viscosity that clog the fuel filter and increase the smoke emission and it results in lower brake thermal efficiency (BTE) as it has lower heating value than diesel[26]. Abedin et al. [27] studied the impact of using biodiesel blends (B10 and B20) on the engine performance, combustion, and emission and compared the results to that of the engine when fueled with diesel and B5.

Brake-specific fuel consumption (BSFC) is increased by an average of 6% to 20% when using B5, B10, and B20 fuels. For emissions, B5, B10, and B20 fuel blends produce less CO and HC than diesel fuel. NO_X is increased by 2.5% to 3% in biodiesel mixed fuels than in diesel fuels. Elkelawy et al. [28-31] explored the impact of using different biodiesel blends (B20, B40, B60 and B80) on the engine performance, combustion, and emissions characteristics, they conducted experiments in a single cylinder, four stroke, direct injection diesel engine and running at constant speed of 1400 rpm. It was observed that by increasing the percentage of biodiesel, BTE

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decreased by 9.6%, CO and HC levels decreased, exhaust gas temperature (EGT) decreased by 7.6% while NOX concentration increased due to high oxygen content in biodiesel. The performance and emissions characteristics of using biodiesel blends on single cylinder, 4-stroke diesel engine were investigated according to Kasaby et al.[32]. The results showed that B30 produced the lowest concentration of CO while B10 showed the highest BTE. Kaya. et al. [33] investigated the performance, combustion, and emissions characteristics of PCCI engine fueled by pure diesel and biodiesel blended diesel. They found that with addition of biodiesel NOx emission decreased but with penalty in soot emissions and BTE.

Second method, using a new technology by adding a small modification to the engine has been used in order to reduce exhaust emissions with high/the same efficiency. This new technology is Low Temperature Combustion (LTC) which is classified as a technology that keeping in-cylinder temperature low to reduce NOx emission and preventing the formation of local rich mixture for reducing the soot production [34-38]. LTC technology includes various modes like Homogeneous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition "Partially Premixed Charge Compression Ignition" (PCCI), Reactivity Controlled Compression Ignition (RCCI) and Stratified Charge Compression Ignition (SCCI)[39-42]. HCCI combustion strategy combines both CI and spark ignition (SI) which provides a homogeneous A/F mixture like SI that auto ignited due to compression like CI [43, 44]. HCCI results in low NOx and soot emission but, HCCI has many challenges such as the operating range limitations, difficult in combustion phase control, high pressure-rise rates at high loads, the cold starting, running at high load produces high pressure-rise (knocking phenomena), high carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions [45, 46]. PCCI combustion is an intermediate strategy between HCCI and traditional CI, where only part of fuel used to provide the homogeneous A/F mixture, but the mixture is not fully homogeneous like HCCI [47, 48]. PCCI strategy compared to HCCI strategy produces higher NOx emission but has lower HC and CO emissions additionally the in-cylinder conditions can be controlled by the amount of the premixed fuel and the timing of the main injection fuel [49, 50]. So PCCI combustion is a promising strategy that provides the advantages of both CI and SI modes as PCCI produces lower NOx, CO, HC, and soot while keep same BTE compared to conventional mode [51].

According to Kimura et al. [52], PCCI mode has a single-phase combustion process, like the premixed phase of conventional diesel mode. Meanwhile, HCCI combustion exhibits two distinct combustion areas with low and high temperature oxidation. While PCCI mode produces lower HC and CO emissions than HCCI mode, it produces higher NOx and soot emissions than HCCI mode. Elzahaby et al. [53] investigated the effect of using various premixed ratio of ethanol-diesel blends on the autoignition timing and combustion properties of PCCI engines. The obtained results show that the mixture auto-ignition is caused by diesel while the combustion process is slowed down by ethanol. Pandey. et al. [54-57] investigated the performance, combustion, and emissions characteristics of PCCI engine fueled by different premixed ethanol ratio injected in manifold at 40 ^{0} C and diesel injected directly at different engine load conditions. In their investigation, they discovered reduction in NOx and smoke opacity, but CO and HC increased due to the high latent heat of vaporization of ethanol with the increment of premixed ethanol ratio. The PPCI combustion mode was studied by Zhang et al. [58] utilizing mixtures of mineral diesel and gasoline. The use of various injection timings and EGR rates led to PCCI combustion. For PCCI combustion mode, in comparison to CI combustion mode, the smoke and NOx emission was reduced. Bhurat. et al. [59] used a light-duty diesel engine (single-cylinder - four-stroke) for investigating PCCI combustion, performance characteristics using external mixture formation and exhaust gas recirculation (EGR). they results showed reduction in NOx and smoke emissions but relatively higher CO and HC emissions and BTE decreased by 2.5% in PCCI compared to DI mode. Jain et al. [60] tested the impact of injection timing and pressure on combustion and emissions characteristics of PCCI engine. They found that, advancing the main injection timing reduced soot emission but increased NOx emission and decreased BTE. While increasing fuel injection pressure (FIP) results in reduction in soot but results in increment HC and reduction in BTE.

It has been clear from the above discussion that the previous studies on the impact using of biodiesel blends in PCCI combustion mode on combustion, performance and emissions characteristics is limited. The guideline of the current study is to investigate in the use of two methods (using biodiesel as a renewable source of energy - using PCCI strategy) for the improvement of engine performance and decreasing exhaust emissions produced from the CI engines. In this work experimental study has been carried out on single cylinder 4-stroke CI engine that was modified to run in PCCI mode to investigate in the utilization of B30D70 (30% biodiesel and 70% diesel) through the main injector along different premixing ratios of diesel vapor (15%, 20%, 25% and 30%) through manifold injection at a premixed temperature of 110 ^{0} C on the engine combustion, performance, and emissions characteristics. Furthermore, the results of this work were utilized to obtain the optimum premixing ratio of the five ratios mentioned above that will achieve the best PCCI mode performance compared it with using diesel in CDC mode.

II. THE EXPERIMENTAL METHODOLOGY AND PROCEDURE

A. *Experimental test setup*

To discuss the characteristics of PCCI combustion fueled by mineral diesel and waste cooking oil (WCO) biodiesel blends. The experiments were performed using "DEUTZ FL 511/W" 4-stroke, single-cylinder, air cooled CI engine modified to operate

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on PCCI combustion mode is as shown in Figure 1 & Figure 2 that represent the schematic diagram and the actual illustration of contents of PCCI engine, respectively. The experiments were conducted to the engine running at a constant speed of 1500 rpm so that, the only variable was the engine load, the lubricating oil temperature at 90 ^{0} C, the direct injection pressure fuel at 220 bar at a 32 CA BTDC, and the engine's compression ratio is 17. The technical specifications of a conventional engine are mentioned detailed in Table 1[61]. The engine has a dedicated electronic control unit (ECU) to control the engine speed and keep it at 1500 rpm by varying the amount of fuel injected directly into the engine. There are two fuel tanks, one is the original tank connected to graduated cylinder for measuring the consumed fuel injected directly into the engine per second and the other one is the external tank used for supplying the fuel of external mixture [62]. The engine was loaded using an eddy current dynamometer [63]. The dynamometer has a 5 kW A.C. Synchronous generator linked to the crank shaft and the generator connected to 6-lamps (each lump has 1 kW power) and an electric voltage variac device to control its output power as shown in Figure 3.

B. Modification in engine to run in PCCI Mode

The engine performance and emissions are greatly influenced by the combustion mode, so the engine has been modified to run at PCCI mode. PCCI mode was created by adding an external homogenous mixture formation unit that consists of a fuel feeding system, vaporization system and mixing chamber system. The fuel feeding system consists of a fuel pump delivered fuel from external tank to an electrical injector. The electrical fuel injector opening crank angle is controlled by an electrical circuit consists of an Arduino and a tachometer sensor connected to the engine shaft. The vaporization system provides air at high temperature, and it consists of an electrical heater and a blower each of them is controlled by a variac device.

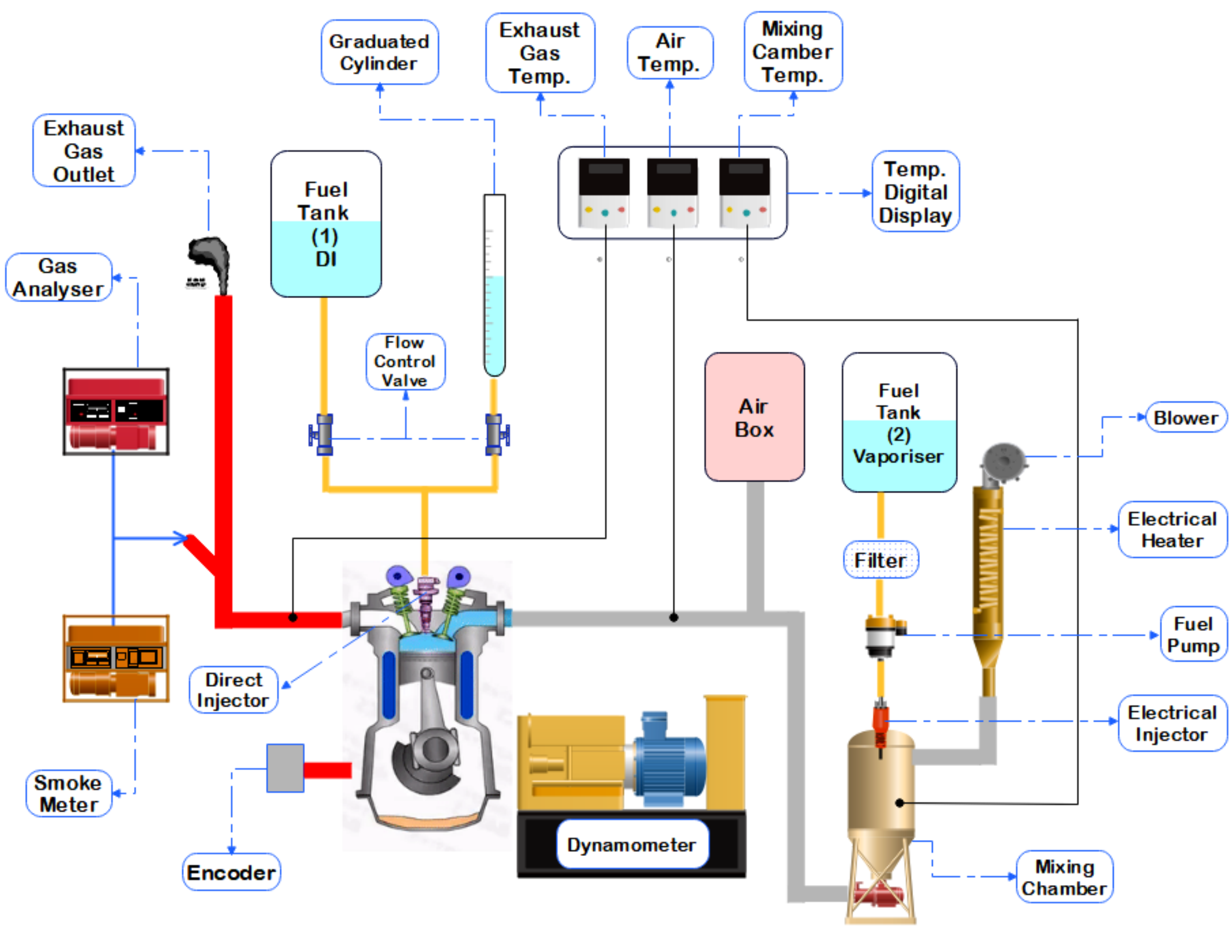

Figure 1. Schematic diagram of the PCCI engine setup with fuel vaporizer

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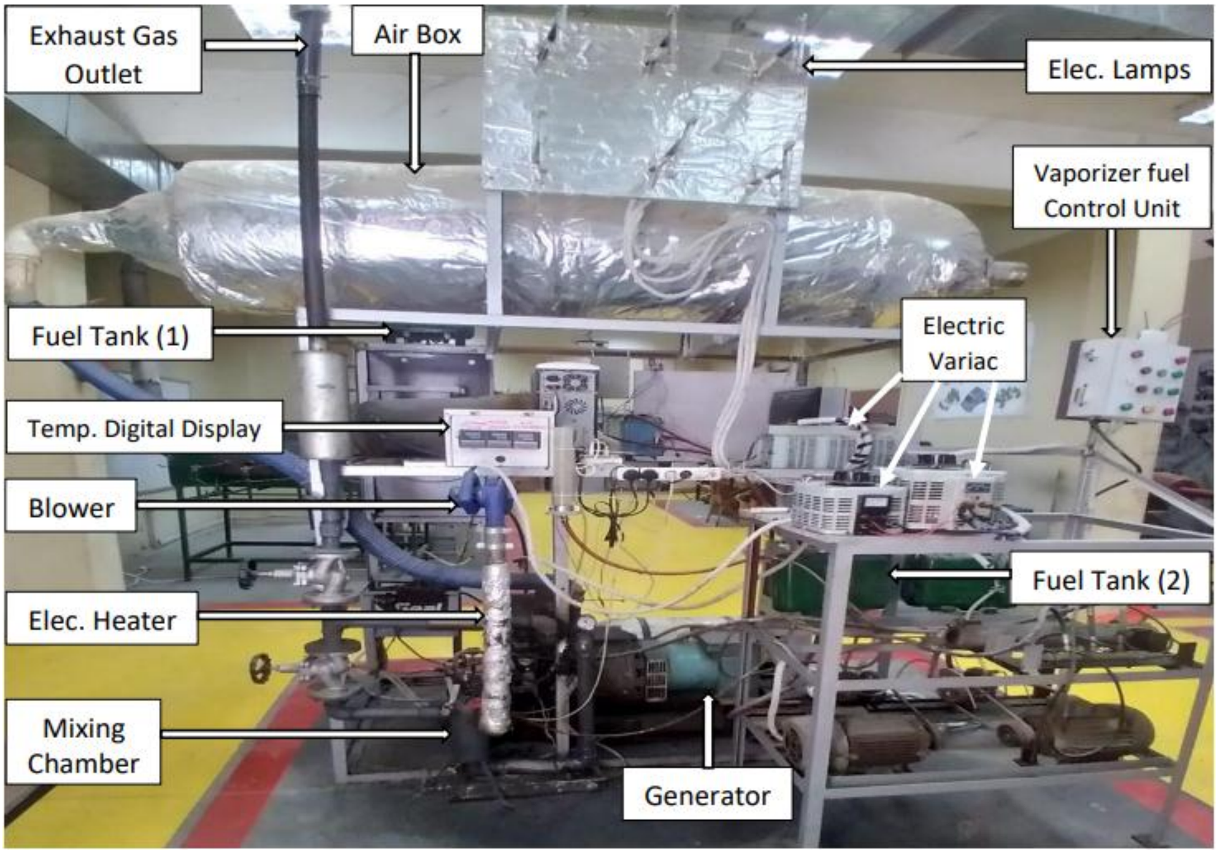

Figure 2. Actual image of the experimental setup of the engine with fuel vaporizer

Table 1: Technical specification of the engine

Parameters	Dimensions
Engine Make	DEUTZ FL 511/W
No. of Cylinders	One
Displacement	825 cm3
Bore × Stroke	10 × 10.5 cm
Cycle	Four strokes
Cooling System	Air Cooled
Injection Mode	Direct injection
Rated Power	5 kW @ 1500 rpm
Compression Ratio	17
Inlet Valve Opening	32 ^{0} CA BTDC
Inlet Valve Closing	59 ^{0} CA ABDC
Exhaust Valve Opening	71 ^{0} CA BBDC
Exhaust Valve Closing	32 ^{0} CA BTDC

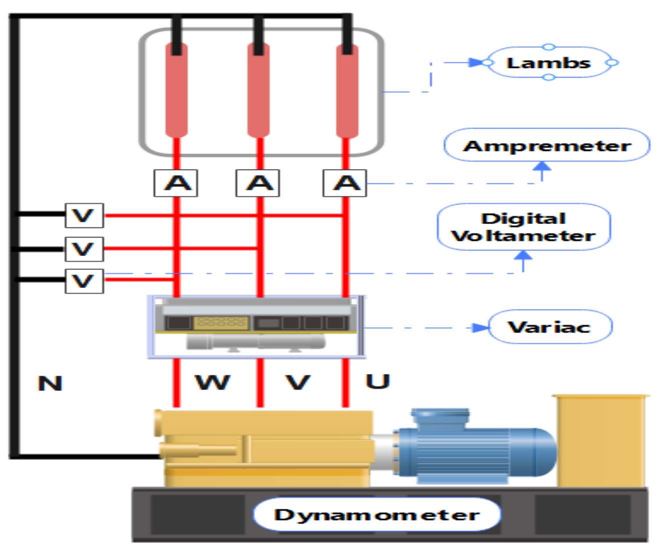

Figure 3. Load and dynamometer circuit schematic diagram

The mixing chamber is a cylindrical box with 2-inlet ports and one outlet port in addition to a vent in its bottom. According to the 2-inlet ports, one is linked to the electrical fuel injector and the other one is linked to the vaporization system for providing a small amount of heated air that used to vaporize the injected fuel into the mixing chamber while the amount of fuel vaporized depending on the mixing chamber temperature and electrical injector opening crank angle. The

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outlet port that provides the homogenous mixture formed is linked to the intake manifold through a piping system. The vent is used to release the amount of fuel condensed on the walls of the mixing chamber. At last, this produced homogenous mixture is mixed with the fresh air in the manifold before interring to the combustion chamber.

C. Fuel preparation and characterization

Two test fuels were utilized in this work, including D100 and B30D70. The D100 fuel is the local commercial diesel, and B30D70 is a mixture of biodiesel blended with diesel with volume ratio of 30% and 70%, respectively. The biodiesel is produced from WCO through a group of steps [64, 65]. At first step, WCO samples were exposed to pre-treatment to remove the impurities. The second step is the production of biodiesel by a chemical process called transesterification. In this step, methanol is used as alcohol with 1:5 volume ratios of methanol and oil and NaOH is used as catalyst with 1% weight of oil[66, 67]. The mixture is stirred for an hour while maintaining a temperature of 60 °C at 550 rpm, and it was then allowed to separate under gravity for one day. This causes the liquid to separate into two layers, with glycerin in the lower layer and raw biodiesel in the upper one. The third step is used to wash the separated biodiesel by using 1:1 volume ratio of warm water for three times and so the pure diesel is ready [7]. The Physical and chemical characteristics of the test fuels were displayed in Table 2.

D. Measurements & Error analysis

In this work, a speed sensor was attached to the engine's crank shaft to measure its speed. Three thermocouples type K were used to measure temperature, one at the inlet of air, one at the outlet of exhaust emissions and the last one at the mixing chamber to measure the premixed mixture temperature. The volume of intake air flowing into the engine is measured using an orifice system, and the pulsations caused by the suction stroke are eliminated using a damping tank. The GASBOARD-5020 emission gas analyzer was used to measure CO2, CO, O2, HC, and NO measurements. While NOX and HC were calculated in ppm, CO2, CO, and O2 were estimated in% Vol. Using an opacity meter called the GASBOARD-6010, soot emissions were measured. Different equipment's and tools were utilized to measure different parameters. These equipment's' accuracy may be affected by the operating conditions and operating environment as this accuracy affects the limiting errors of the measurements. So, the uncertainty of measured and calculated parameters may be estimated by the following equations 1 & 2 [68-70]. The precision and uncertainty analysis for different equipment's was calculated and displayed in Table 3.

$$COV = \frac{\sigma}{X_m} \text{ X } 100\% \qquad \textbf{(Eq. 1)}$$

$$\sigma = \sqrt{\frac{\sum_1^n (x_i - X_m)^2}{n-1}} \qquad \textbf{(Eq. 2)}$$

where, $\boldsymbol{\sigma}$ is the standard deviation, $\mathbf{X_m}$ is the average of the variable (x), $\mathbf{n}$ is the number of samples cycle

Table 2: Properties of Diesel and Biodiesel fuel

Fuel type	Diesel	Biodiesel
Kinematic Viscosity (at 30 ^{0}C) (mm^2/s)	2.75	3.84
Specific Gravity (@ 15 ^{0}C)	0.83	0.87
Pour Point (^{0}C)	-12	-8
Flash Point (^{0}C)	45	185
Fire Point (^{0}C)	56	156
Calorific Value (MJ/kg)	43	41.28
H to C (mole ratio)	1.8	1.9
Cetane Number	5	61
Flammability range (vol. %)	0.6 – 5.6	–
Sulfur Content (% wt.)	0.154	0.0
Ash Content (% mass)	0.013	0.016
Carbon Reside (% wt.)	0.014	0.0252
Oxygen (% wt.)	–	10.7

Table 3: Instrumentation specifications and uncertainty

Instrument	Parameter	Accuracy	Range
Emission gas analyzer	CO2	± 4%	0-20%
	CO	± 1%	0-20%
	O2	± 3%	0-25%
	HC	± 5%	0-9999 ppm
	NO	± 5%	0-5000 ppm
Opacity meter	Smoke opacity	± 0.01%	0-100%
K-type thermocouple	Exhaust gas Temperature	±1%	0 to 800 ◦C
Shaft encoder	Speed	±0.2%	0–720 ^{0} CA
Inclined manometer	Airflow rate	±2%	0–2.99 m3 /h
Graduated cylinder/stopwatch	Diesel flow meter	± 1 %	1 to 30 cm3
Load indicator	Load	±0.2%	1 to 1000 W

E. Experimental methodology

All experiments in this work were carried out at a single-cylinder, 4-stroke, DI diesel-engine running at a constant

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rotational speed "1500 rpm" with efficient modification to working at PCCI mode under various load conditions, such as no load, part load, and full load. The current experiments have been done through two stages. At First, the impact of using biodiesel blend (B30D70) was studied on the combustion, performance, and emissions properties of the engine in CDC mode. And then, the impact of using PCCI mode was studied on the combustion, performance, and emissions properties of the engine running with biodiesel blend (B30D70) injected directly into the engine as a primary fuel and pure diesel (D100) injected in the manifold at various ratio as a secondary fuel at a premixed temperature of 110 ^{0} C as listed in table 4. The premixed injection quantity is calculated using the following equations 3 & 4 [71]. The combustion, performance, and emissions properties of the engine in each stage were calculated and compared to results obtained in CDC mode running with pure diesel to investigate the impact of using biodiesel and PCCI strategy.

$$Q_{Premixed} = Q_{injected} - Q_{condenced} \qquad \textbf{(Eq. 3)}$$

where $\mathbf{Q_{Injected}}$ is the electrical injector fuel volume flow rate, $\mathbf{Q_{Condenced}}$ is the condensed fuel volume flow rate in the mixing chamber.

$$PMR = \frac{(\rho*Q*LHV)_{Premixed}}{(\rho*Q*LHV)_{Premixed} + (\rho*Q*LHV)_{Direct}} \qquad \textbf{(Eq. 4)}$$

where, $\boldsymbol{\rho_{Premixed}}$ is the direct injected fuel density, $\mathbf{Q_{Premixed}}$ is the premixed fuel volume flow rate, $\mathbf{LHV_{Premixed}}$ is the premixed fuel lowering heating value, $\boldsymbol{\rho_{Direct}}$ is the direct injected fuel density, $\mathbf{Q_{Direct}}$ is the direct injected fuel volume flow rate, $\mathbf{LHV_{Direct}}$ is the direct injected fuel lowering heating value.

Table 4: Fuel and Blends used for Experimentation

Samples	Mode	Fuel injected directly	Fuel injected in mixing chamber	Premixed Percentage
1	CDC Mode	Diesel	_____	_____
2		B30D70	_____	_____
3	PCCI Mode	B30D70	Diesel	15 %
4		B30D70	Diesel	20 %
5		B30D70	Diesel	25 %
6		B30D70	Diesel	30 %

III. RESULTS AND DISCUSSION

According to our results, using biodiesel and the premixed ratio in PCCI mode are important methods for producing better combustion and decreasing emissions of the engine.

A. Brake thermal efficiency-BTE

Brake thermal efficiency is the amount of chemical energy converted from fuel into useful work, which is considered one of the most important engine parameters. Figure 4 shows the variation in brake thermal efficiency for using B30D70 in CDC and for different premixed ratios in PCCI mode. It is evident from the figure that, the BTE increases with the increment in load at all operating conditions because of the decrement in heat lost and the increment in produced power due to better quality of combustion. For first stage, using B30D70 decreases the BTE due to the lower heating value of biodiesel blends and its higher viscosity that leads to poor spray formation and droplet distribution which deteriorates the quality of the combustion. For the second stage, in PCCI mode for 15%, 20%, and 25% premixed ratio with increasing the premixed ratio the BTE increases due to the formation of homogenous mixture externally which leads to complete and better quality of combustion. While still increasing the premixed ratio to 30%, the BTE decreases as the external mixture is loaded with more fuel that leads to a large quantity of fuel trapped in the crevice volumes and so results in incomplete combustion. 25% premixed ratio has shown maximum BTE at rated load and has an increment by 1.3% at full load compared to CDC mode.

B. Brake specific energy consumption-BSEC

Brake specific fuel consumption (BSFC) is considered the amount of fuel required to produce the unity of brake power and it is dependent on the calorific value of the fuel. Diesel and biodiesel blends have different calorific values, so it isn't appropriate parameter to express the engine performance. Brake specific energy consumption (BSEC) is the suitable parameter in the case of using multifuel with various calorific values. BSEC is the total amount of energy consumed divided by the brake power produced. BSEC value in MJ/kW.hr is calculated by using the following equation 5. Figure 5 shows the variation in brake specific energy consumption for using B30D70 fuel in CDC mode and for different premixed ratios in PCCI mode. The figure indicated that for all operating conditions with the load increases, the BSEC decreases due to better quality of combustion and more controllability of energy. It is clear from the figure that, for using B30D70 fuel BSEC increases compared to diesel fuel due to lower heating fuel of biodiesel fuel and its higher viscosity that leads to poor spray formation which deteriorated the combustion quality. For PCCI mode, for 15%, 20%, and 25% premixed ratio the BSEC decreases with increasing the premixed ratio due to lean mixture which reduces the fuel consumption and homogenous mixture formation which results in better quality of combustion but increasing premixed ratio to 30% the BSEC increases due to rich mixture formation and the occurrence of incomplete combustion. The best case of combustion of B30D70 blend is at PCCI with 25% premixed ratio as shown from figure the BSEC at average load decreased from 31 MJ/kW.hr at CDC mode to 28 MJ/kW.hr at PCCI mode with 25% PR.

$$BSEC = \frac{[(m^{\circ}*LHV)_{Premixed} + (m^{\circ}*LHV)_{Direct}]*3600}{Power} \qquad \textbf{(Eq. 5)}$$

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where, **BSEC** in terms of (MJ/kW.hr), **m˚** in terms of (kg/sec), **LHV** in terms of (MJ/kg), **Power** in terms of (kW)

C. Exhaust gas temperature-EGT

Exhaust gas temperature is an important parameter as it uses to be an indication of the combustion temperature and the heat loss from the exhaust gases that refers to the thermal stresses on the engine. The variation in engine exhaust gas temperature with engine load for using B30D70 in CDC mode and for various premixed ratios in PCCI mode is plotted in Figure 6. It is observed that in all cases when the load increases, the exhaust temperature rises; this may be due to the increment of fuel consumption that releases more energy due to the higher the combustion rate. For using B30D70 fuel, it is noted that the EGT is to be lower compared to diesel fuel because of lower heating value of biodiesel and its higher viscosity. For PCCI mode, it can be found from the Fig 6. that at any load the exhaust gas temperature reduces as the premixed ratio of diesel raised because of the lean A/F mixture leads to lower combustion temperature and the better homogeneity of the charge that help in control the combustion and reduce the diffusion combustion which responsible for the exhaust gas temperature. An average reduction of EGT is observed to be 3.2% and 13.8% for B30D70 fuel in CDC mode and 30% premixed ratio of diesel in PCCI mode respectively.

D. Oxides of nitrogen

The NOx emission is highly depending on oxygen availability, combustion chamber temperature, and residence time of the combustion. Figure 7 shows the NOx variation with brake power for biodiesel blends and PCCI mode. According to the figure, it is found that in all cases NOx emission in exhaust increases with raising the engine load because of increasing the combustion chamber temperature. For B30D70 blend, the NOx emission is higher than of diesel fuel due to the higher oxygen content in the biodiesel blends that leads to a leaner air-fuel mixture which increases the reaction between oxygen and the nitrogen which forming NOx emission.

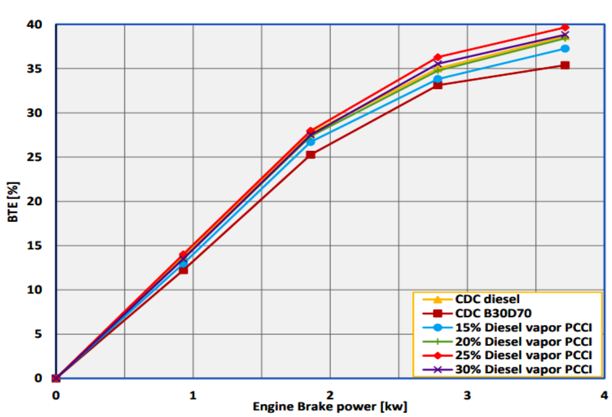

Figure 4. The variation of the BTE under various loads conditions

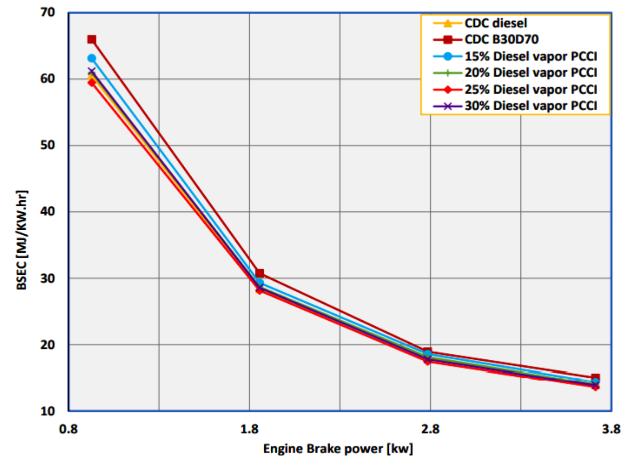

Figure 5. The variation of the BSEC under various loads conditions

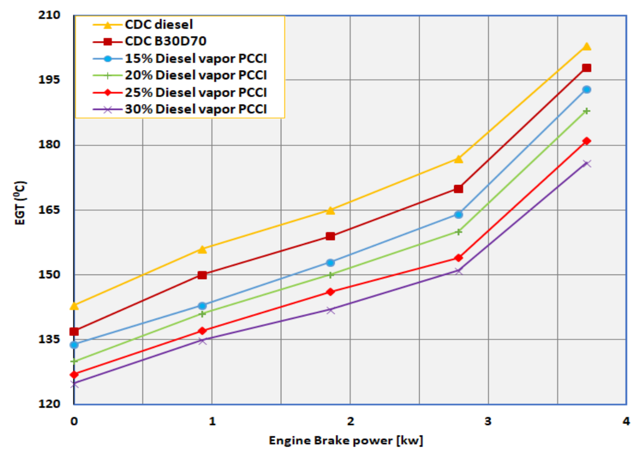

Figure 6. The variation of the EGT under various loads conditions

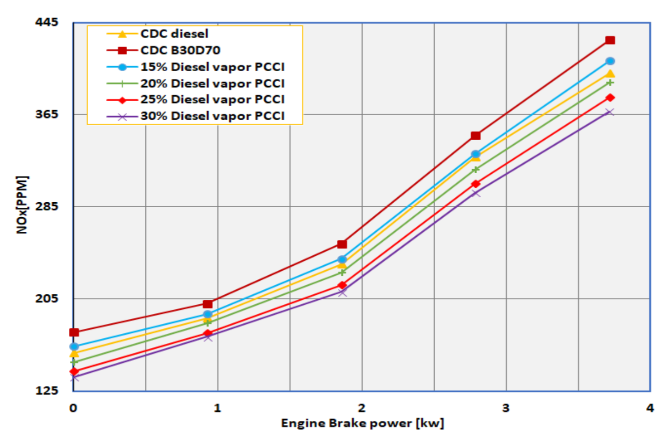

Figure 7. The variation of the NOx under various loads conditions

For PCCI mode, the NOx emission decreases with increasing the premixed ratio in all operating range because of the low combustion temperature achieved due to the good homogeneity formation of A\F mixture. The maximum NOx emission is observed to be 430 ppm at full load for B30D70

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blend in CDC mode. The minimum NOx emission is noted to be 368 ppm at full load for 30% premixed ratio in PCCI mode.

E. Unburned hydrocarbons-HC

The unburned hydrocarbons formation results from incomplete combustion of the fuel trapped in the crevice volumes, over-lean or over-rich mixture and the liquid wall wetting. The HC emission variations of the engine using B30D70 fuel and different premixed ratios in PCCI mode are shown in Figure 8 In all operating cases; the increment in HC emissions was observed when the load increases due to the complete combustion which increases the combustion temperature and efficiency. It is observed from the graph that, for using B30D70 fuel HC emission decreases compared to diesel fuel because of the oxygen content of biodiesel blend that leads to complete combustion. For PCCI mode, at 15% and 20% premixed ratio the HC emission decreases due to more homogenous mixture formation which leads to complete combustion. At 25% and 30% premixed ratio the HC emission increases due to lower combustion temperature and diesel trapped in the crevice volumes and its cylinder wall wetting of the premixed diesel. The highest values of HC emission are observed for diesel fuel in CDC mode and the lowest values is found for 20% premixed ratio of diesel vapor in PCCI mode.

F. Carbon monoxide-CO

Carbon monoxide is an important parameter as it is a poisonous and flammable gas. The CO concentration depends on the incomplete combustion that leads to partial oxidation of carbon due to low combustion temperature and lacking oxygen content. The variation in CO emission with engine load for using B30D70 in CDC and for different premixed ratios in PCCI mode is shown in Figure 9. The figure shown that for all operating cases with the load increases, the CO emission decreases due to the combustion temperature increases. It is observed from the graph that using B30D70 fuel CO emission decreased when comparing with pure diesel because of complete combustion due to the oxygen present in biodiesel fuel. For PCCI mode, diesel vapor may enhance mixture homogeneity, but it limits the volumetric efficiency, so keep increasing the premixed ratio causing rich air–diesel vapor mixture leading to improper combustion which increases CO emission. 15% and 20% premixed ratio of diesel vapor in PCCI mode decreases CO emission but keep increasing premixed ratio for 25% and 30% CO emission increases. From figure, the minimum CO emission level is found for 20% premixed ratio of diesel vapor with biodiesel directly injected into the combustion chamber.

G. Smoke Opacity

Figure 10 shows the smoke opacity variation with engine load for using B30D70 in CDC and for different premixed ratios of diesel vapor in PCCI mode. The obtained results show that smoke opacity increases by rising engine load at all operating cases due to richer A/F mixture. B30D70 fuel produces higher smoke opacity when comparing with pure diesel because of the higher viscosity of biodiesel. It is found from the graph for PCCI mode that 15% and 20% diesel vapor promote the homogeneity of air-fuel mixture leads to combustion improvement and so decreases smoke opacity. While 25% and 30% diesel vapor decrease the volumetric efficiency leads to rich mixture and deterioration of combustion and so increases smoke opacity.

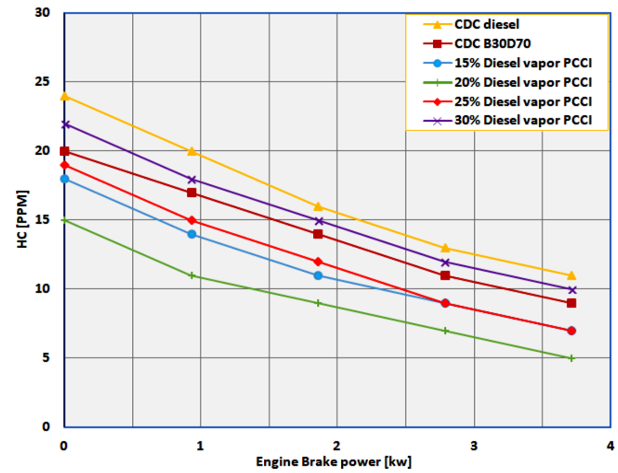

Figure 8. The variation of the HC under various loads conditions

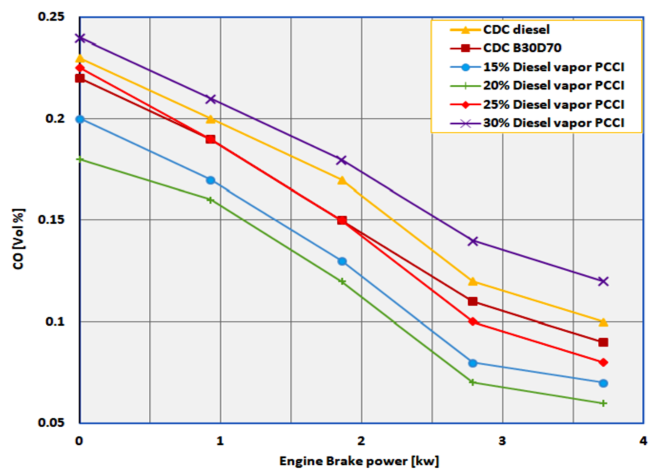

Figure 9. The variation of the CO under various loads conditions

IV. CONCLUSION

The effects of using biodiesel blend (B30D70) in CDC mode and external mixture of air/diesel-vapor at different proportions in PCCI mode such as (15%, 20%, 25% and 30%) were examined on the combustion, performance, and emissions properties of the engine under various load conditions and these results was compared with diesel fuel in CDC mode. The experiments showed that biodiesel is a suitable fuel to replace diesel, but it has a penalty on BTE, NOx, and smoke opacity.

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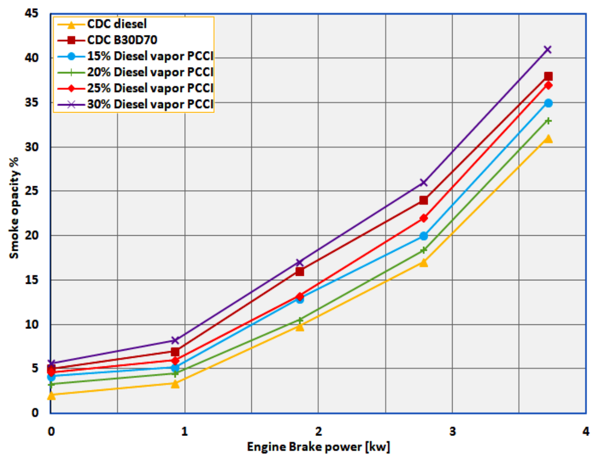

Figure 10. The variation of smoke opacity under various loads conditions

While, adding the PCCI strategy when using biodiesel blends may be more benefit to overcome the drawbacks of biodiesel. The following conclusions are drawn from the experiments:

- BTE decreased on average 7.54% using B30D70 fuel and BSEC increased on average 7.73% while using 30% diesel vapor has almost the same BTE.
- EGT goes down with using B30D70 fuel and EGT still reduced with increasing premixed ratio in PCCI mode.
- NOx emissions reduced with the use of B30D70 fuel due to its oxygen content and more reduction achieved with increasing diesel vapor ratio due to lower combustion temperature.
- Smoke opacity was increased for B30D70 fuel with an average 26.3%. 20% diesel vapor ratio produced an average 21.27% of smoke opacity compared to an average 19.8% for diesel in CDC mode while 30% diesel vapor ratio produced the maximum percentage of smoke.
- HC emissions reduced with the use of B30D70 fuel due to its oxygen content and PCCI mode produced lower HC emissions but then produced higher HC due to its lower volumetric efficiency.
- CO emissions reduced with the use of B30D70 fuel due to its oxygen content and PCCI mode showed lower CO emissions due to better mixture homogeneity, but 30% diesel vapor produced the maximum CO emission due to its lower volumetric efficiency.

Finally, we can use PCCI strategy with 20% premixed ratio of diesel vapor with simple modification to the engine when using biodiesel as an alternative fuel to diesel to combine between the advantages of both PCCI strategy and biodiesel.

V. FUTURE RESEARCH DIRECTION

Future research on the following critically intriguing subjects has been recommended as a result of the discussion of biodiesel blend and fuel vaporizer technology implications on PCCI engine emissions, performance, and combustion characteristics that were just mentioned.

1. Adding EGR and fuels with higher calorific value when using Biodiesel blends fuels may be helpful in improving combustion and reducing NOx emissions.
2. For controllability, reliability, and a huge working capacity in combustion, using an electrical injector is regarded as an effective method as compared to the mechanical injector with the suitable fuel injection pressure to have the ability to control the amount of fuel that is directly injected into the cylinder according to the premixed fuel vapour in the mixing chamber and avoid knocking occurrence.
3. Using fuel vaporizer technology, a turbocharger is considered a better method to increase the volume of fresh air flowing into the combustion chamber and could avoid the formation of over-rich mixture which is beneficial because it decreases fuel impingement and trapping into crevice volumes, which helps to minimize HC and CO emissions.

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Conflicts of Interest:

The authors do not have any conflict of interest.

NOMENCLATURE

ICE	Internal combustion engine	**LTC**	Low-temperature combustion
CI	Compression ignition	**SI**	Spark ignition
PCCI	Premixed charge compression ignition	**RCCI**	Reactivity Controlled Compression Ignition
HCCI	Homogeneous charge compression ignition	**SCCI**	Stratified Charge Compression Ignition
BSEC	Brake specific energy consumption	**BSFC**	Brake specific fuel consumption
ATDC	After top dead center	**BTDC**	Before top dead center
PM	Particulate matter	**CO2**	Carbon dioxide
NOx	Nitrogen oxide	**CO**	Carbon monoxide
HC	Hydrocarbon	**FIP**	Fuel injection pressure
BMEP	Brake mean effective pressure	**RPM**	Revolutions per minute

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COV	Coefficient of variance	**BTE**	Brake thermal efficiency
EGR	Exhaust gas recirculation	**EGT**	Exhaust gas temperature
WCO	Waste cooking oil	**ECU**	Electronic control unit

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