

Experimental Investigation of Performance and Emission Characteristics of IDI Diesel Engine Using Homogenized Water in Bio-Diesel Emulsion

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Abstract. Water in diesel emulsion when used as fuel in diesel engine has shown simultaneous reduction in both nitrogen oxides and particulate matters. However, when water in bio-diesel emulsion is used, the effect of simultaneous reduction of nitrogen oxides and particulate reduction is not achieved. The current study aims at investigating the diesel engine performance and exhaust emissions using water in bio-diesel fuel prepared by a homogenizer that produced micro-water particles in the emulsion. A 1.8L indirect injection diesel engine was operated using bio-diesel fuel which contains 95% diesel and 5% palm oil methyl ester, mixed with 5%, 10% and 20% by volume of water. Engine testing was conducted at full load condition with the engine speeds ranges from 1000 to 4000 rpm. Torque, engine speed and fuel consumption were measured along with emissions of NO_x, CO, CO₂, HC, O₂. The results showed small reduction in brake power, 1.4% and 2.1% for WBDE-5 and WBDE-10 respectively, at maximum torque. While, reduction in exhaust gas temperature, CO₂ and smoke opacity for all the tested emulsions were exhibited. On the other hand, NO_x was found to increase with increase in water contents due to the higher oxygen content in the bio-diesel fuel. WBDE-20 showed the worst efficacy due to having water content of 20% by volume.

1 Introduction

Diesel engines are preferred over the gasoline engines because of their robustness, fuel economy and high power output either in automobiles or in industrial applications. However, diesel fuel is considered as a major air polluting source especially for particulate matter (PM) and Nitrogen Oxides (NO_x) [1]. Water in diesel emulsion has been proven to be a promising alternative fuel to provide clean and renewable fuel source. Out of several methods available for the introduction of water in to the combustion chamber, emulsified diesel fuel has been widely accepted practice for its efficacy in reducing both NO_x and PM, and also it does not require any engine modification. Emulsified diesel fuel is characterised by the micro-water particles encapsulated in the diesel fuel with the presence of surfactant or emulsifier. It has

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been found that when WiDE is used as fuel, the decrease in the temperature of the combustion products causes the reduction in NO_x. Also the presence of water in the fuel seems to reduce the rate of formation of soot particles. The occurrence of micro explosion during combustion is often referred as the reason behind exhaust emission reductions of emulsified fuel. Micro explosion is accomplished due to the difference in the volatility between the water and diesel. Micro-water particles in the emulsion droplets reach the superheated state much earlier than diesel fuel which in turn leads to secondary atomization of the droplets, resulting in better air-fuel mixture and hence better combustion is achieved. WiDE is capable of overcoming the traditional trade off by reducing simultaneously both NO_x and PM [2]. Outcomes of various studies on WiDE as fuel claimed that NO_x has been reduced. When WiDE was tested on multi cylinder industrial diesel engine, a maximum of 37% reduction in NO_x has been reported under steady state operation [3]. Another study with a single cylinder diesel engine claimed that 10% and 25% NO_x reduction has been achieved with 10% and 20% water content respectively [4]. With a lower injection pressure, Maiboom et al. [5] reported NO_x reduction between 30-50% using a 4 cylinder, HSDI diesel engine. Park et. al [6] reported 11.6% reduction in NO_x was achieved when tested on 6- cylinder TCI diesel engine, while 18-20% NO_x reduction was reported by Samec et al. [7] with water content of 10 to 15%. With a 6% water content WiDE, a 24% reduction in NO_x was reported by Gonguntla et al. [8]. Many other experimental studies under different testing conditions also indicated that achievable NO_x reductions [9-10]. As for PM, at low load engine testing conditions a reduction of 94% was reported [5] and approximately 34% PM reduction was achieved [6]. On a separate study by Barnaud et al. [9] and Matheaus et al. [10], a drop of 50% and 16% of PM was observed, respectively.

As a penalty, the engine power and torque were found to decreased slightly when using WiDE as as fuel to achieve the emission reduction [2, 3, 11, 12]. This reduction is attributed to the presence of water which does not possess any calorific value. Abu-Zaid [13] observed an increase in engine torque and power as the water content in WiDE increases. Also an increase in brake thermal efficiency for WiDE with 20% water has been reported from other studies [2, 3, 13, 14]. On the other hand, most of the researchers reported that specific diesel for the same power output [2]. An increase of 22- 26% in sfc was mentioned by Maiboom et al. [5], while Nadeem et al. [11] reported a 15% increase of sfc, while 26% increase in sfc has been reported by [3]. Despite of different engine setups and testing methodologies, there was a common agreement that simultaneous reduction of NO_x and PM is achievable with WiDE as fuel.

In all the previous studies on WiDE in diesel engine combustion, the preparation of emulsions was either by using neat diesel, low grade diesel or Ultra Low Sulfur Diesel (ULSD). Very little information is available on the use of bio-diesel as the base fuel for the emulsion. In the present study the emulsions were prepared using bio- diesel fuel which contains 95% diesel and 5% palm oil methyl ester. The experimental work aims to ascertain the effect of homogenized water in bio-diesel emulsion (subsequently, abbreviated as WBDE) on engine performance and exhaust emissions with three different percentage of water content, i.e. 5, 10 and 20%. The testing was carried out at engine full load condition for seven different engine speeds. The exhaust gas emissions such as NO_x, CO, CO₂, HC, O₂ and smoke opacity were measured and analyzed in addition to the engine torque, brake power and bsfc.

2 Materials and Methods

Three blends of water in bio-diesel emulsions (WBDE) were prepared with 2% blend of commercially available surfactants. B5 diesel which contains 95% diesel and 5% palm oil

methyl ester was used to produce the emulsion. In order to achieve emulsion droplet size at micro size level and to ensure uniform distribution, the emulsion was made to pass through a homogenizer having a stator and a rotor spaced at 50 microns gap with a rotating speed of 3000 rpm.

The process was repeated to ensure emulsion homogeneity. The WBDE was visualized at 400X magnification using digital microscope and the micro- water particles in the emulsion droplets were found to be uniformly distributed and in order of size less than 2.0 μm. The WBDE is considered stable when there was no observable separation for a period of 336 hours. Physical properties of B5 diesel and the WBDE are tabulated in Table 1. Anton Paar Micro viscometer Lovis 2000ME and density meter DMA 4500M were used to measure the viscosity and density of WBDE and B5 diesel. Calorific values of the fuels were obtained using Leco AC-350 bomb calorimeter which was calibrated using standard benzoic acid as standard. Chemical characteristics were analysed using CHNS analyser.

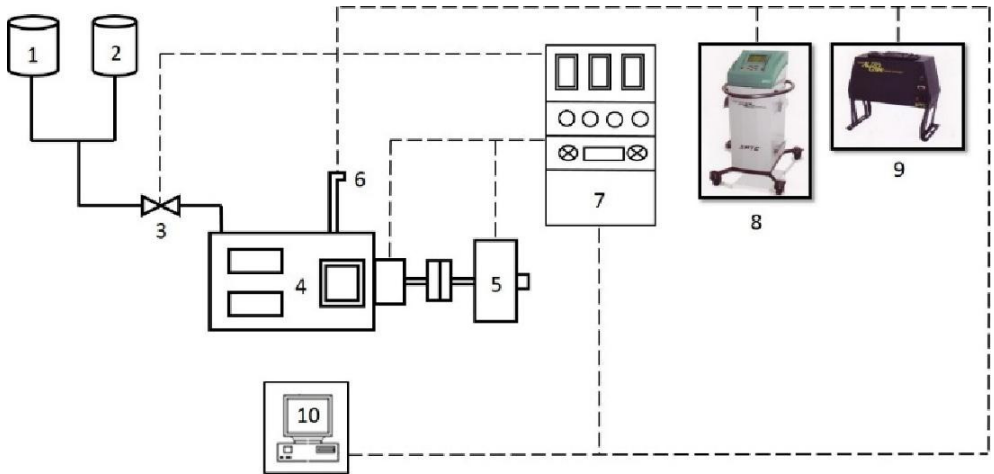
The schematic illustration of the experimental setup is shown in Figure 1. The experiments were performed on a FORD XLD 418 IDI engine and some of the important specifications of the engine is given in Table 2. Separate tanks were used to store B5 diesel and WBDE. There were no modifications made on either engine or injection pump setting. The engine was coupled with an eddy current dynamometer rated at 150 kW between 2800 and 8000 rpm and a maximum torque rating of 500 Nm. Autotest IV engine control unit was used to control and for data management. In addition, Autochek exhaust gas analyzer capable of measuring NOx, CO₂, CO, HC and O₂ was used to measure the combustion exhaust gases. A smoke opacity meter combined with the analyzer with an accuracy scale range of +/- 2% was employed to measure the exhaust smoke.

Table 1. Physical properties of WBDE samples

Sample	Density @20°C {kg/m ³ }	Viscosity @40°C {mm ² /s}	Calorific Value {J/g}	Carbon % {w/w}	Hydrogen % {w/w}	Nitrogen % {w/w}	Sulphur % {w/w}
B5 Diesel	842.90	3.409	42600	81.38	11.86	0.1013	0.126
WBDE-5	849.76	5.792	37460	80.32	16.42	0.1123	0.821
WBDE-10	854.44	6.146	36942	78.65	12.40	0.1930	0.679
WBDE-20	870.17	7.969	32481	68.94	9.73	0.2210	0.479

Table 2. Engine specifications

Engine Type: Diesel,4-cylinder, Inline OHC, Indirect Injection	
Bore	82.5 mm
Stroke	82 mm
Cubic Capacity	1753 cc
Compression Ratio	21.5:1
Power output	44 kW at 4800 rpm
Design Injection Pressure	118 bar
Maximum Engine "No Load" Speed	5350 ± 50 rpm
Idle Speed	850 ± 50 rpm



1. Diesel tank 2. Emulsion tank 3. Fuel flow meter 4. Engine 5. Eddy current Dynamometer 6. Exhaust pipe 7. Engine Control Unit 8. Gas Analyser 9. Smoke Opacity Meter 10. Computer
Fig. 1. Schematic drawing of the experimental setup

2.1 Experimental Procedure

Experiments were conducted at full load condition at seven different speeds starting from 1000 rpm to 4000 rpm at an interval of 500 rpm. Initial warm up of the engine was done using diesel and later switched to WBDE. Each speed was maintained until a stable condition is achieved before the required data was recorded. Exhaust emissions and smoke opacity were measured simultaneously.

3 Results and Discussion

The following sections discuss the results on the engine performance and exhaust gas emission measurements.

3.1 Engine Torque

The influence of WBDE on the engine torque output is plotted against the engine speed as shown in Figure 2. At initial speeds there were no significant difference noticed between B5 diesel and WBDE.

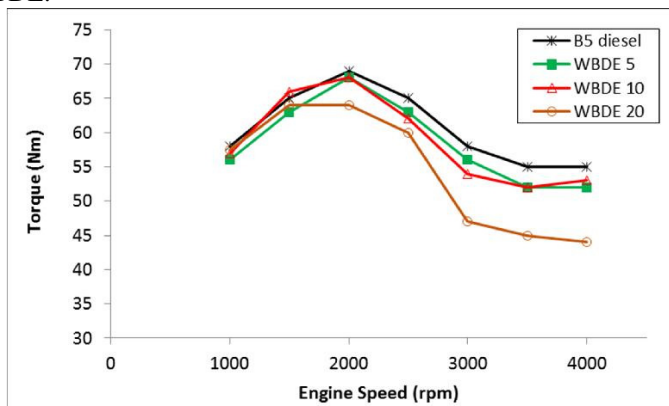


Fig. 2. Torque versus engine speed for B5 diesel and WBDE.

All the tested fuels achieved the maximum torque at 2000 rpm, with WBDE-5 and WBDE-10 exhibiting similar torque with B5. Emulsion with 5% water attained closest torque to that of diesel has been reported [11, 14]. Only WBDE-20 showed lower torque at all engine speeds. The difference in the torque developed by B5 diesel and the emulsions is attributed to the fact that increase in water contents results in lower calorific value. WBDE-20 exhibited the lowest torque after 2000 rpm with a maximum reduction of 20% compared to B5 diesel.

3.2 Engine Brake Power

The brake powers produced by all the emulsions in Figure 3 were less than B5 diesel at all engine speeds. However, the differences in brake power were small, especially at engine speed below 2000 rpm. The power produced by the emulsions compared to diesel decrease with increasing water content in the WBDE.

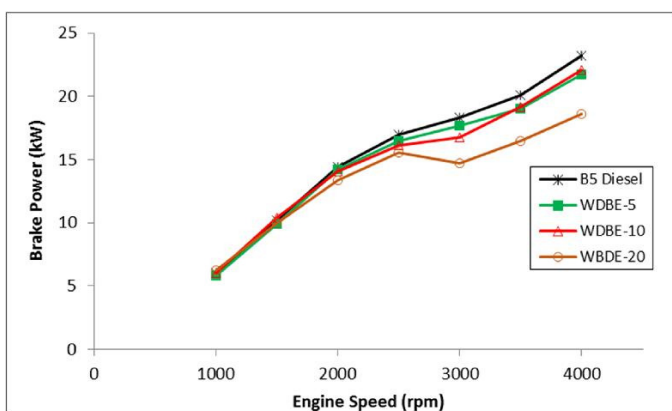


Fig. 3. Brake power output versus engine speed for B5 diesel and WBDE

The maximum power reduction with WBDE-5 was 6.4% which is in agreement with results obtained by Alahmer et al. [14], when emulsion with 5% water was tested on a 4-cylinder Di engine. For WBDE-10 the power reduction was found to be 8% which is similar to the findings of Barnes et al. [15] that for 10% water content by volume resulted in a power loss of 7-8%. In the case of WBDE-20, a maximum of 19.8% loss in power was observed. Again, WBDE-20 showed the lowest brake power at all engine speeds, which indicates the limit to the amount of water that can be effectively added to the diesel fuel.

3.3 Brake Specific Fuel Consumption

The relationship between brake specific fuel consumption (bsfc) against engine speed for the B5 diesel and WBDE is plotted in Figure 4.

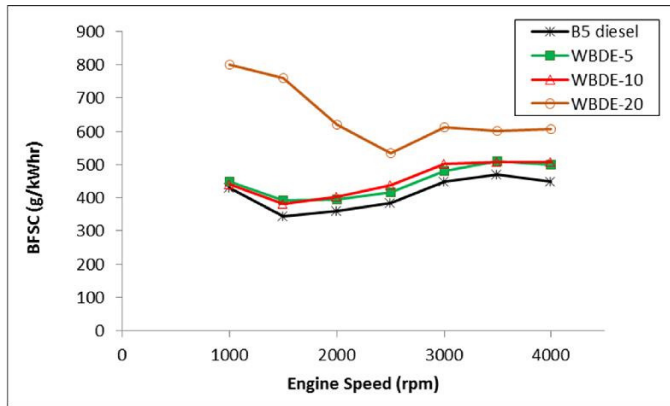


Fig. 4. bsfc versus engine speed for B5 diesel and WBDE

The bsfc initially decreases then increase as engine speed is increased. This is due to the fact that at lower speed, the engine consumes more fuel for the same output, and increased heat transfer to the cylinder wall and frictional losses. The figure shows the trend for fuel consumption which is similar to all emulsions except for WBDE-20. Specific fuel consumption for the WBDE is higher because of its lower calorific value and higher density compared to B5 diesel. Hence more fuel is required to maintain the engine speed at the given load. Similar trend of increase in bsfc has been reported by other researchers [2, 14, 16]. It is also observed that the bsfc for WBDE-5 and WBDE-10 are close to each other since the difference among these emulsions were small. WBDE-20 recorded the highest fuel consumption because of its lowest calorific value among the other emulsions.

3.4 Exhaust Gas Temperature

The relationship between the exhaust gas temperature and the engine speed at full load condition is plotted in Figure 5. The exhaust temperatures for all WBDE were found to be less than B5 diesel, with WBDE-5 exhibiting close values to B5 diesel. Increase in water content in WBDE proportionately reduces the exhaust temperature. Similar trends were reported by Abu-Zaid [13] when 5- 20% water content in the emulsion was tested on a single cylinder diesel engine. B5 diesel produced the highest exhaust temperature at all speeds. At the maximum speed and full load condition the exhaust temperature reduction for WBDE-5, WBDE-10 and WBDE-20 were 3.36%, 9.39% and 21.63% respectively. It is also observed that the difference in CO₂ emission among the WBDE and B5 diesel was very small in the range of 0.46% to 0.6% only.

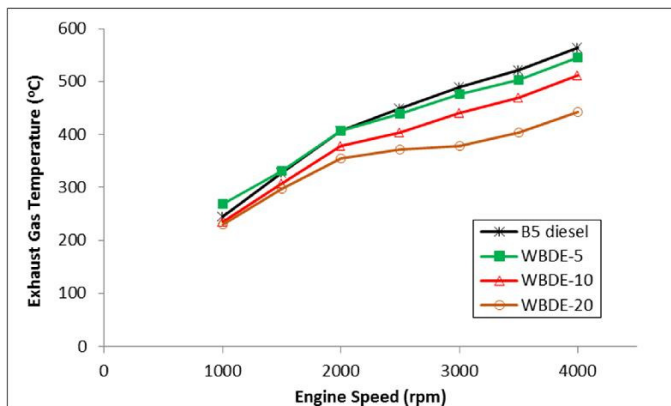


Fig. 5. Exhaust gas temperature versus speed for diesel and WBDE

3.5 Carbon Monoxide (CO) Emission

Figure 6 depicts CO emissions of B5 diesel and WBDE at full load at various engine speeds. The emissions of CO for both WBDE-5 and WBDE-10 showed higher than B5 diesel at the initial engine speed, while WBDE-20 was lower than the diesel at all speeds. The probable reason for increasing CO trend is due to the lower combustion temperature at lower speeds, similar to the reports by [12, 17], since the oxidation of CO into CO₂ is not possible when the temperature is lower than 1400 K. As the engine speed increases and at higher combustion temperatures, CO tends to decrease. This finding indicates that WBDE might have better air-fuel mixture, as was also observed by [18].

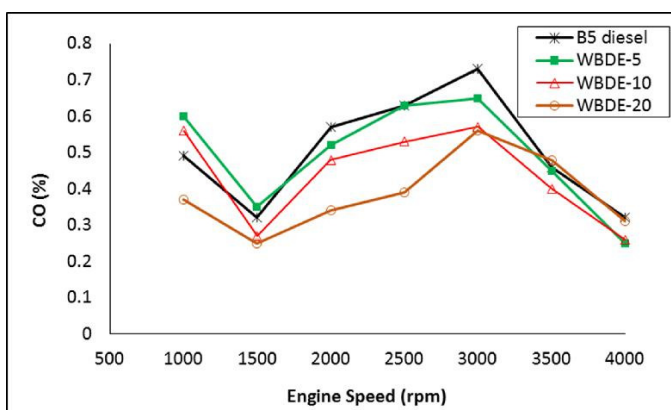


Fig. 6. CO emissions for B5 diesel and WBDE

3.6 Carbon Dioxide (CO₂) Emission

The CO₂ for B5 diesel and WBDE is plotted against the engine speed as shown in Figure 7. The CO₂ emissions increases with engine speed and for all WBDE fuels, CO₂ emissions were found to be less than B5 diesel. Both WBDE-5 and WBDE-10 followed a similar trend and the differences were insignificant. WBDE-20 produced lowest CO₂ between the speeds range of 1500 rpm to 4000 rpm.

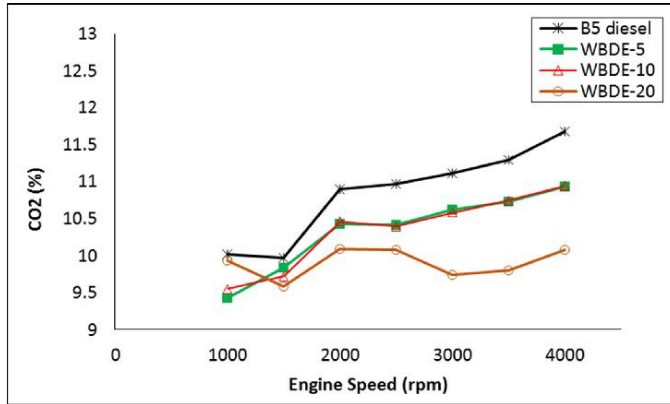


Fig. 7. CO₂ emissions for B5 diesel and WBDE

3.7 Nitrogen Oxide (NO_x) Emission

The emissions of NO_x are plotted against engine speed for both B5 diesel and WBDE as shown in Figure 8.

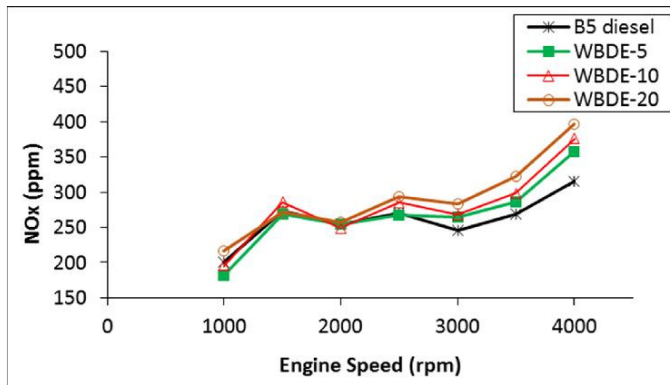


Fig. 8. NO_x emissions for B5 diesel and WBDE

For engine speeds up to to 2000 rpm there were no prominent difference between B5 diesel and WBDE, but as the speed increases, NO_x showed an increasing trend. In this study, NO_x was found to be increasing with the increase in the water content, although the exhaust temperature was reduced for all WBDE. This finding indicates that the additional oxygen content in the bio- diesel fuel might be the contributing factor in the NO_x formation, which was also reported by [19]. At the maximum speed of 4000 rpm the NO_x for WBDE-20, WBDE-10 and WBDE-5 were 20.65%, 16.22% and 12.01% higher the B5 diesel.

3.8 Smoke Opacity of WBDE and B5 Diesel

The smoke opacity of WBDE and B5 diesel are plotted in Figure 9. Smoke opacity for all the fuels decreased with engine speeds. The combustion of B5 diesel produced the highest opacity, whereas the WBDE showed decreasing trends, with more significant reduction for WBDE with higher water contents. The presence of water increases the ignition delay which resulted in better air fuel mixing which lead to improved combustion. In addition, more smoke reduction with WBDE is due to high oxygen content which increases the flame speed

during the air fuel interactions [20]. The finding proves that WBDE can significantly reduce the emissions of smoke from a diesel engine.

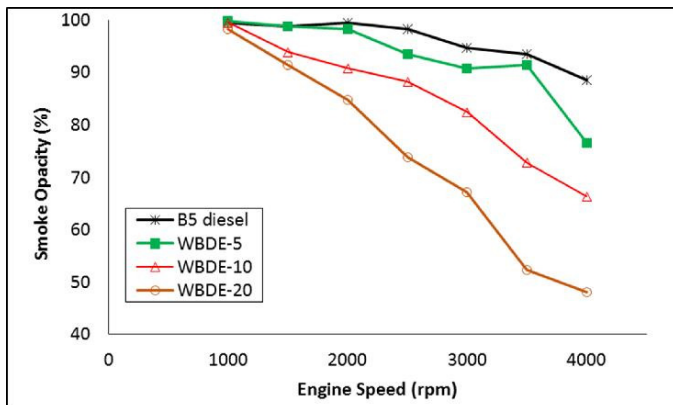


Fig. 9. Smoke opacity for B5 diesel and WBDE

4 Conclusions

Homogenized water in diesel emulsion (WiDE) with 5%, 10% and 20% of water content was tested on an IDI diesel engine without any modification. The current study found that the presence of water in WBDE leads to small loss in torque and brake power, with minor increase in brake specific fuel consumption. The advantage of using WBDE as alternative fuel is exemplified by the reduction of exhaust gas temperature and significant reduction in smoke emissions. Contradictorily, increase in NO_x was observed with increase in water contents of WBDE due to the use of bio-diesel fuel.

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