EXPLORING THE EFFECTS OF PILOT INJECTION TIMING ON CRDI ENGINE OPERATION UNDER VARYING LOADS

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ABSTRACT

In this study, a single-cylinder CRDI engine running on 20MEWCO (20 % Methyl Esters of Waste Cooking Oil + 80 % diesel) fuel was used to test various pilot injection timing modifications, including 34°, 36°, and 38° bTDC with a dwell period of 15° and 10 % pilot mass at a pressure of 500 bar. The analysis focused on cylinder pressure, heat release rate, fuel consumption, brake thermal efficiency, and emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and smoke.

As a result of advanced pilot injection timings, at 38° bTDC, the cylinder pressure, heat release rate, and brake thermal efficiency were 63.73 bar, 34.04 J/°CA, and 30.74 %, respectively. Emissions of HC, CO, and smoke increased significantly, while NO_x emissions were significantly reduced. Advanced pilot injection timing at maximum load caused a decrease in ignition delay, while shorter combustion duration resulted in more efficient combustion.

Keywords: pilot injection timing, waste cooking oil, dwell period, CRDI engine, emissions, combustion, ignition delay.

INTRODUCTION

Diesel engines with CRDI technology decrease emissions through various features and strategies. Test results show that using a diesel/natural gas dual-fuel engine with optimized pilot injection timing significantly reduces combustion noise [1 - 5]. Improving injection timing can substantially decrease driver perception, particle number, and mass concentration [6 - 10]. The findings showed that increasing the pilot injection timing to 17° bTDC (before top death centre) increased the maximum cylinder pressure, improved thermal efficiency, enhanced the heat release rate, and significantly reduced HC, CO, and smoke emissions. Even though adding pilot injection timing under high load causes an ignition delay, reducing the combustion duration improves combustion performance [11]. Jwa et al. discussed application of the blend of 80 % diesel and 20 % soybean biodiesel to investigate how injection timing and pressure affect combustion and exhaust metrics [12]. The 700-bar injection pressure caused the lowest CO_2 emissions and the longest ignition delay. Pilot injection timing was set at 5°, 10°, 15°, and 20° bTDC (before top death centre), with volumes ranging from 5 % to 20 %, and as the amount and timing of pilot injection were optimized, NO_x emissions decreased and brake thermal efficiency increased [13]. Experiments were conducted with varying pilot injection timing and EGR rate for

B20 fuel at 2000 rpm. As the injection time increased at 2000 rpm, maximum combustion pressure and specific fuel consumption (SFC) were increased marginally [14].

The influence of pilot injection parameters on the engine's emission characteristics was described. Specifically, it was found that pilot injection timing significantly affects NO_x emissions, with a more substantial impact observed at lower engine loads and speeds [15]. The effects of both pilot injection (PI) and main injection (MI) on combustion and emission parameters (NO_x, CO, HC, and smoke) in a direct-injection diesel engine were examined. The engine's performance was characterized in terms of emissions and operating characteristics for various air-fuel ratios and pilot injection timings [16, 17]. The test of the engine injection pattern using a hydraulic injection analyzer was explained and the speed profile for each test cycle was obtained [18]. High-speed imaging provides temporal and spatial resolution data on the maximum ignition temperature and flame shape during combustion were provided by high-speed imaging. The uses of numerical experiments were studied, and the effects of split injections were compared with the proposed method on a diesel engine, leading to a significant reduction in NO_x emissions [19, 20]. It has been shown that the average exhaust gas temperature is reduced by pilot injection through a decrease in premixed combustion and diffusion combustion rates at low speeds [21]. A pilot-main injection ratio and a pilot-to-main injection interval were used by the authors. Specifically, it is predicted by the model that the maximum NO_x production rate in the premixed zones increases with changes in ignition delay. The common rail injection system was explained, and the number of injections per cycle can be performed, resulting in reduced emissions and increased performance [22 - 24]. The feasibility and utility of several technologies using biodiesel fuel in the CRDI engine were discussed. The main, pilot, and post-injection timings were delayed by 3° compared to the recommended TDC of 23°, resulting in decreased emissions [25, 26]. The effects of combustion, fuel consumption, and heat release rate were focused on by the authors, using various pilot injection parameters and timings in the CRDI engine. The control of emissions and the increase in thermal efficiency are analyzed, requiring careful consideration of pilot mass injection timing and rates [27 - 32].

The various types of biodiesel blends fuel used in the CI engine were focused on, and the best engine performance was analyzed and provided, while CO_2 and smoke emissions were significantly reduced, along with a moderate increase in NO_x emissions [31]. Despite this research, further studies are needed on pilot and main injectors. Most research on biodiesel has focused on its production, fuel properties, and use in diesel engines.

The main objective of this study is to comprehensively evaluate the performance, emissions, and combustion characteristics of a Common Rail Direct Injection (CRDI) engine operating on 20MEWCO biodiesel at 1500 rpm while maintaining a 10 % pilot mass (Fig. 1). This evaluation will be conducted by systematically varying the pilot injection timing. The goal is to understand how changes in pilot injection timing (at 34°, 36°, and 38° bTDC) influence critical engine parameters, such as power output, fuel efficiency, and emission levels, including NO_x, CO and smoke. Additionally, the study will assess the impact of pilot injection timing on combustion processes to better optimize engine performance while reducing harmful emissions.

EXPERIMENTAL

Preparation procedure of methyl ester of waste cooking oil

The transesterification reaction was carried out in a 500 mL spherical glass reactor equipped with a condensation system, sample outlet, mechanical stirrer and thermostat. The reactor was preheated to 75°C. Next, 250 g of used cooking oil was added. As soon as the catalyst, methanol, and mixing system were added to the reactor at the appropriate temperatures, this was regarded as the start of the reaction. Each combination was well mixed and refluxed for the necessary amount of time. After the reaction, the excess ethanol was distilled under vacuum (150 mm Hg absolute pressure). Glycerol is separated using the transesterification product in separator funnels. Due to the production of solid emulsions in products, gravity alone could not separate the glycerol from the ethyl ester phase. Therefore, 10 g of pure glycerol was added to the product. The glycerol layer and ester layer split apart after an hour. The catalyst and soap remnants from the transesterification reaction were added to the mixtures along with pure glycerin, which caused a density difference between the

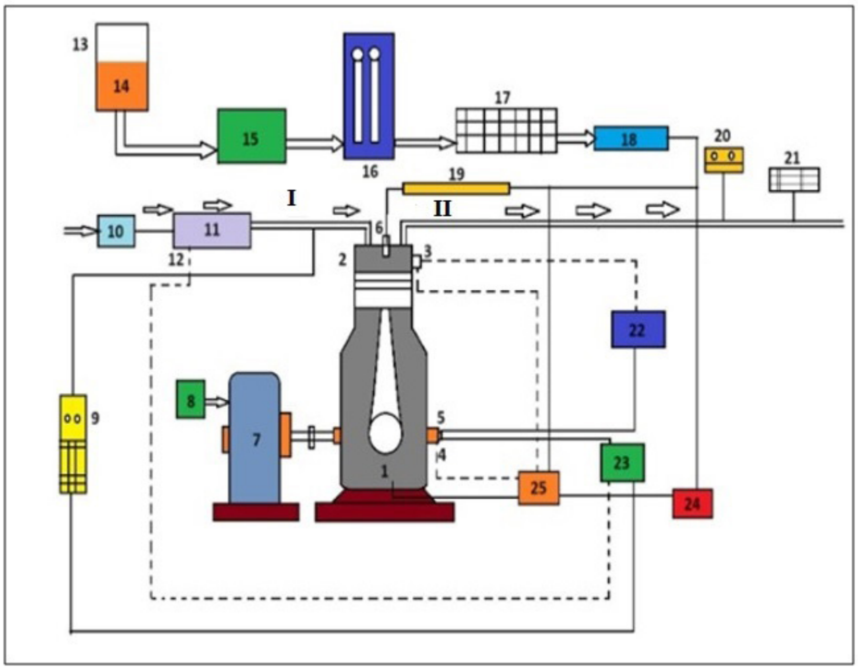

Fig. 1. Schematic diagram of CRDI engine: 1 - CRDI engine, 2 - pressure sensor, 3 - coolant temperature sensor, 4 - cam sensor, 5 - crank angle sensor, 6 - solenoid injector, 7 - eddy current dynamometer, 8 - dynamometer controller, 9 - charge amplifier, 10 - surge tank, 11 - air flow meter, 12 - air flow sensor; 13 - diesel tank, 14 - biodiesel, 15 - fuel pump, 16 - fuel measuring unit, 17 - fuel filter, 18 - high-pressure fuel pump, 19 - common rail, 20 - exhaust gas analyser, 21 - smoke meter, 22 - combustion analyser, 23 - data acquisition system, 24 - programmable ECU controller, 25 - A-D converter. I - Inlet manifold, II - Exhaust manifold.

two phases and aided in their gravity-based separation. Following the separation of the two layers, the crude methyl esters were repeatedly (up to 10) reacted in a separator with 50 cm^3 of hot distilled water (50°C) until a neutral reaction occurred. Heating to 110°C was used to remove the remaining water. Table 1 includes information on diesel fuel and cooking oil methyl ester.

Experimental setup and testing procedure

Table 2 provides the detailed specifications for the test engine. Emissions are measured using a five-gas analyser, capable of detecting carbon monoxide (CO), nitrogen oxides (NO_x), and unburned hydrocarbons (HC). The analyser's detection ranges are as follows: CO: 0 to 20 % by volume, NO_x: 0 to 5,000 ppm, and HC: 0 to 20,000 ppm. The exhaust gases are collected and analysed after the engine has been run under each set of different pilot injection timings (34°, 36° and 38° bTDC) and various engine load percentages (25 %, 50 %, 75 % and 100 %). For each test, emissions are monitored and recorded at regular intervals to assess the levels of CO, NO_x, and HC produced during combustion. The analyser provides real-time measurements of the exhaust composition, which are recorded for further analysis. Emission data, including CO, NO_x, and HC levels, are logged for each test run. Other engine parameters, such as temperature, pressure, fuel consumption, and engine speed, are also monitored and recorded to assess overall engine performance. Combustion efficiency is evaluated by analysing the emissions data alongside performance parameters like brake thermal efficiency and specific fuel consumption. The study focuses on how varying the pilot injection timing influences combustion characteristics such as heat release rate, peak pressure, and combustion duration. These metrics are compared across different pilot injection timings (34°, 36°, and 38° bTDC) to identify the optimal timing for balancing performance and emissions.

The test examines the combustion and emission efficiency under varying pilot injection timings. The engine operates on specially developed B20 fuel, a blend of 80 % clean diesel and 20 % biodiesel made from used methyl esters of used cooking oils (20MEWCO). The pilot injection timing varies between 34°, 36°, and 38° bTDC, while the main injection timing is maintained with a 15° dwell period and an injection pressure of 500 bar. Fig. 2 shows the fuel injection pattern for the experimental

Table 1. Property of diesel and biodiesel.

ASTM Norms	Diesel	20MEOWCO	Properties
ASTM D1298	860	873	Density at 16° C, kg m^{-3}
ASTM D445	3.2	4.15	Kinematic viscosity at 40°C, cst
ASTM D93	75	184	Flashpoint, °C
ASTM D2500	18	15.5	Cloud point, °C
ASTM D613	49	51	Cetane number
ASTM D240	43.0	38.012	Calorific Value, MJ kg^{-1}
ASTM D130	3.1	2.4	Copper strip corrosion
EN14214	-	19.0	Iodine value (I_2/100 g)
ASTM D6584	-	41.1	Palmitic (C10.0), wt. %
ASTM D6584	-	4.4	Stearic (C18.0), wt. %
ASTM D6584	-	41.9	Oleic (C18.1), wt. %
ASTM D6584	-	9.6	Linoleic (C18.2), wt. %
ASTM D6584	-	0.49	Linolenic (C18.3), wt. %

Table 2. Test engine specifications.

No	Parameters	Specifications
1	Model of the engine	Kirloskar
2	Type of engine	Four strokes and single-cylinder diesel engine at a constant speed
3	Capacity	660 cc
4	Engine bore and stroke length	87.5 mm×110 mm
5	Machine programmable ECU	Model Nira (Solenoid injector)
6	Variable Compression ratio	from 12 to 18
7	Speed	1500 ~1600 rev min^{-1}
8	Rate of power	3.5 kW
9	Type of loading	Eddy current dynamometer
10	Variation of injection pressure	200 bar - 800 bar
11	Variation of injection timing	29°~15° bTDC
12	Temperature sensor	K-Type thermocouple

study with 10 % pilot injection, where 10 % of the B20 fuel is introduced during the pilot injection period, and the remaining 90 % is injected during the main injection phase, with a dwell period of 15°.

The results from the testing procedure are compiled into comprehensive graphs, showing the relationship between injection timing, emissions, and combustion performance.

RESULTS AND DISCUSSION

The analysis of the combustion and emission parameters of the CRDI engine by using biodiesel blend fuel (20MEWCO) was conducted with the engine running continuously at a speed of 1500 rpm, with a constant injection pressure of 500 bar, a pilot mass of 10 %, and a dwell period of 15°. The influence of various pilot injection timings (34°, 36°, and 38° bTDC) was also examined. The following list includes the various combustion parameters of the CRDI engine, such as SFC, brake thermal efficiency, cylinder pressure, heat release rate, and emissions (NO_x, CO, HC, and smoke efficiency).

Cylinder pressure and the various timings of the pilot injection

Fig. 3 depicts the cylinder pressure versus crank angle for various pilot injection timings at maximum load. As the pilot injection timing is advanced, the start of the combustion process also advances. For pilot

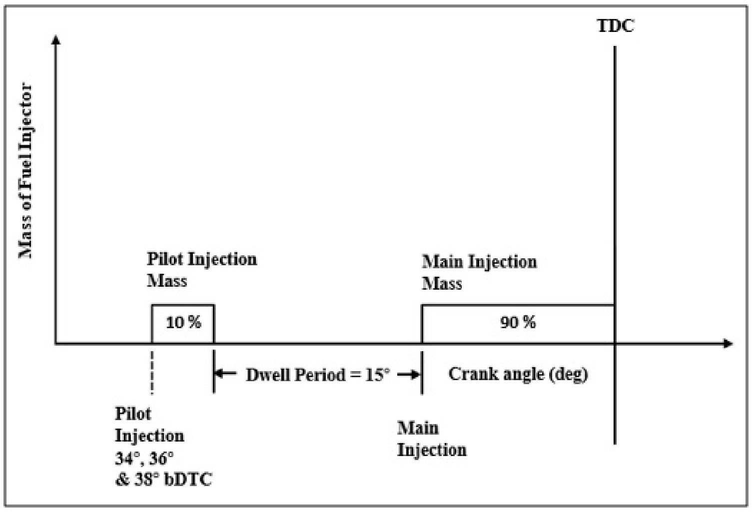

Fig. 2. Fuel injection pattern for the experimental study.

injection timings of 34°, 36°, and 38° bTDC, the cylinder pressures for biodiesel (20MEWCO) are 68.56 bar, 66.35 bar, and 63.78 bar, respectively. In contrast, without pilot injection (at 23° bTDC), the cylinder pressure is higher, reaching 73.55 bar.

This trend indicates that advancing the pilot injection timing results in a reduction of peak cylinder pressure. Consequently, the ignition delay and combustion duration are shortened. Advancing the pilot injection timing reduces the peak pressure by shifting a portion of the combustion to an earlier, lower-pressure phase, resulting in a smoother and less intense main combustion event.

Furthermore, it is evident that the reduction in peak pressure significantly lowers NO_x emissions, as shown in Fig. 7.

Heat release rate and the various timings of the pilot injection

Fig. 4 shows the heat release rate versus crank angle for various pilot injection timings at maximum load. As the pilot injection timing advances by 2° with each increment from 34° bTDC, the pressure and temperature available at the time of fuel injection decrease, limiting pilot combustion and resulting in a reduction in the heat release rate. The heat release rates for pilot injection timings of 34°, 36°, and 38° bTDC are 37.05 J/°CA, 36.05 J/°CA, and 34.04 J/°CA, respectively, while the heat release rate without pilot injection (at 23° bTDC) is significantly higher at 52.1 J/°CA. It is evident that the reduction in heat release rate significantly contributes to a decrease in NO_x emissions, as illustrated in Fig. 7.

Specific fuel consumption and the various timings of the pilot injection

Fig. 5 shows the specific fuel consumption versus various loads for different pilot injection timings. For 20MEWCO biodiesel, a decrease in specific fuel consumption as the pilot injection timing advances across different load conditions. Compared to the case without pilot injection, the specific fuel consumption decreased. As the pilot injection timing advances, the specific fuel consumption decreases to 0.29 kg kWh^{-1}, 0.28 kg kWh^{-1}, and 0.27 kg kWh^{-1} at injection timings of 34°, 36°, and 38° bTDC, respectively. It was also observed that advancing the pilot injection timing reduces specific fuel consumption and improves efficiency because early fuel injection allows better utilization of the injected fuel, with a shorter ignition delay compared to operating without pilot injection.

Brake thermal efficiency and the various timings of the pilot injection

Fig. 6 shows the brake thermal efficiency versus various loads for different pilot injection timings. Advancing the injection timing to 34°, 36°, and 38° bTDC resulted in an increase in brake thermal efficiency due to higher temperatures and a shorter delay period. However, advancing the injection timing to 38° bTDC led to a more notable improvement in combustion quality, which is one of the most crucial parameters for regulating the combustion process and an effective strategy for optimizing heat release. At 38° bTDC, the highest thermal efficiency (32.48 %) was achieved at

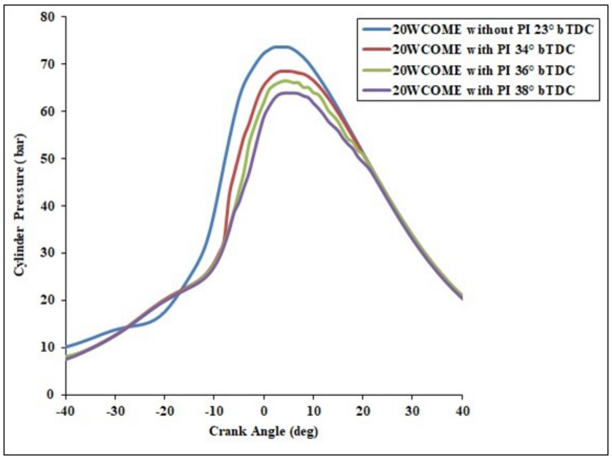

Fig. 3. Cylinder pressure vs crank angle.

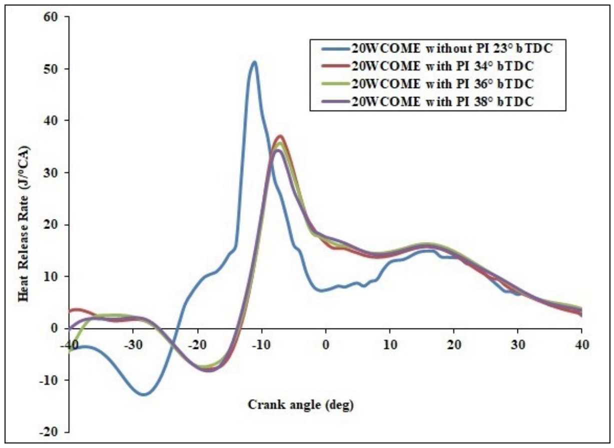

Fig. 4. Heat release rate vs crank angle.

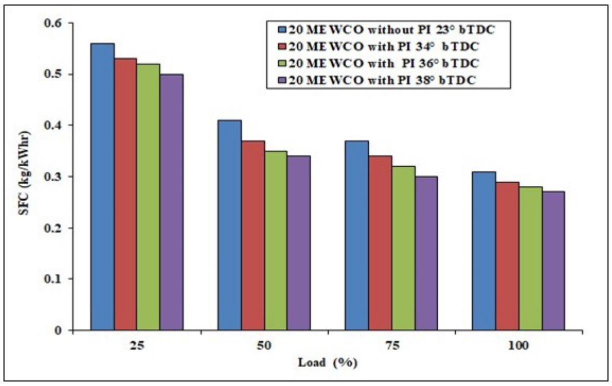

Fig. 5. SFC vs crank angle.

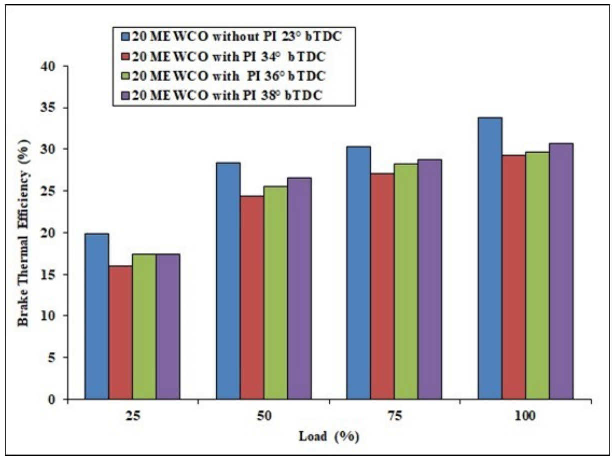

Fig. 6. Brake thermal efficiency vs load.

maximum load, representing a 0.9 % increase compared to the without pilot injection.

The increase in brake thermal efficiency can be attributed to more efficient combustion, reduced ignition delays, better air-fuel mixing, and minimized heat losses. These factors contribute to more effective fuel utilization and improved overall engine performance.

Oxide of nitrogen emissions and the various timings of the pilot injection

Fig. 7 illustrates the variation of NO_x emissions versus various loads for different pilot injection timings. The effect of various pilot injection timings significantly reduced NO_x emissions under maximum load conditions, with NO_x emissions for pilot injection timings of 34°, 36°, and 38° BTDC being 1567 ppm, 1500 ppm, and 1473 ppm, respectively, compared to the NO_x emission of 1982 ppm without pilot injection.

With lower NO_x emissions at maximum load due to advanced pilot injection with short ignition delay. The CRDI engine's combustion and emissions performance are influenced by advancing the pilot injection timing. The pilot-injected fuel mass evaporates quickly after injection, initiating the ignition process. These reactions, which prepare the combustion chamber, significantly reduce the ignition delay of the main injection. As a result, NO_x emissions decrease while smoke production increases, as shown in Fig. 10.

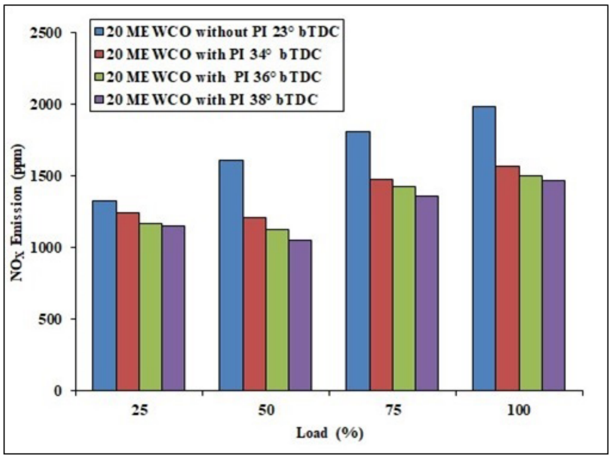

Fig. 7. NO_x emission vs load.

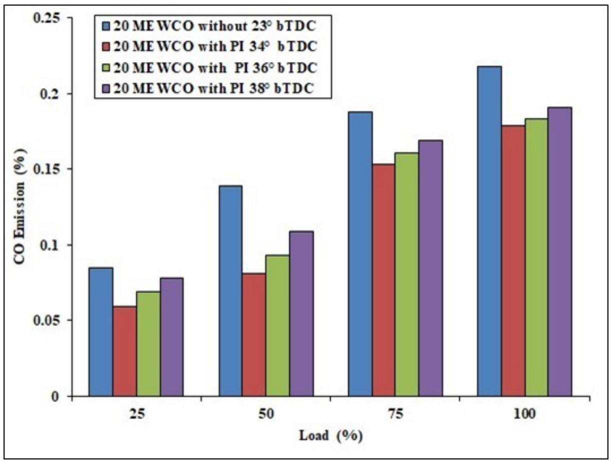

Fig. 8. CO emission vs load.

Carbon monoxide emissions and the various timings of the pilot injection

Fig. 8 illustrates the CO emissions versus various loads for different pilot injection timings. It was observed that pilot injection timing was advanced at 34°, 36°, and 38° bTDC and increase of carbon monoxide emissions are 0.16, 0.17 and 0.18 % respectively. Compared to the case without pilot injection (23° bTDC), and carbon monoxide emissions decreased (0.23 %). The biodiesel burned less completely due to the short interval between the pilot and main injections, which led to an increase in CO emissions. The delay period when using pilot injection is typically short because biodiesel has higher viscosity, density, and iodine value compared to diesel, making it more difficult to burn completely. However, as the load increases, the maximum CO emission value is reached.

Hydrocarbon emissions and the various timings of the pilot injection

Fig. 9 shows the hydrocarbon emissions with several of load and different pilot injection timings. The carbon monoxide emissions increased to 60 ppm, 62 ppm, and 63 ppm for pilot injection timings of 34°, 36° and 38° bTDC respectively. It was found that various pilot injection timing results in lower hydrocarbon emissions compared to without pilot injection value of 69 ppm at 23° bTDC. As the pilot injection timing is advanced, the fuel injected has less time to mix thoroughly with the air during the delay period, leading to incomplete combustion and increased HC emissions. Therefore, when the pilot injection timing is advanced, HC emissions tend to rise due to incomplete combustion caused by early injection and insufficient time for proper air-fuel mixing.

Smoke emissions and the various timings of the pilot injection

Fig. 10 shows the smoke emissions versus various loads for different pilot injection timings, which increase smoke emissions for the 20MEWCO blended fuel. As the pilot injection timing advanced, the percentage of smoke emissions increased to 49.1 %, 49.9 % and 53.0 % at 34°, 36°, and 38° bTDC, respectively. In the case without pilot injection, smoke emissions were 44.9 %. It was observed that when pilot injection was used, smoke emissions were higher compared to the case without pilot injection. However, as the pilot injection timing was advanced, smoke emissions increased. Smoke emissions increased due to incomplete combustion caused by the early injection of pilot fuel, which can lead to higher soot and particulate formation, especially at high engine loads where combustion conditions are already stressed.

CONCLUSIONS

This study used 20MEWCO biodiesel in a CRDI engine with an injection pressure of 500 bar to examine

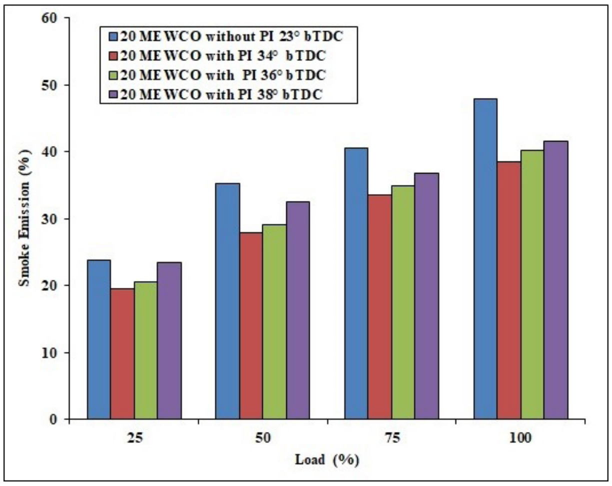

Fig. 9. HC emission vs load.

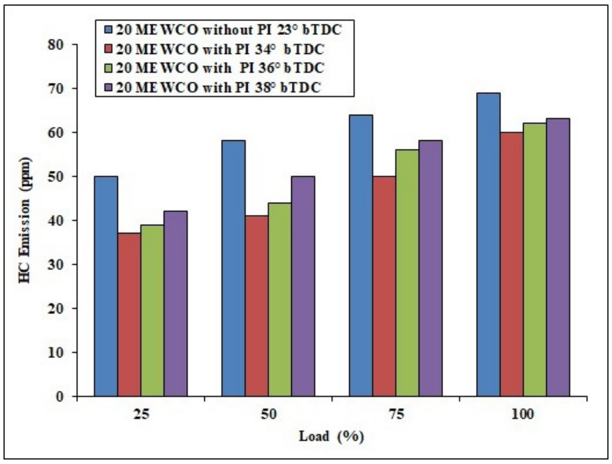

Fig. 10. Smoke emission vs load.

the combustion and emission characteristics at various pilot injection timings (34°, 36°, and 38° bTDC), with a dwell angle of 15°, at different engine loads. The cylinder pressure, heat release rate, and specific fuel consumption (SFC) decreased with advancing pilot injection timing at various engine loads.

The 20MEWCO fuel was tested by varying the pilot injection timing to 34°, 36°, and 38° bTDC at different engine loads and a pressure of 500 bar, with the results compared to those without pilot injection. As a result, with the advancement of pilot injection timing, smoke emissions increased compared to those without pilot injection, while NOx emissions were reduced by 25 % to 100 % as the engine load increased. At a constant fuel injection pressure with 20MEWCO, hydrocarbon and carbon monoxide emissions increased with advanced pilot injection timings.

As a result, compared to the without pilot injection, hydrocarbon and carbon monoxide emissions were reduced.

Author Contributions*: Conceptualization: R. A.; Data curation: S. S.; Formal analysis: K. R., L.S.; Funding acquisition: R. A.; Investigation: S. S., K. R., R. A.; L.S.; Methodology: R. A., S. S.; Project administration: R. A., K. B.; Resources: R. A., L.S.; Software: K. R., K. B., Supervision: R. A., S. S.; Validation: K. R.; Visualization: K. R.; Writing - original draft: R. A., L.S., S. S.; Writing - review and editing: R. A., L.S., S. S..*

Abbreviation

Abbreviation	Abbreviation explanation
20MEOWCO	20 Methyl Esters of Waste Cooking Oil
CA	Crank Angle
deg	degree
EN-14214	European biodiesel standard
ASTM 6751	American Society for Testing and Materials
TSME	Tamarind seed methyl ester
FIP	Fuel Injection Pressure
EGR	Exhaust Gas Recirculation
BSFC	Brake Specific Fuel consumption
SOI1	Start of injection first
SOI2	Start of injection second
SFC	Specific Fuel Consumption
CRDI	Common Rail Direct Injection
TDC	Top Dead Centre
BDC	Bottom Dead Centre
TDC	Before Top Dead Centre
M	Main injection
PI	Pilot Injection
HC	Hydrocarbon

Abbreviation	Abbreviation explanation
BTE	Brake Thermal Efficiency
CO	Carbon monoxide
ppm	Parts Per Million
BHP	Brake Horse Power
WCO	Waste Cooking Oil
B20	80 % of Petroleum Diesel + 20 % of Waste Cooking Oil Bio-Diesel Blend

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