Effect of direct water injection in diesel engine operated with palm oil fuel blends

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Abstract- This study investigates the effect of direct water injection into a PB10 palm oil fuel blend. For this, a stationary diesel engine was used, in which different operating conditions were defined at a maximum load of 9 Nm and at a rotation speed of 3000, 3250, 3500, 3750, and 4000 rpm. The investigation consisted of evaluating engine performance using the parameters of BSFC and BTE, and analysis of CO_2, HC, CO, NOx emissions and smoke opacity. The results obtained demonstrate that direct water injection causes an increase in the engine's BSFC. However, for PB10W25, PB10W50, and PB10W100 blend, the increase remained below 0.8% compared to PB10. In the case of the engine BTE, the results indicate that the maximum reduction produced is 1.28% compared to diesel. On average, the PB10W25, PB10W50, and PB10W100 blends achieved a 12% decrease in NOx emissions. Direct water injection also allowed improvements in the combustion characteristics of PB10 biodiesel to achieve a greater reduction in CO_2, CO emissions, and smoke opacity. Despite the above, the blends of PB10W25, PB10W50, and PB10W100 show a 25% increase in HC emissions, compared to diesel.

Keywords –Direct water injection, Emissions, Engine, Performance

I. INTRODUCTION

Fuels called biodiesel to refer to those fatty acids from animal fats or vegetable oils, which can be used in diesel engines [1][2]. Biodiesel is considered an acceptable alternative to partially replace the diesel content in the fuel of internal combustion engines, which helps to reduce emissions that mainly impact the greenhouse effect [3]. Due to this characteristic, these types of fuels have been implemented considerably in those countries in which strict regulations have been imposed to control polluting emissions [4][5].

In the current literature, different types of research have been registered that analyze the effect of biodiesel fuels on the characteristics of emissions and the impact on engine performance [6][7]. In general, it is concluded that the addition of biodiesel in the fuel contributes to the reduction in emissions of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), sulfur dioxide (SO_2) and particulate matter. However, research indicates that nitrogen oxide (NOx) emissions increase with the presence of biofuels in diesel [8]. Therefore, different methodologies have been analyzed to eliminate this problem.

One of the high potential methodologies is the addition of water in the combustion chamber to minimize NOx emissions [9][10]. Different methods have been investigated for the addition of water to the engine cylinder, among which are fumigation (in liquid or vapor form) [11][12], water emulsions [13][14], added together with air intake [15] and direct injection of water into the combustion chamber [16]. The studies indicate in their results that the presence of water in the combustion process produces a decrease in NOx emissions, without causing a significant reduction in engine efficiency. The research by Tsukahara et al. [17] shows that water emulsions cause a reduction in specific fuel consumption, which is a consequence of an improvement in the spraying process. Additionally, his study reports a reduction in particulate matter and NOx emissions when using water emulsions. However, the fuel used caused engine noise, low temperatures, and delayed ignition.

Despite the advantages of the presence of water for reducing NOx emissions, studies have also reported a number of problems associated with the inclusion of water in the combustion process. Among these problems is the cold starting of the engine, whereby water emulsions are limited when transition conditions occur in engine operating modes [18]. In the case of fumigations, the amount of water can create a risk of contamination in the fuel. In general, the inclusion of water in the combustion chamber causes a risk of wear and corrosion in the engine due to condensation water and the agents present in water emulsions.

Unlike other methodologies, direct water injection has certain advantages, since it is introduced into the chemical reaction zone of the cylinder chamber [18]. Therefore, the water is far from the cylinder walls. Additionally, the water injection can be controlled, which allows modifying the water intake depending on the engine operating conditions. This mainly facilitates the cold starts of the engine. Compared to other methods, direct water injection does not require a high entry of water into the chamber, thus helping to minimize the risk of contamination in the fuel.

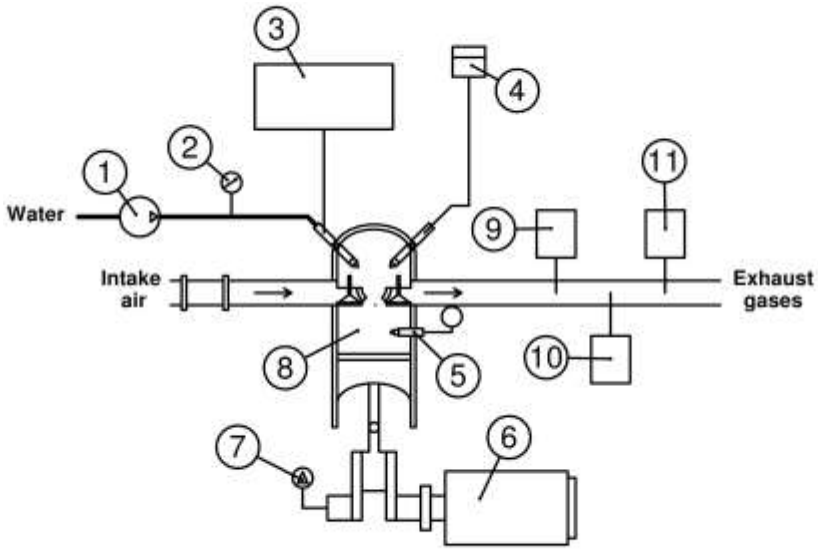
The previous results show that direct water injection is the method that has the least negative impact on the engine. However, few studies in the literature focus on this method to search for the reduction of NOx emissions. Due to the above, this study investigates the effect of direct water injection in a stationary diesel engine used mainly for power generation. For this analysis, the effect of direct water injection on engine performance and emission characteristics is evaluated.

The rest of the paper is organized as follows. Section II shows the configuration of the experimental bench, the emission measurement equipment, the conditions of the experimental tests, and the characteristics of the fuels used in the study. The results and experimental discussions, which involve the analysis of performance parameters and exhaust gas emissions are presented in section III. Finally, section IV shows the conclusions obtained.

II. MATERIAL AND METHODS

2.1 Experimental setup

Figure 1 shows the experimental bench used in the present study. The test engine consists of a stationary, single-cylinder diesel engine, direct injection system, four-stroke, naturally aspirated, and air-cooled. The technical specifications of the engine are described in Table 1.



1. Water pump, 2. Pressure indicator, 3. Electronic control unit, 4. Fuel tank, 5. Piezoelectric pressure transducers, 6. Dynamometer, 7. Encoder, 8. Engine, 9. BrainBee AGS-688, 10. BrainBee OPA-100, 11. PCA® 400.

Figure 1. Test engine bench

Table -1 Engine technical specifications

Engine type	Single-cylinder
Model	SK-MDF300
Cycle	4 strokes
Ratio compression	20:1
Bore	78 mm
Stroke	63 mm
Maximum power	3.43 kW @3600 rpm

The conditions of load and speed of rotation in the engine are established by means of a hydraulic dynamometer. Fuel consumption is measured through a volumetric flowmeter. The BrainBee AGS-688 gas analyzer was used to measure CO_2, HC, and CO emissions. In the case of NOx emissions and smoke opacity, the PCA® 400 gas analyzer and the BrainBee OPA-100 opacimeter were used. The measurement of the pressure in the combustion chamber was carried out by installing piezoelectric pressure transducers.

For water injection, an electronically controlled injection system was used to supply a specified amount of water-based on the position of the crankshaft. In order to overcome the high pressures in the combustion chamber, the water is pressurized by means of a pump to a constant pressure condition at 90 bar. The injection of water is done at different angles of the crankshaft, starting with an angle of 270° CA. In the experimental tests, the effect of different percentages of water is considered, 25% (W25), 50% (W50), and 100% (W100). The injection angle specifications and the amount of water supplied in each percentage are indicated in Table 2.

Table -2 Conditions for water injection

Water injection rate	Injection angle [°]	Injection duration [ms]	Amount of water injected [mg]
25%	288	1.2	15
50%	310	2.7	30
100%	350	5.5	50

2.2 Test conditions and fuel type

The experimental tests on the diesel engine are established at the maximum load condition (9 Nm) and at a rotation speed of 3000, 3250, 3500, 3750, and 4000 rpm. This describes the different operating conditions that the engine may experience. To assess the impact of direct water injection into the engine, different percentages of water injection were used in a PB10 palm oil biodiesel blend. Additionally, commercial diesel was used to obtain a comparative line in the results. Table 3 shows the nomenclature and composition of the fuels used with their respective water injection.

Table -3 Test fuel nomenclature

Nomenclature	Composition
D	100% Diesel
PB10	90% Diesel + 10% Palm oil
PB10W25	90% Diesel + 10% Palm oil + 25% Water injection rate
PB10W50	90% Diesel + 10% Palm oil + 50% Water injection rate
PB10W100	90% Diesel + 10% Palm oil + 100% Water injection rate

For each of the test conditions, three repetitions were carried out, in order to guarantee the reliability of the recorded data and perform the corresponding uncertainty calculations for each measured parameter. Table 4 shows the uncertainty percentages of the measured variables.

Table -4 Uncertainty of the measured variables

Parameters	**Uncertainty [%]**
Time [s]	0.15
Load [Nm]	0.1
Fuel consumption [g/s]	0.025
Pressure [bar]	0.01
CO2 [g/kWh]	0.5
HC [g/kWh]	0.25
CO [g/kWh]	0.2
NOx [g/kWh]	0.3
Smoke opacity [HSU]	0.5

III. RESULTS AND DISCUSSION

3.1 Engine performance

To analyze the engine performance when implementing the water injection system, the calculation of the parameters of brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) is performed. For this, equations (1) and (2) described below are used:

$$BSFC = \frac{\dot{m}_{fuel}}{N \cdot \omega} \quad (1)$$

$$BTE = \frac{N \cdot \omega}{\dot{m}_{fuel} \cdot LHV} \quad (2)$$

where $\dot{m}_{fuel}$, N, ω, and LHV are the mass fuel flow, the engine torque, the rotation speed, and the lower heating (calorific) value of the fuel. Fig.2 shows the results of the BSFC obtained from each fuel for the different conditions of rotation speed.

The results obtained in Fig.2 indicate that palm oil biodiesel (PB10) shows a higher fuel consumption compared to commercial diesel. In general, the use of PB10 causes an increase in the BSFC of 1.56% when compared to diesel. This can be a consequence of the lower LHV in biodiesel. It was observed that the presence of water in the combustion chamber slightly increases fuel consumption. In the case of the PB10W25, PB10W50 and PB10W100 blends, an increase in the BSFC of 0.38%, 0.76%, and 1.10% was obtained compared to PB10. This increase is attributed to the absorption of heat experienced by the water for its evaporation process, which reduces the working capacity of the detonation produced. This is compensated by a greater fuel flow in the combustion chamber.

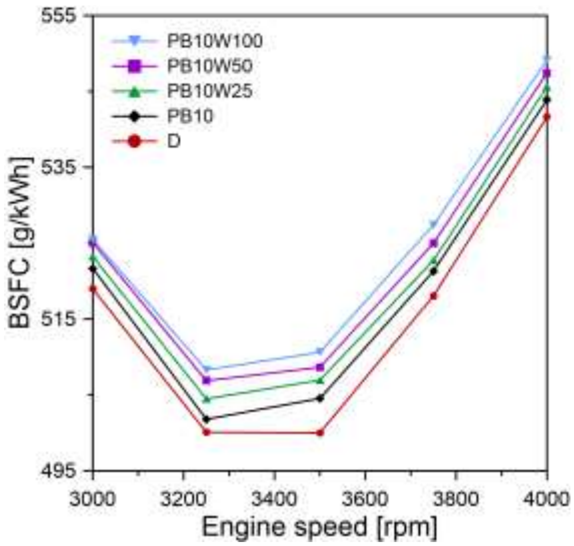


Figure 2. Brake Specific Fuel Consumption

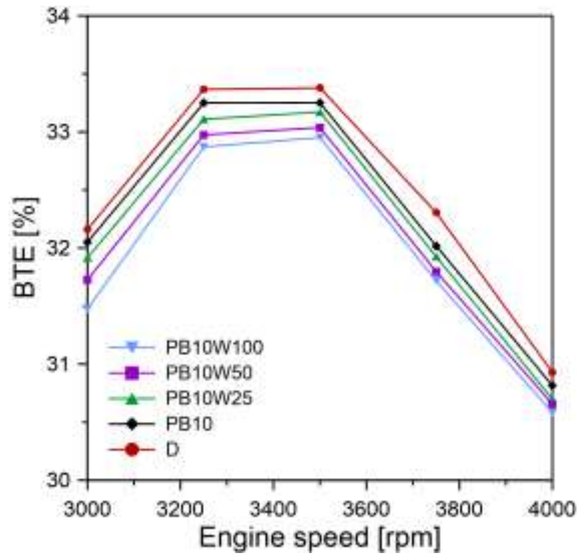


Figure 3. Brake Thermal Efficiency

Figure 3 shows the BTE comparison for each test fuel. The results obtained indicate that commercial diesel presents the highest efficiency, followed by biodiesel PB10 and different water injections. This behavior can be a consequence of the higher fuel consumption of the latter, as discussed in Fig.2. However, the greatest reduction in BTE when using water injection is 1.28%, obtained when using PB10W100 fuel. Therefore, it is concluded that the ingress of 50 mg of water into the engine cylinder does not cause a significant negative effect on efficiency.

3.2 Engine emissions

Figure 4 shows the carbon dioxide (CO_2) emissions for each test condition and the different types of fuel. It is observed that the highest levels of CO_2 emissions are obtained when using commercial diesel. The results indicate that biodiesel PB10 reduces CO_2 emissions by 2.5% compared to diesel. The presence of water in the combustion chamber contributes to the reduction in CO_2 emissions. In the case of the PB10W25, PB10W50 and PB10W100 blends, a decrease of 0.89%, 1.47%, and 2.27% were obtained, compared to PB10. These results are attributed to the contribution of oxygen in the combustion process, provided by the injection water. This contributes to a more complete and cleaner combustion process.

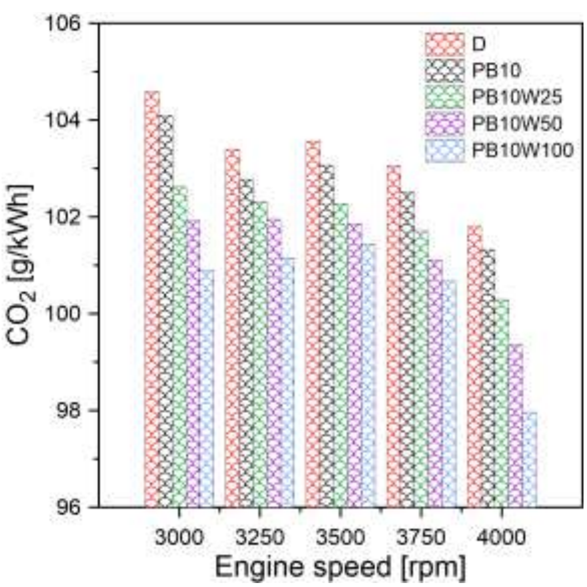


Figure 4. Carbon dioxide emissions

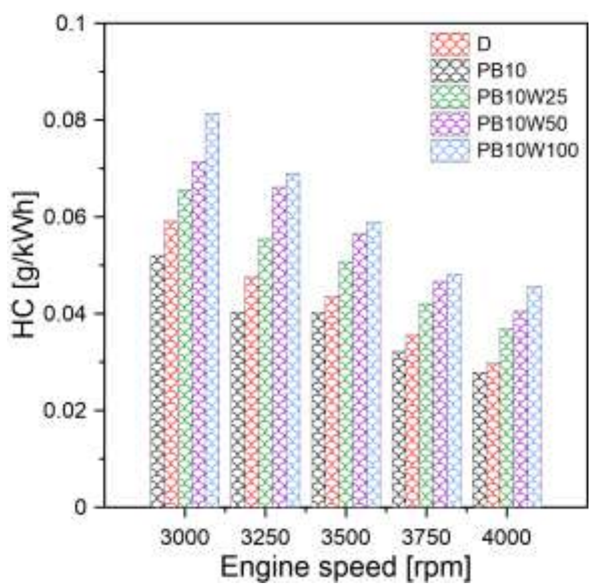


Figure 5. Hydrocarbons emissions

Figure 5 shows the hydrocarbon (HC) emissions from commercial diesel and blends with water injections. The results indicate that PB10 biodiesel reduces HC emissions by 10% when compared to commercial diesel. However, when carrying out the water injection process in biodiesel PB10, an increase in HC emissions of 11%, 26%, and 37% was obtained for the PB10W25, PB10W50 and PB10W100 blends, respectively. The previous behavior is attributed to the reduction of the temperature in the combustion chamber by the presence of water, which produces a cooling in the cylinder liner that hinders the formation of the flame in this region. This reduction of the flame in the vicinity of the cylinder walls facilitates the formation of HC emissions.

Figure 6 shows carbon monoxide (CO) emissions for the experimental conditions. In the case of CO emissions, a behavior similar to that recorded in CO_2 emissions was observed. The use of PB10 biodiesel causes a 3.21% reduction in CO emissions, compared to commercial diesel. Water injection allows a further decrease in CO emissions. In the particular case of the blends of PB10W25, PB10W50, and PB10W100, they caused a reduction of 5.17%, 9.28%, and 15.25%, compared to PB10. This is attributed to the additional oxygen, which improves the combustion characteristics.

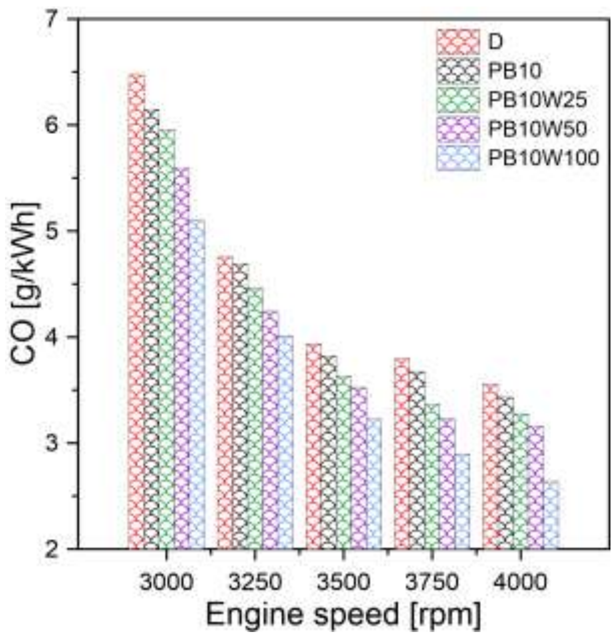


Figure 6. Carbon monoxide emissions

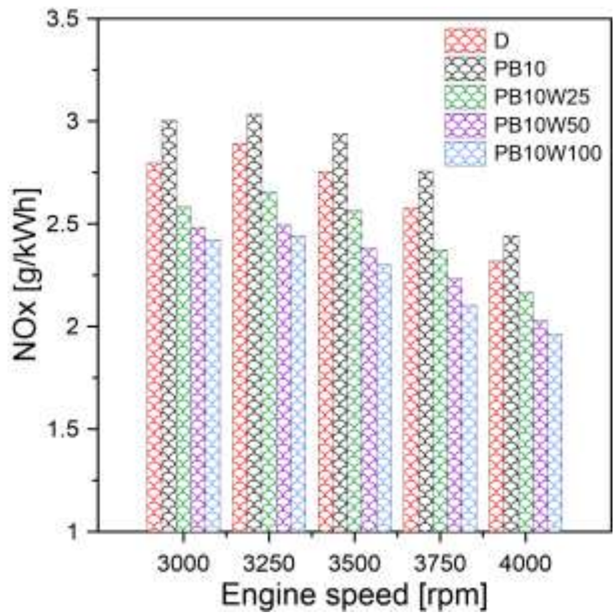


Figure 7. Nitrogen oxides emissions

The formation of nitrogen oxide (NOx) emissions is highly dependent on high temperatures in the combustion chamber. Fig.7 shows the NOx emissions for each fuel.

The results obtained from Fig.7 show that PB10 biodiesel produces 6.25% more NOx emissions, compared to commercial diesel. This behavior can be attributed to the higher combustion temperature present in this type of fuel. However, the injection of water into the chamber allowed a reduction in NOx levels. The results indicate that PB10W25, PB10W50, and PB10W100 blends cause a decrease of 7.45%, 12.88%, and 15.85%, compared to commercial diesel.

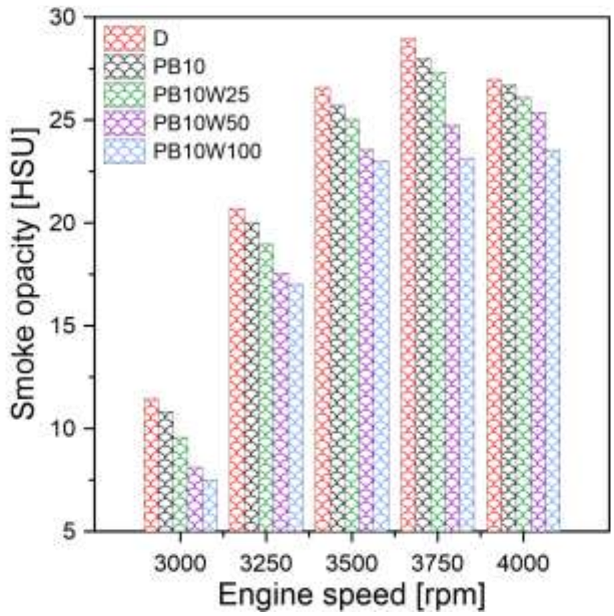


Figure 8. Smoke opacity emissions

Figure 8 shows the opacity of smoke in each fuel. It was observed that the addition of water in the chamber reduces the level of opacity of the exhaust gases compared to commercial diesel and biodiesel PB10. This can be a consequence of the better formation of the blend, caused by the turbulence of the water vapor.

IV.CONCLUSION

In the present study, an investigation of the effect of direct injection of water into a biodiesel blend of palm oil (PB10) is carried out. For the analysis, the performance of the engine is evaluated using the parameters of BSFC and BTE, and CO_2, HC, CO, NOx emissions, and smoke opacity are recorded.

BSFC analysis indicates that PB10 biodiesel causes a 1.56% increase in engine fuel consumption. The direct injection of water causes an increase in this consumption. However, for PB10W25, PB10W50, and PB10W100 blend, the increase remained below 0.8% compared to PB10. Therefore, it is concluded that water injection does not cause a significant increase in fuel consumption. In the case of the engine BTE, the results indicate that the maximum reduction produced is 1.28% compared to commercial diesel, which is similar to the decreases caused by biodiesel blends.

The results obtained demonstrate the use of biodiesel PB10 allows a reduction of 2.5%, 10%, 3.21% and 3.29% in CO_2, HC, CO emissions and smoke opacity, compared to commercial diesel. However, an increase in NOx emissions was reported by 6.25%. The injection of water into biodiesel allowed the reduction in NOx emissions, below PB10 fuel and commercial diesel. On average, the PB10W25, PB10W50, and PB10W100 blends achieved a 12% decrease in NOx emissions when compared to diesel.

Direct water injection also allowed improvements in the combustion characteristics of PB10 biodiesel to achieve a greater reduction in CO_2, CO emissions, and smoke opacity. However, the presence of water in the combustion chamber causes an increase in HC emissions. On average, the blends of PB10W25, PB10W50, and PB10W100 show a 25% increase in HC emissions, compared to diesel.

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