ATTAINING SIMULTANEOUS REDUCTION IN NOX AND SMOKE BY USING WATER-IN-BIODIESEL EMULSION FUELS FOR DIESEL ENGINE

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ABSTRACT

This paper presents the study of water-in-biodiesel emulsions (WiBE) stabilized by surfactants with different hydrophilic-lipophilic balance (HLB) on a single-cylinder diesel engine. The engine performance and exhaust emissions were compared against the base fuel biodiesel (B5 diesel) which contained 5% palm oil methyl ester (POME) in the diesel fuel, at a constant engine speed of 2000 rpm with different engine loads. 36 emulsion blends of B5 diesel mixed with 9%, 12% and 15% volume of water, HLB values of 6, 7, 8 and 9, and surfactant dosage of 5%, 10% or 15% by percentage volume of water added. The results exhibited 11.7% lower engine power with WiBE as compared to B5 diesel. It was also observed that WiBE produced higher in-cylinder pressure and heat release rate. WiBE with higher water content at high load condition produced up to 15.2% higher peak pressure with a significant reduction in both NOx and smoke opacity, while a moderate decrease in the exhaust temperature was recorded for WiBE. The research work proved that WiBE with 15% water content with optimum HLB value is capable of reducing up to 79% NOx and 23% smoke opacity simultaneously, due to the heat sink effect during combustion.

***Keywords:** emulsified fuels, surfactant, microexplosion, exhaust emission, palm oil, heat sink effect*

INTRODUCTION

Stricter level of regulatory standards on exhaust emissions of diesel engines on passenger cars and light commercial vehicles following the transition from Euro 5 (2011) to Euro 6 (2015) demands significant reduction of NOx, CO, HC and PM emission levels [1]. In the near future, Euro 7 is planned to be introduced with even tighter limits. Significant targets include further reduction of NOx emissions from 0.40 g/kWh in Euro 6 (2015) to 0.20 g/kWh in Euro 7 (2020) whilst PM emissions remain unchanged at 0.01 g/kWh with a reduction of the size of particles counted from 23 nm to 10 nm [2]. In order to meet the strict emission standards, various efforts have been made both on engine development and also on developing new alternative fuels.

Researches showed that water added to diesel fuel which is used as an alternative fuel in diesel engines could lead to measurable reductions in the NOx emissions [3, 4, 5]. This happens during combustion when the water particles in the emulsion vaporize and adsorb the heat causing a drop in the flame temperature [3]. Studies by Suresh et al. [6] proved the effectiveness of using water-in-diesel emulsions in reducing various exhaust emissions. However, water-in-diesel emulsion triggers a higher concern due to the high-pressure nature in the working principle of a diesel engine [5]. There are many advantages in using emulsion fuels, such as achieving more complete combustion, leading to better fuel economy and cleaner-burning fuels with lower emissions levels. Tran and Ghojel [7] reported that the water in the emulsified fuel caused the drop in combustion temperature which also decreased the rate of soot formation and enhanced their burnout. Matheaus et al. [8], studied the effects of commercial emulsion with 20% water by mass, called PuriNOx, on the emissions of heavy-duty diesel engine and reported a reduction in NOx by 19%, while PM (particulate matter) by 16%.

Their findings also indicated an increase of 28% in HC and 42% in CO emissions. In the same research group, Musculus et al. [9] observed that the ignition delay in water diesel emulsions with 20% water content was 30-60% longer that of diesel which would lead to a leaner mixture during the initial premixed combustion, resulting in the decrease in soot formation. Another study by Barnaud et al. [10], with a different commercial emulsion, is known as AQUAZOLE on a heavy-duty resulted in the reduction of NOx, smoke density and PM emissions up to 30%, 80% and 50% respectively.

Studies showed that optimised water-in-diesel emulsions improved engine efficiency and reduce exhaust emissions, particularly NOx and PM [6, 11] while maintaining similar or better performance and operation limits [12]. However, results from studies by Ithnin et al. [11] and Lif and Holmberg [5] found that UHC and CO exhaust emissions increased when using water-in-diesel emulsions. The researchers reasoned these due to the variation on the strength of the micro-explosion process. Although the use of water-in-diesel emulsion has resulted in considerable reduction on the NOx and PM emissions, contrarily many studies have reported that the brake power and the torque were found to be reduced [13, 14]. Reports on the specific fuel consumption (SFC) while using the emulsions were contradicting. Nadeem et al. [15] reported that SFC decreases with an increase in water content in the emulsions. A reduction in SFC of 0.7% was reported by Matheaus et al. [8] and 1-4% by Barnaud et al. [10]. On the other hand, many of the other studies found that using emulsion led to an increase in SFC. Ghojel et al. [4] reported an increase of 22-26% in SFC and an increase of 26% was observed by Kannan and Udayakumar [3]. Similarly, other researchers also reported increase in SFC [13, 16, 17, 18, 19, 20].

As a part of renewable fuel strategy, biodiesel is considered as an important alternative fuel when used as a blend with petroleum-derived diesel or when used in neat form (100% esters) to reduce several harmful exhaust emissions such as CO, HC and PM, although, an increase in NOx has been recorded [21]. Haas et al. [22] stated that there was a decrease in PM but increase in NOx with an increase in the content of biodiesel when involving the blends of diesel and biodiesel. However, when the biodiesel is used in the form of an emulsion, lesser NOx emissions was observed when compared to diesel and biodiesel [23, 24, 25]. Emulsified *jatropha* methyl ester biodiesel with 5% water was tested by Basha et al. [26] and found that NOx and smoke opacity were reduced. While, in another study by Raheman [27] with *jatropha* biodiesel emulsions containing 10%-15% water, resulting in a NOx reduction up to 28%.

The present work on emulsified fuel defers from previous studies due to the use of palm oil methyl ester (POME) which was prepared by mixing a commercially available B5 diesel (95% diesel with 5% POME), as opposed to using neat diesel, low-grade diesel or Ultra-low sulphur diesel (ULSD). The present experimental work aims to ascertain the effects of water-in-biodiesel emulsion (WiBE) on engine performance, combustion and exhaust emissions with three different percentages of water content of 9, 12 and 15% stabilized with either 10% surfactant dosage having an HLB value of 6 or with 15% surfactant dosage having an HLB value of 9. The engine test was carried at an engine speed of 2000 rpm for different engine loads. The exhaust gas emissions such as NOx, CO, CO_2, smoke opacity and exhaust gas temperature were measured and analysed in addition to the engine power and specific fuel consumption.

MATERIALS AND METHODS

The following sections discuss the materials used and methodology employed for the current study.

Table 1 Emulsion blends for engine test

Sample ID	Water Content (%)	Water (ml)	Biodiesel (ml)	Surfactant Required (ml)		HLB value	Surfactant Dosage (%)
				Tween-85	Span-80		
WiBE-13	9%	450	4505.0	11.50	33.5	6	10
WiBE-14	12%	600	4340.0	15.25	44.75		
WiBE-15	15%	750	4175.0	19.00	56.00		
WiBE-34	9%	450	4482.5	47.25	20.25	9	15
WiBE-35	12%	600	4310.0	63.25	26.75		
WiBE-36	15%	750	4137.5	79.00	33.50		

Preparation of water-in-biodiesel emulsions

The base fuel used in this work is a commercially available B5 biodiesel which contains 95% diesel and 5% palm oil methyl ester (POME). Distilled water is added to the B5 by the required water volume of the total emulsion volume. Hence, the amount of B5 in the emulsion is reduced accordingly to ensure the percentage of water and the total volume of the emulsion are kept constant. The volume of B5 is further displaced by the addition of the surfactant at the respective amount of 5, 10 or 15% of the added water volume. The amount of diesel required for a 100 ml emulsion is calculated by:

$$B5\ (ml) = 100\ ml - \%\ \text{of}\ H_2O - (\%\ \text{of surfactant mixture})\ \%\ \text{of}\ H_2O \qquad (1)$$

Two commercial surfactants, Span 80 with an HLB value of 4.3 of Merck KGaA, Germany and Tween 85 with an HLB value of 11 of Acros Organics Belgium respectively were used as received in the present study. These surfactants are the lipophilic and hydrophilic type of surfactants which increases the diesel-water affinity and help to reduce the interfacial tension and hence increases the emulsion stability. The two surfactants were first mixed prior to adding to B5 at different volume in order to achieve the required HLB values. The following equation is used to ascertain the quantity of both surfactants:

$$\%\ A = 100 * (x - HLB_B)/(HLB_A - HLB_B) \qquad (2)$$

Where, $\%\ A$ is the required quantity of surfactant A, HLB_A is the HLB value of surfactant A, HLB_B is the HLB of surfactant B, and x is the targeted HLB value. The amount of surfactant B is found by:

$$\%\ B = 100 - \%\ A \qquad (3)$$

A total of 36 samples of water-in-biodiesel emulsions (WiBE) having HLB values of 6, 7, 8, and 9 were blended with three different surfactant dosages of 5%, 10% and 15%. The water content in the emulsions was at the amount of 9%, 12% and 15% of the total emulsion volume. For each emulsion types, a 200 ml sample was prepared and kept motionless in graduated clear glass bottles to evaluate the stability of the emulsion. Clear glass allows immediate observation and periodic physical measurements if required. All of the blended WiBE were visually observed for stability over a period of one month. For the engine test, only 6 emulsions were selected due to the emulsion stability, which is discussed in detail in Section 3. The preparation matrix for the selected six emulsions for the engine test is shown in Table 1.

Experimental setup and measurements

The engine test was carried out on a single-cylinder four DI diesel engine testbed at loads from 0 to 100 % with increments of 10% at a constant engine speed of 2000 rpm. The experimental test matrix is shown in Table 2. The engine test for all the emulsions was compared against the base fuel B5 diesel. Two separate containers were used for B5 diesel and the emulsions. The engine was operated using first B5 diesel at the beginning during the warming up of the engine. Then the fuel was switched to the emulsion. At the end of each test, diesel fuel was used again to run the engine to flush out the emulsified fuel from the fuel line and injection system. The engine testbed is equipped with instrumentation for airflow, fuel mass, in-cylinder pressure transducer and crank angle encoder as shown in Figure 1.

Brake power, airflow rate, fuel mass flow rate and thermal efficiency were automatically displayed on the PC, based on the data recorded by the data acquisition system developed using NI controls and Lab VIEW programming. The exhaust emissions and smoke opacity were measured using emissions analyzer and smoke meter respectively. The engine was allowed to run for at least for ten minutes to stabilize before recording all the readings. The engine speed, torque exhaust temperature, air inlet temperature and engine body temperatures are displayed real-time on the screen. The fuel consumption was automatically calculated by sensing the change in weight of the fuel tank weighing scale for 60 sec. using the software program and displayed on the screen.

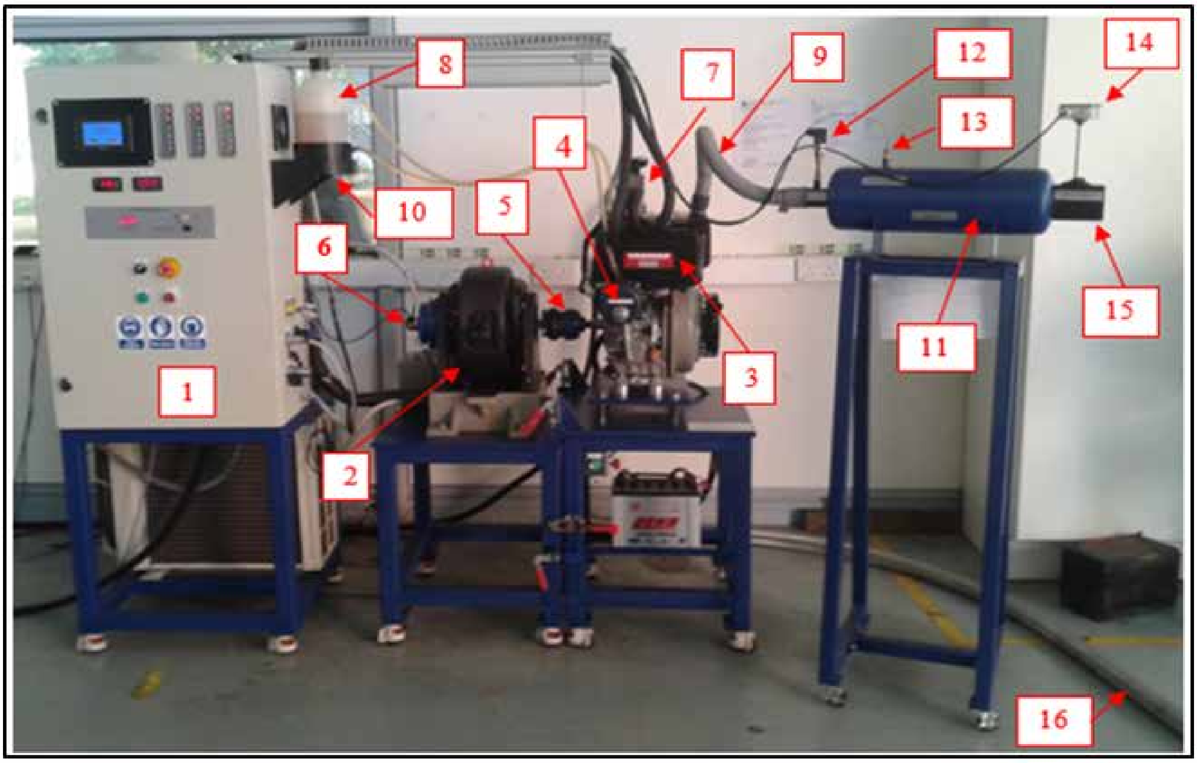

Figure 1 Picture of the engine test rig in the lab

1. Instrument control panel. 2. Eddy current dynamometer. 3. Diesel engine. 4. Motorized actuator for throttle control.
5. Flexible coupling. 6. Crank angle encoder with. 7. Water-cooled in-cylinder pressure transducer. 8. Fuel tank.
9. Air intake connecting hose. 10. Fuel weighing balance. 11. Air plenum. 12. Air pressure sensor. 13. Temperature sensor.
14. Hotwire airflow meter. 15. Air intake pipe. 16. Exhaust pipe.

The other engine performance parameters are calculated automatically based on the formula programmed into the software once the fuel mass flow rate measurement was obtained. The crank angle encoder connected to the dynamometer shaft is capable of producing 360 pulses per revolution hence a total of 720 data is collected for a complete cycle of the engine. The net heat release was calculated separately by post-processing the obtained pressure, cylinder volume and the crank angle data based on the formula obtained from the first law analysis,

$$\frac{dQ_n}{d_\theta} = \left(\frac{\gamma}{\gamma-1} \times P \times \frac{dV}{d\theta}\right) + \left(\frac{1}{\gamma-1} \times V \times \frac{dP}{d\theta}\right) \quad (4)$$

where γ is the specific heat ratio, P is the in-cylinder pressure, V is the cylinder volume and θ is the crank angle.

result. The dynamometer load cell was calibrated before starting the experiments using known weights. Thermocouples used for temperature measurement were of K type with a measuring accuracy of ± 1°C with an uncertainty of ± 1%. Engine speed at any applied load is ± 30 rpm. The pressure sensor used for measuring in-cylinder pressure has a measuring range of 0-100 bar with an integrated precision of 0.5% FS. The crank angle encoder records the crank angle position at a resolution 360 pulses/revolution with a response time of 1 µs.

Calorific value and CHNS value of emulsions

The calorific values and the elemental analysis for carbon, hydrogen, nitrogen and sulfur (CHNS) for the selected emulsions were determined and tabulated in Table 3. The calorific values indicate that the emulsions have lower heating values compared with the base fuel B5 diesel. It is due to the fact that the water does not possess any heating value. Also, it should be noted that the calorific value of the emulsions reduced with increase in the water content. It can be observed that the carbon content in the emulsions reduced with an increase in the water content. There were no significant changes in hydrogen observed among all the emulsions. On the other hand, elements such as nitrogen and sulfur contents were almost the same for all the emulsions.

Table 2 Yanmar L100V engine specifications

Engine Model	L100V
Type	Vertical cylinder, 4-cycle, air-cooled diesel engine
Bore x Stroke	86 x 75 mm
Displacement	0.435 liters
Compression ratio	20.0 ± 0.3
High idling (rpm)	3800 ± 30
Low idling (rpm)	1250 ± 30
Fuel injection timing	13° BTDC
Valve opening pressure	19.6 Mpa
Fuel injection pump	Bosch type with an upper lead plunger

Engine exhaust emissions and smoke opacity measurements

For each test, the emission gases were measured along with the smoke opacity. Kane Autoplus 5-2 exhaust gas analyzer was used to measure nitrogen oxides (NO_X). carbon monoxide (CO), carbon dioxide (CO_2) and oxygen (O_2). The exhaust smoke from the engine is measured by the smoke opacity meter (AUTOCHEK 4/5) gas analyzer unit. The opacity is measured in percentage and each measurement is measured three times and the average opacity is displayed as the final

Table 3 Calorific and CHNS values of base fuel and selected emulsions

Sample ID	**Calorific value (J/kg)**	**Carbon (%)**	**Hydrogen (%)**	**Nitrogen (%)**	**Sulfur (%)**
B5 diesel	45135	83.23	11.020	0.018	0.000
WiBE-13	38989	76.30	12.493	1.000	0.064
WiBE-14	37904	73.39	12.631	1.100	0.062
WiBE-15	36432	69.14	12.265	0.910	0.718
WiBE-34	39422	75.78	12.654	1.050	0.105
WiBE-35	38061	73.45	12.557	1.050	0.141
WiBE-36	37151	68.72	12.340	0.800	0.008

RESULTS AND DISCUSSION

The following sections present the results obtained followed by a detailed discussion of the findings.

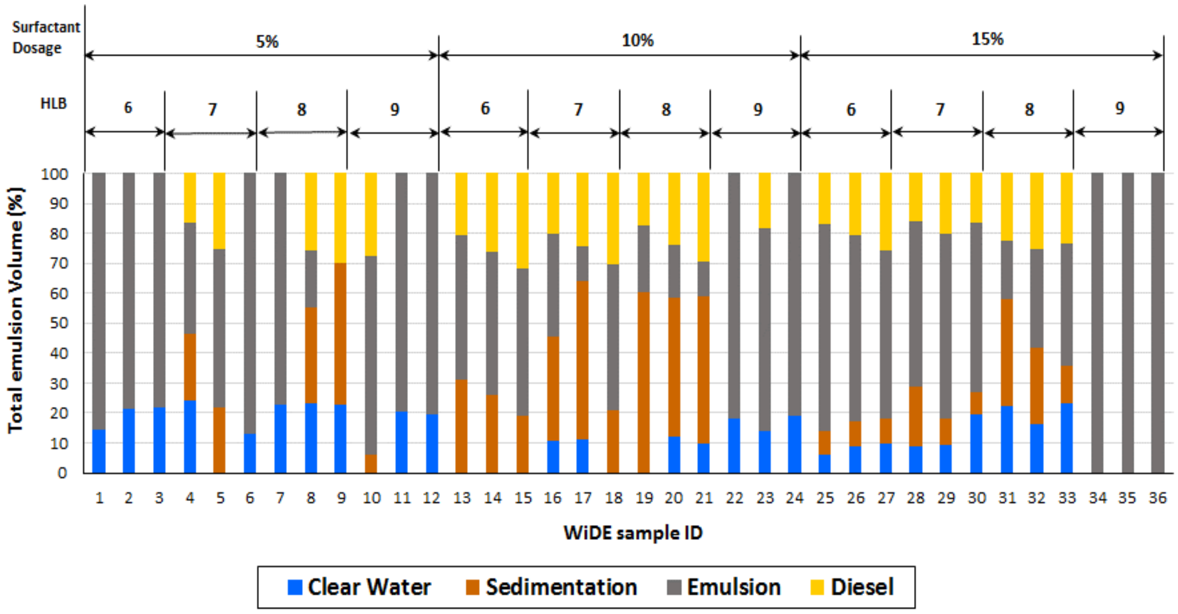

Figure 2 Stability observation of 36 emulsions

Stability of WiBE

The stability observation of the emulsions after 30 days are shown in Figure 2. The morphology of the emulsions starts to change immediately upon blending due to several time-dependent processes. From Figure 2, it was found that only six emulsions were stable without any clear water or layer separations during the observation period. Emulsions stabilized with 10% surfactant dosage, and HLB value of 6 (WiBE-13, 14 and 15) was found to be stable for 16 days, while the emulsions stabilized with 15% surfactant dosage with an HLB value of 9 (WiBE-34, 35 and 36) were stable for more than 30 days. These six emulsions were selected for engine testing since these samples represent two sets of emulsions stabilized each with the same HLB values and surfactant dosages but with different percentage of water content i.e., 9%, 12% and 15%. Several other emulsions such as WiBE-5, 10, 18 and 19 were also found to be stable with sedimentation. It is clear from Figure 2.

HLB value plays an important role in deciding the emulsion stability than the surfactant dosage because for the same surfactant dosages emulsion stability was determined by different HLB values. On the other hand, HLB values become less dominant to provide stable emulsions if the surfactant dosage is very low. All prepared emulsions with 5% surfactant dosage were found to be unstable, except for WiBE-10. It is due to insufficient dosage (5%) of the surfactant which is not enough to cover the overall surface of the dispersed phase (water) to form a stable emulsion. In the case of emulsions stabilized with 15% surfactant dosage (WiBE-25 to 36), all emulsions having HLB values of 6, 7 and 8 were unstable.

Effect of WiBE on engine power

The engine brake power at different load conditions for base fuel B5 and WiBE are shown in Figure 3. It is observed that the engine power increased with increase in applied load, while all WiBE is found to produced lower engine brake power compared to B5 diesel. Base fuel B5 diesel produced the highest power of 3.4 kW at maximum load condition. Whereas, the closest power produced by the emulsions was 3.2 kW (6% lesser than B5 diesel) for WiBE-14 and WiBE-36. While WiBE-34 and 35 attained 11.7% lesser power at maximum engine load conditions. There were no statistically significant changes noticed in the power produced by the WiBE with different surfactant

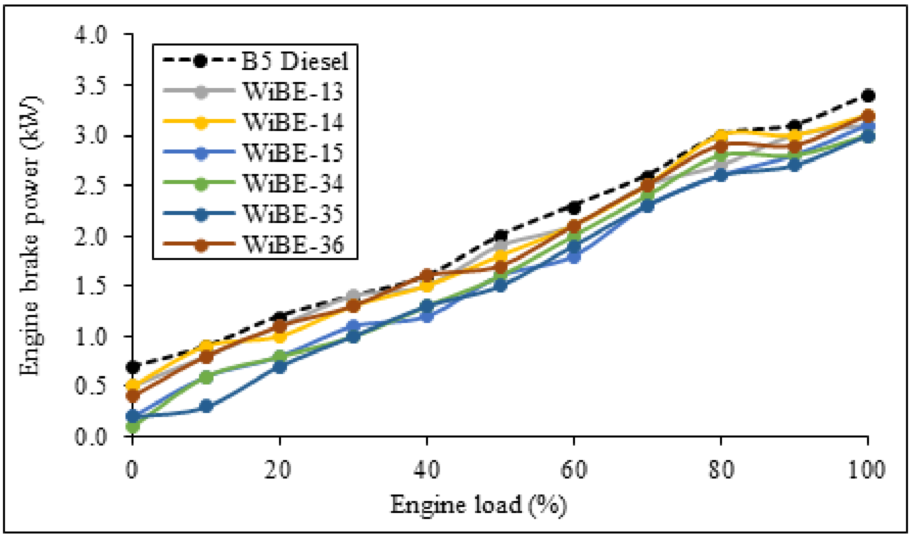

Figure 3 Engine power at different loads for B5 and WiBE

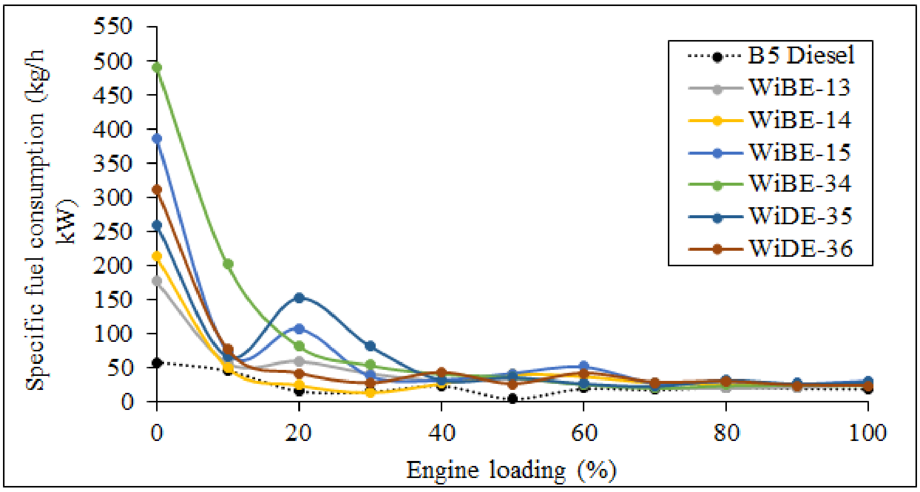

Figure 4 BSFC at different loads for B5 and WiBE

dosages and HLB values. The slight reduction in the power output for WiBE is attributed to the lower heating value of the emulsions and correlate to the amount of water added to the emulsions. The reduction in the power produced with water diesel emulsions was also reported by other researchers [13, 16, 28].

Brake specific fuel consumption (BSFC)

Figure 4 shows the brake specific fuel consumption of both base fuel B5 diesel and WiBE under various engine loads. For all the applied engine loads, B5 diesel recorded the lowest BSFC. Whereas, all the emulsions showed higher fuel consumption compared to B5 diesel up to the engine loading of 70%, upon which the BSFC were similar to B5 diesel. This reduction in BSFC at higher engine load indicates that the combustion was more efficiently and this behavior is similar to the findings of Ithnin et al. [29]. The higher BSFC depicted by WiBE shows that more fuel was needed to maintain the same engine output due to the displacement of diesel fuel by water. The deceased in BSFC with an increase in load is due to the fact that the total energy increases as engine load increases, however, the friction loss is almost the same, so the proportion of output increases. [18, 30].

Effect of WiBE on combustion characteristics – in-cylinder pressure

The in-cylinder pressure traces of the base fuel B5 and the emulsions are shown in Figure 5 to Figure 10. The figures depict the pressure traces under the constant speed of 2000 rpm at various loads from 10% to 100% load in steps of 10%. The pressure traces in the figures are chosen around the crank angles before TDC, just prior to the SOC (start of combustion) to the opening of the exhaust valve. Also, the load conditions were grouped into three i.e., 10-30% as low load, 40-60% as intermediate load and 70-100% as high load.

Figure 5 and Figure 6 depict the peak pressure of the fuels at two low load conditions, i.e. 10 and 20% loads. At low load conditions, the peak pressure for WiBE is slightly lower than base fuel B5 diesel, which could be due to the low heating value of the emulsions and also the presence of water that absorbs heat both in the form of sensible and latent heat [13]. The peak pressure rise at low load for WiBE was found to be delayed due to the lower residual gas temperature and lower cylinder wall temperature which lead to lower charge temperature at the time of injection [29]. Furthermore, the higher viscosity of the WiBE lengthens the ignition delay (ID) resulting in the retarded SOC. Both WiBE 15

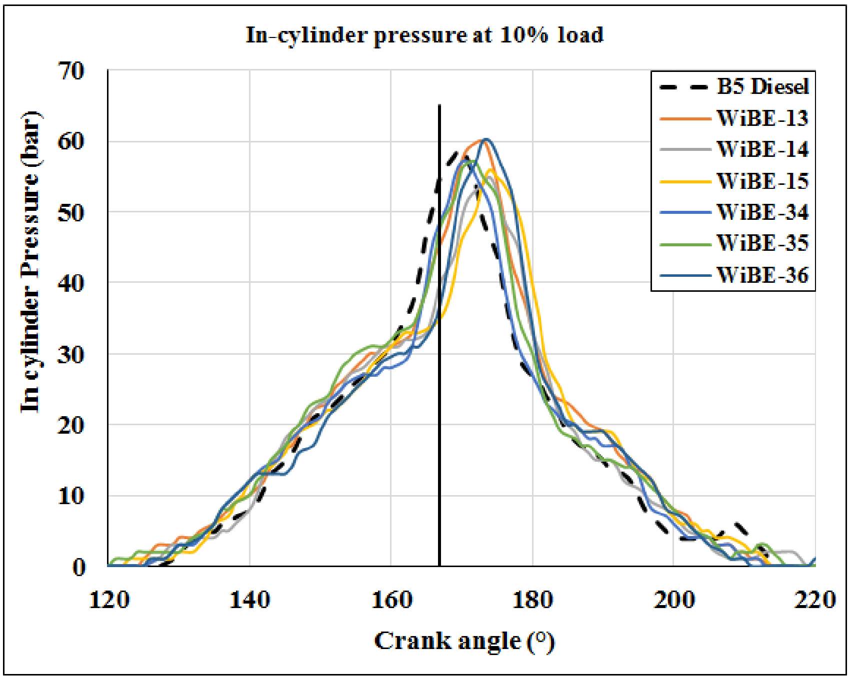

Figure 5 In-cylinder pressure traces of B5 and WiBE at 10% load

and WiBE 36 which had the maximum water content recorded the maximum delay, as compared to the base fuel B5 diesel and other emulsions. At low load conditions, the combustion rate was still high during the expansion stroke as compared to the base fuel B5 diesel. Termination of the pressure seems to occur at the same °CA (crack angle), perhaps due to the opening of the exhaust valve.

The pressure traces of selected intermediate loads (40 and 50% loads) are shown in Figure 7 and Figure 8. All the emulsions indicated higher pressure rise compared to the base fuel B5 diesel. WiBE-15 and WiBE-36 still exhibited a maximum delay in SOC. Also, in the case of WiBE, the peak pressure was observed to reach a peak at a later degree of the crank angle after TDC (top dead centre) in all load conditions. The highest

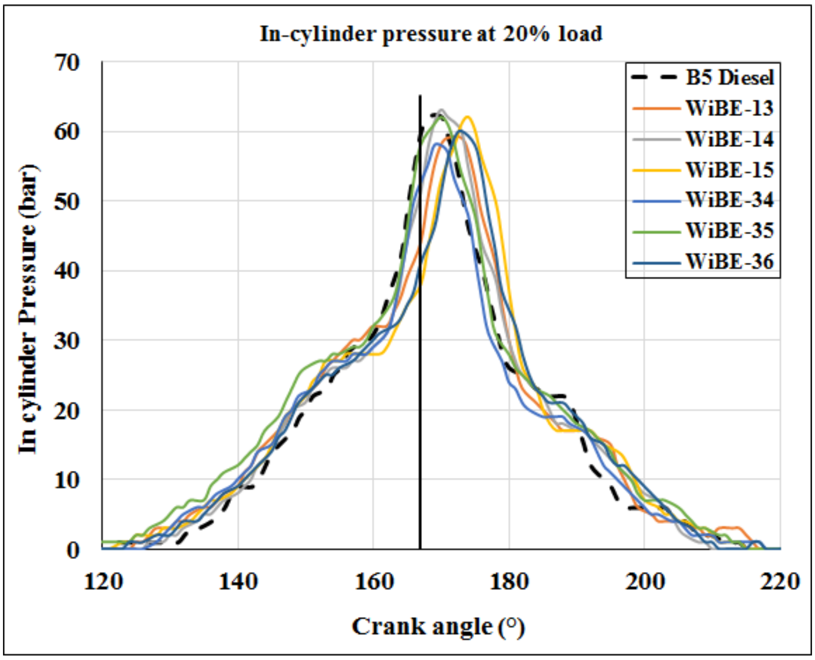

Figure 6 In-cylinder pressure traces of B5 and WiBE at 20% load

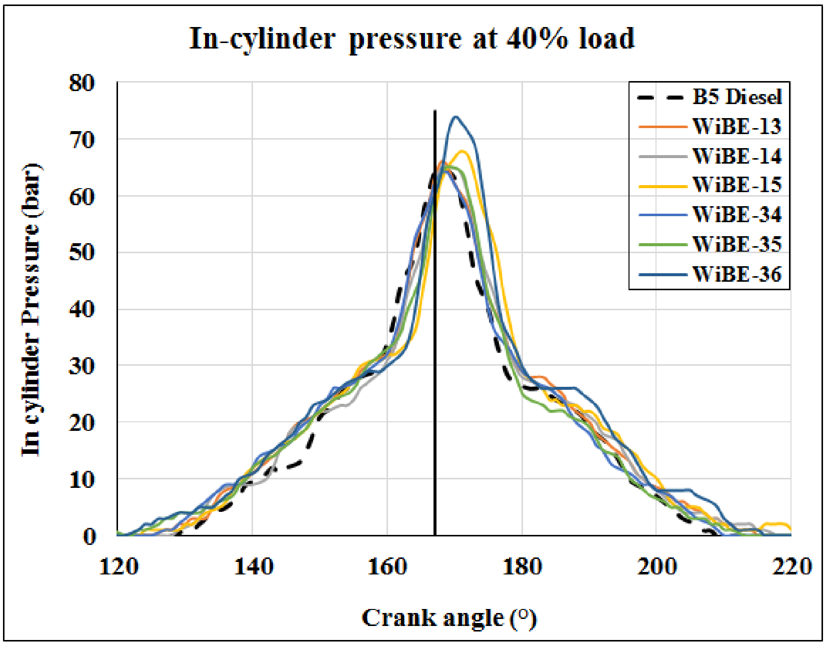

Figure 7 In-cylinder pressure traces of B5 and WiBE at 40% load

peak pressure was achieved by WiBE-36 followed by WiBE-15, 34, 13, 14 and 35. At the intermediate load conditions, all emulsions showed the delay in SOC, but peak pressure increased as compared to base fuel B5 diesel. It can be observed that the combustion continued several crank angles longer than B5 diesel, indicating improvement in the combustion of fuel, hence potential in soot reduction.

The in-cylinder pressure traces of the emulsions and base fuel B5 diesel for selected high loads (90 and 100% loads) are shown in Figure 9 and Figure 10. It is noted that the delay in attaining the maximum pressure is reduced when compared to the lower and medium load conditions. It might due to that the gas temperature inside the cylinder and the wall temperature are higher which reduces the delay in

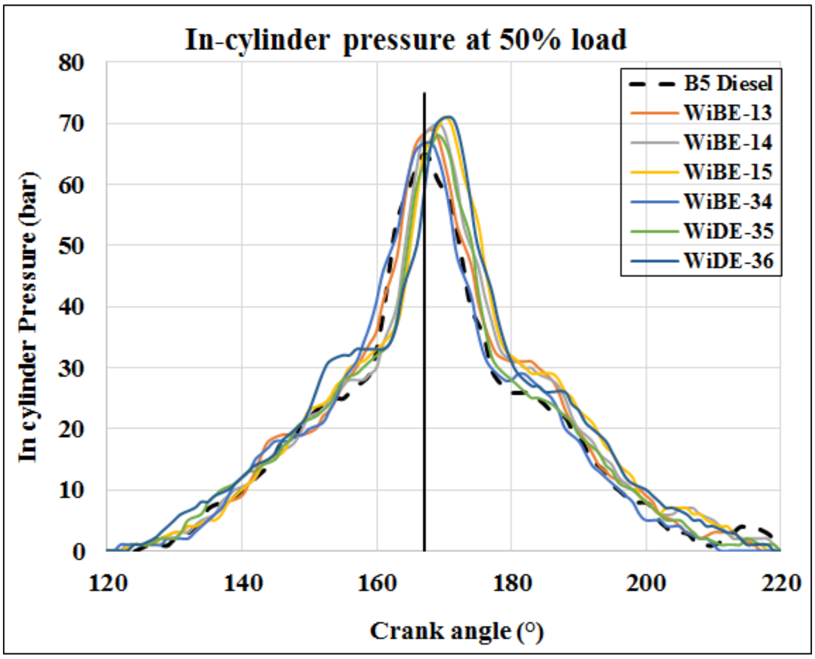

Figure 8 In-cylinder pressure traces of B5 and WiBE at 50% load

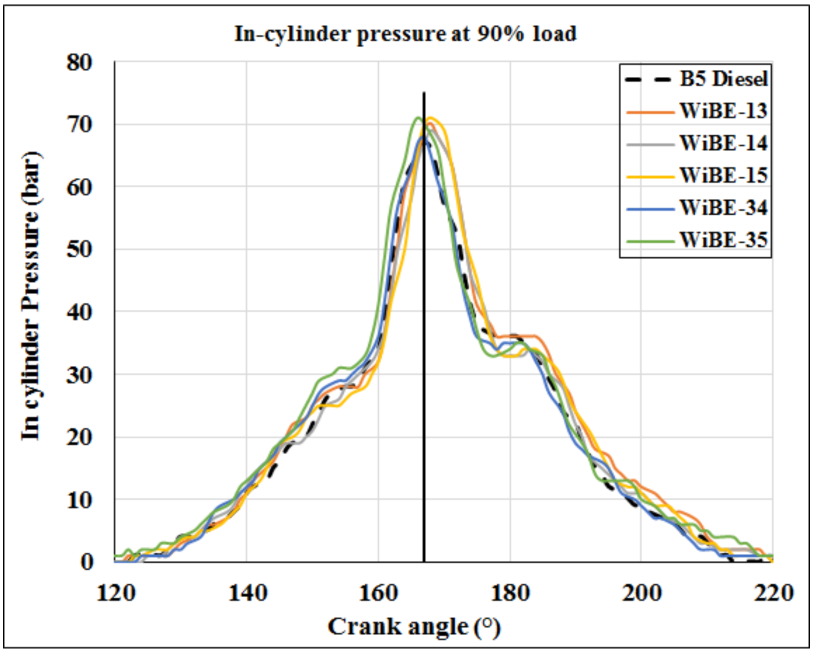

Figure 9 In-cylinder pressure traces of B5 and WiBE at 90% load

the injection timing and advances the SOC. However, emulsions with maximum water content have a delay in reaching the maximum pressure rise among other emulsions. At higher load conditions, especially at 90% and 100% load, the SOC happened at almost similar °CA for all fuels and so do the pressure traces. From the in-cylinder pressure plots, several relationships can be envisaged. First, the emulsions with maximum water content produced higher in-cylinder pressure for all the higher load conditions. According to Jeong and Lee [31], emulsions having higher water content resulted in higher intensity of micro-explosion and the waiting time for micro-explosion was also delayed. It can be seen in the pressure traces of WiBE-15 and WiBE-36 (of higher water content), high load conditions produced 15.2 and 9.1% higher peak pressures respectively, against B5. This behavior can be attributed to the micro-explosion occurrence during combustion of the fuel with higher water content. Secondly, contrary to the study by Ithnin et al. [29], in the present study, WiBE with 15% water produced higher pressure rise than the base fuel B5 diesel. This might be the influence of the surfactants used and the HLB (hydrophilic-lipophilic balance) values which affect the process of micro-explosion phenomenon.

Heat Release Rate

Figure 11 to Figure 16 shows the heat release rate (HRR) of the base fuel B5 diesel and the six emulsions are shown. Similar groupings of the load conditions are presented in this section for the HRR analyses. The HRR was calculated based on the in-cylinder pressure data using Eq. 4. At the low load conditions, the HRR of both base fuel B5 diesel and the emulsions were found to be the same. In particular, the HRR of the base fuel B5 diesel was higher at 10% loading. At low load condition for WiBE, the diffusion combustion phase produced higher HRR compared to the premixed combustion phase. However, the HRR during the premixed combustion phase increases as the load increases. The combustion trends of the emulsions as depicted in Figure 11 and Figure 12, indicate that the mixing of emulsion fuels was not intensive resulting in the second peak in the diffusion phase.

The HRR for the selected intermediate engine load conditions (40% and 50%) are shown in Figure 13 and Figure 14. The rate of heat release was found to be increasing with the increase in load. The emulsions WiBE-15 and WiBE-36, which had larger volume of water, attained the highest peak HRR compared to base fuel B5 diesel and other emulsions. This higher

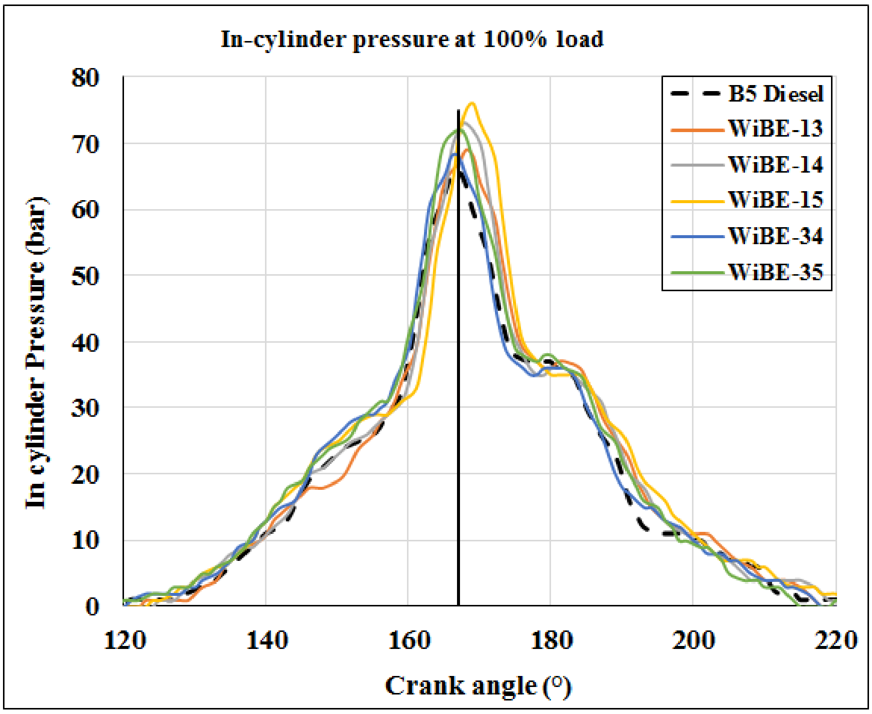

Figure 10 In-cylinder pressure traces of B5 and WiBE at 100% load

HRR can be related to the longer ignition delay (ID), as the WiBE fuel spray has more time to mix with the air leading to higher HRR due to premixed combustion [13, 32, 33]. This trend was similar to Park et al. [34]. It is also observed that the premixed combustion has the peak HRR compared to diffusion combustion phase as the engine load is increased. This behavior can be attributed to the micro-explosion phenomenon which promotes improved air-fuel mixing and enhance the premixed combustion.

For the higher engine load conditions (90% and 100%) as shown in Figure 15 and 16, the HRR for all the emulsions were found to be higher than the base fuel B5 diesel. Notably, WiBE with the larger volume of water were found to have high heat release rate compared to the other emulsions. At higher engine loads, the fuel injection pressure is increased which could have improved the fuel atomization. For loads at 90% and 100%, clear differences among the base

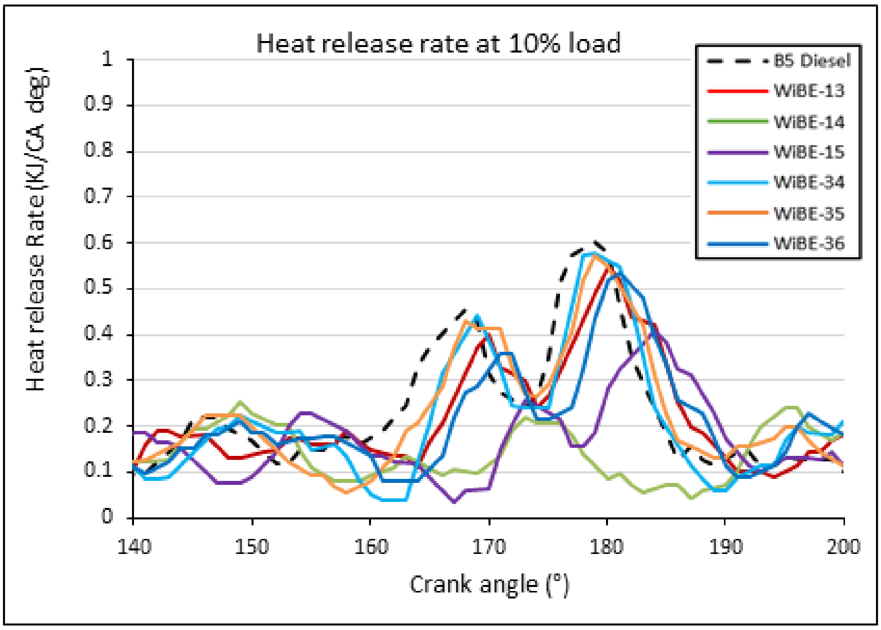

Figure 11 The heat release rate for B5 and WiBE at 10% load

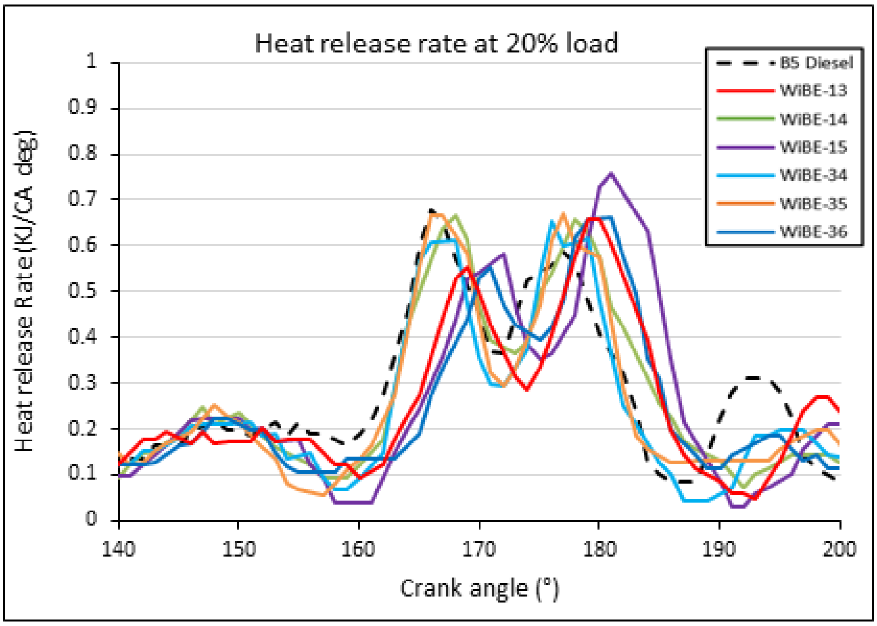

Figure 12 The heat release rate for B5 and WiBE at 20% load

fuel B5 diesel and the emulsions can be seen, evidence of micro-explosion occurrences. The micro-explosion is very intensive leading to better mixing and more rapid combustion in the premixed phase and hence the HRR of the emulsions are found to be higher than that of B5.

Effect of WiBE on engine emissions

The impact of WiBE on the engine exhaust gas temperature, smoke opacity and emissions at a single-engine speed of 2000 rpm and under different load conditions are discussed in this section in detail.

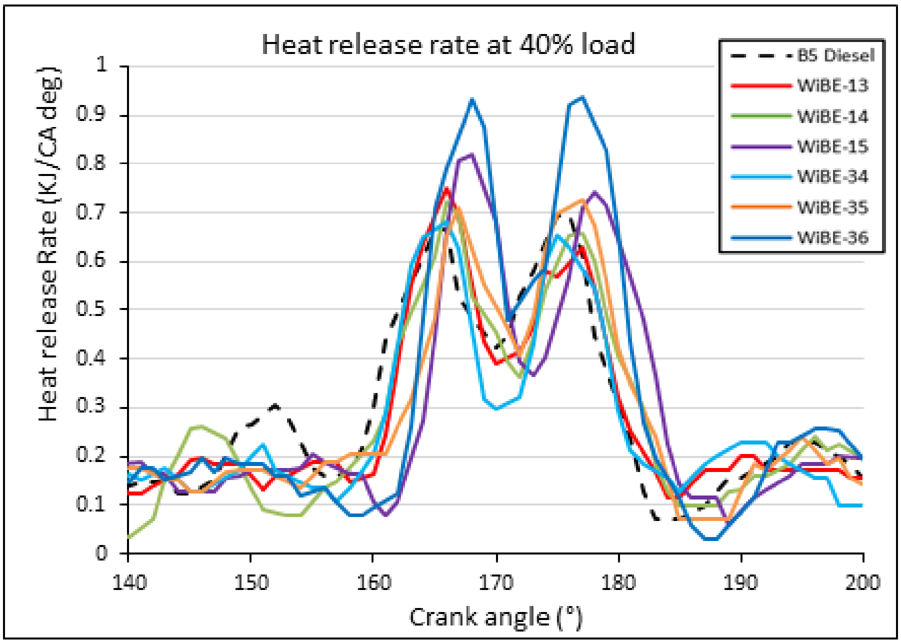

Figure 13 Heat release rate for B5 and WiBE at 40% load

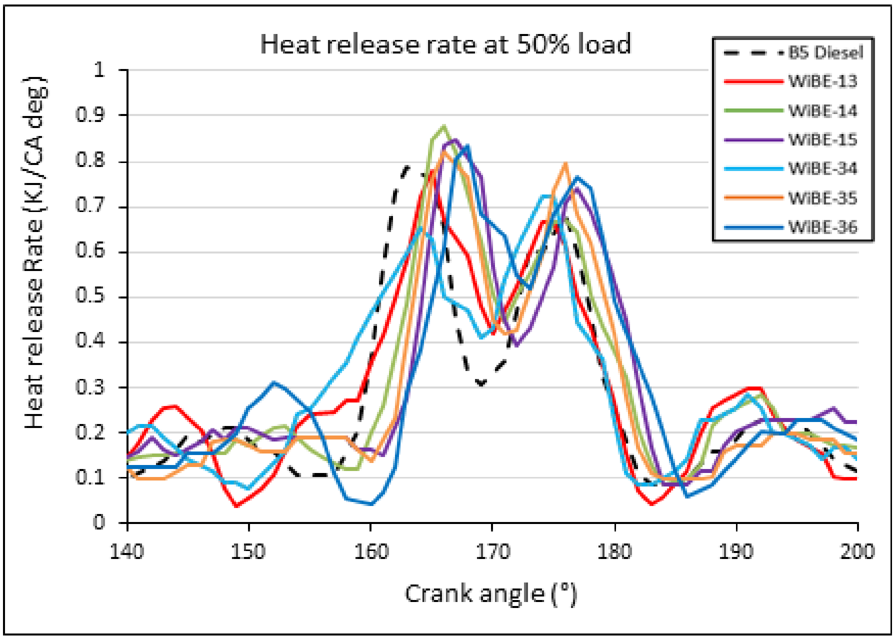

Figure 14 Heat release rate for B5 and WiBE at 50% load

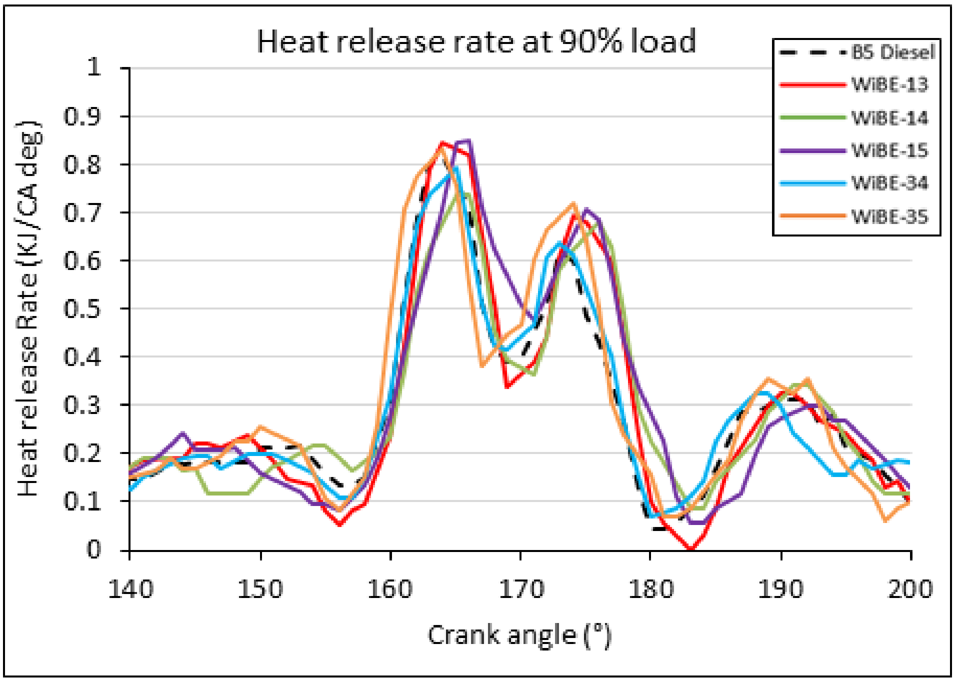

Figure 15 Heat release rate for B5 and WiBE at 90% load

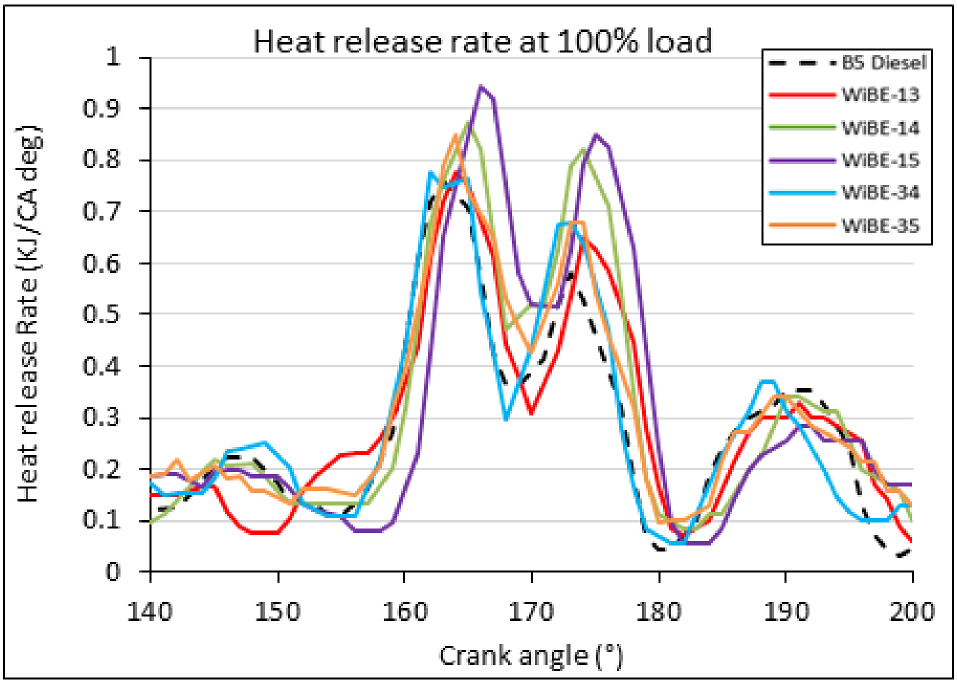

Figure 16 Heat release rate for B5 and WiBE at 100% load

Effect on exhaust gas temperature

As exhibited in Figure 17, base fuel B5 diesel depicted maximum temperature at all the loads. In general, all of the WiBE showed lower exhaust temperature at all loads. It is observed that in case of emulsions stabilized with 10% surfactant dosage and an HLB of 6, WiBE with the maximum water content of 15% (WiBE-15) produced higher exhaust gas temperature followed by the WiBE-14 with 12% water content and WiBE-13 with 9% water content. On the other hand, emulsions stabilized with 15% surfactant dosage with an HLB of 9, WiBE with the minimum water content of 9% (WiBE-34) has produced closest to the base fuel B5 diesel followed by WiBE-35 with 12% water and WiBE-36 with 15% water content.

WiBE-34, 35 and 36 have smaller water droplet sizes due to the increase in the surfactant concentration. As a result, the micro-explosion phenomenon could have been more intensive as compared to WiBE- 13, 14 and 15. In addition, larger heat sink effect adds to further reduced the bulk temperature. Exhaust temperature was found to be reduced proportionately with respect to the water content in these emulsions. Similar behaviour was also reported by Abu Zaid et al. [35] when he tested water-in-diesel emulsions. Koc et al. [28] also confirmed that the exhaust temperature reduced according to water content. Hence, increase in exhaust temperature with increase in water content with the emulsions (WiBE- 13, 14 and 15) stabilized by 10% surfactant dosage might be an outcome of lower heat sink effect due to the presence of larger water droplets.

Effect on smoke opacity

The smoke opacity of the base fuel B5 diesel and the WiBE for all the engine loads are shown in Figure 18. The smoke opacity was found to increase as the engine load increases and was higher at the engine load above 60%. The base fuel B5 diesel has the highest smoke opacity for all the loads, whereas all the WiBE produced comparatively less smoke. At low load conditions (10% to 30%), WiBE-15 and WiBE-36 produced higher smoke opacity compared to other emulsions. It should be noted that at this low load condition, heat release in the diffusion combustion was higher compared to the premixed phase.

Whereas in the intermediate load conditions (between 40-60%) the HRR in the premixed phase was found to be almost similar, compared to diffusion phase and in case of high load conditions premixed combustion was found to be intensive and hence the trend of smoke opacity of all the tested fuels found to increase as the load increases in accordance with HRR. At the maximum load condition i.e., at 100% load, WiBE-13, 14 and 15 having 10% surfactant dosage and with an HLB of 6 produced smoke opacities of 13.5%, 11.7% and 7.6% lesser smoke compared to base fuel B5

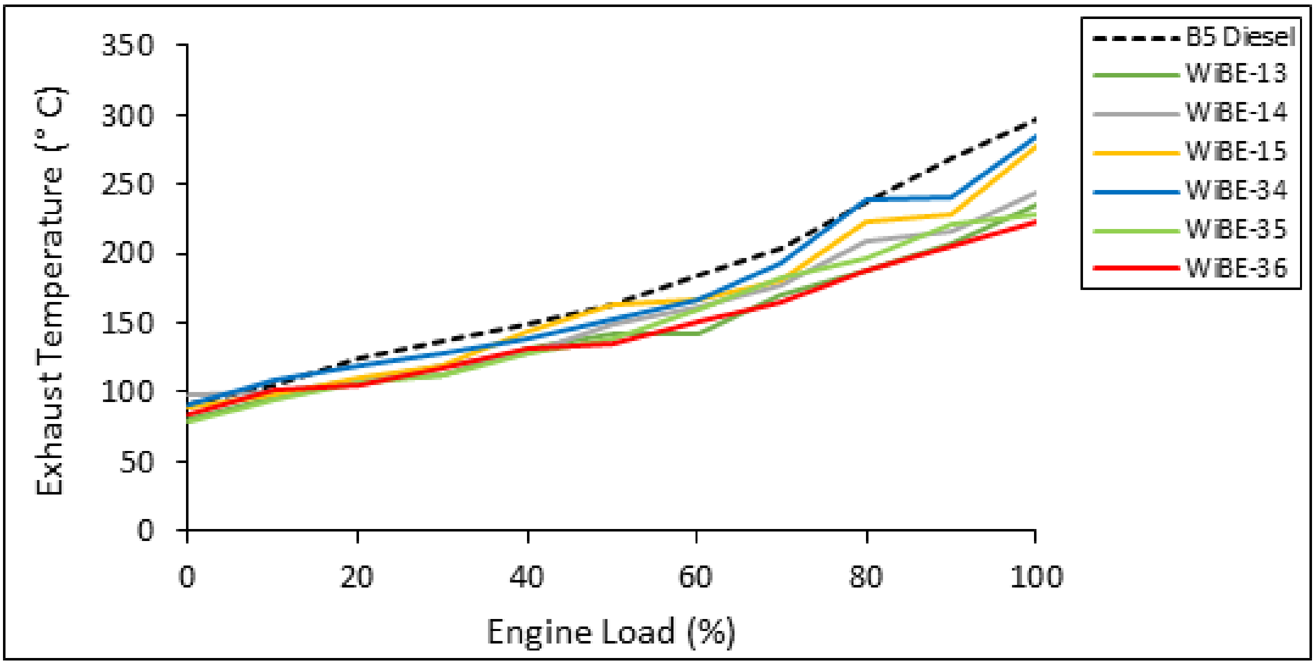

Figure 17 Exhaust gas temperature for B5 and WiBE

diesel, respectively. Whereas, it was 5.6%, 20.2% and 23% reduction in smoke opacities by WiBE-34, 35 and 36 compared to base fuel B5 diesel.

WiBE-13 (with 9% water) has the lowest smoke opacity at higher loads compared to other two emulsions stabilized with 10% surfactant with an HLB value of 9. Whereas, for the same water content (9% water) emulsions stabilized with 15% surfactant dosage with an HLB of 9, WiBE-34 has the highest smoke opacity compared to the base fuel B5 diesel followed by the WiBE-35 and WiBE-36 especially at intermediate to higher engine load conditions. The WiBE produced higher exhaust gas temperature resulted in higher smoke opacity also. In general emulsions with 15% surfactant dosage, the smoke opacity decreases with an increase in the amount of water.

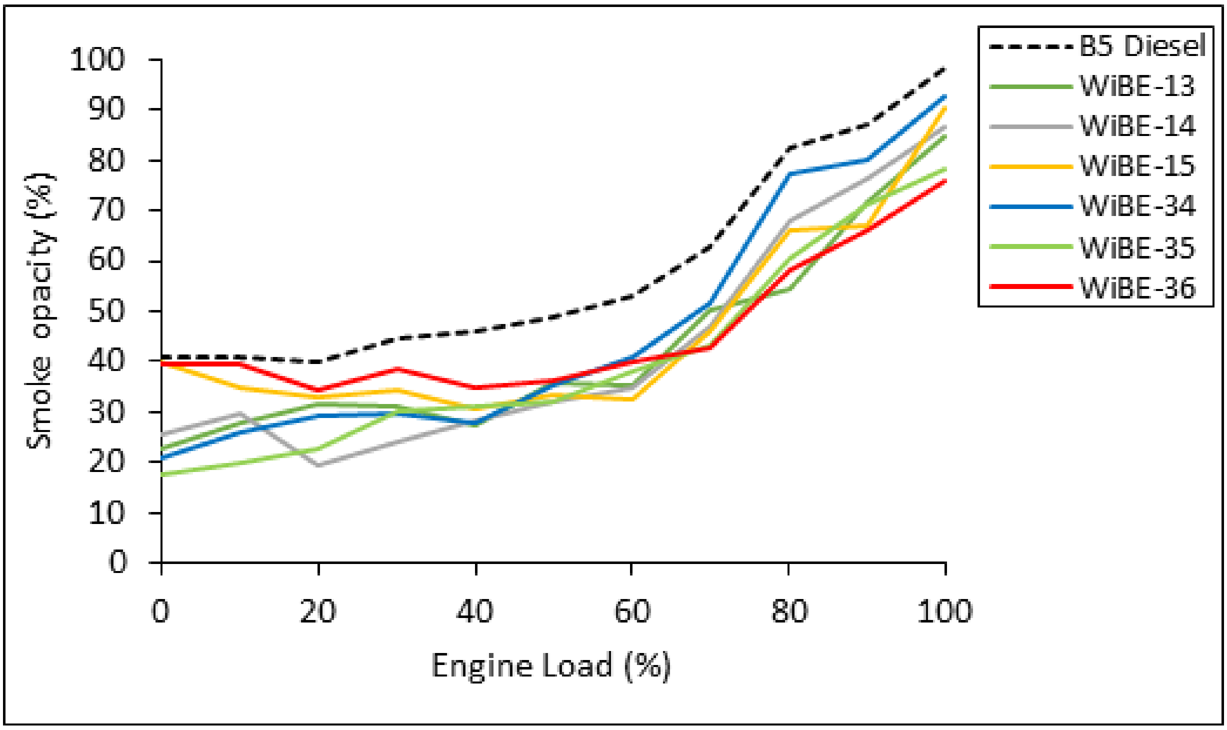

Figure 18 Smoke opacity of B5 and WiBE

Effect on Nitrogen Oxide (NOx)

The nitrogen oxide emissions for the base fuel B5 diesel and the emulsions are shown in Figure 19. The NO_X was found to be increasing with an increase in engine load up to 60% load, which later started to decrease. Irrespective of the water content, all WiBE showed the reduction of NOx significantly at all loads. Emulsions with maximum water resulted in a higher reduction in nitrogen oxide compared to other emulsions. This indicates strong evidence that the presence of water in the fuel reduces the combustion temperature due to heat sink. Similar observations were also reported by Fahd et al. [13], Alahmer et al. [16] and Koc et al. [28]. WiBE stabilized with 15% surfactant dosage with an HLB of 9 produced lesser NO_X compared to the WiBE stabilized with 10% surfactant dosage with an HLB of 6.

For an instant, at 50% load WiBE-34 reduced 49%, WiBE-35 reduced 42% and 38% for WiBE-35 in terms of NO_X reduction compared to WiBE-13, 14 and 15. At 80% engine load condition, emulsions stabilized with 15% surfactant and with an HLB of 9 reduced 19%, 46% and 15% of NO_X when compared to the emulsions stabilized with 10% surfactant dosage with an HLB value of 6. At 100% load, compared to base fuel B5 diesel, the reduction NO_X by the emulsions were 59%, 57% and 66% for WiBE-13, 14 and 15 and it was 60%, 59% and 79% in case of WiBE-34, 35 and 36. Hence, it is clear that for the same amount of water added, these results showed a different rate of reduction in NO_X for at different surfactant dosage and HLB values. The difference in the amount of surfactant and HLB values might influence the intensity of micro-explosion and the heat sink effect [36] which resulted in the peak temperature reduction of the flame inside the combustion chamber.

Effect on Carbon Monoxide and Oxygen

The effect of WiBE and the base fuel B5 diesel on CO and O_2 are shown in Figure 20 and Figure 21, respectively. It is found from Figure 20 that there is no significant increase in CO for the emulsions with an increase in load and CO was comparatively less with the base fuel B5 diesel. The CO was observed to

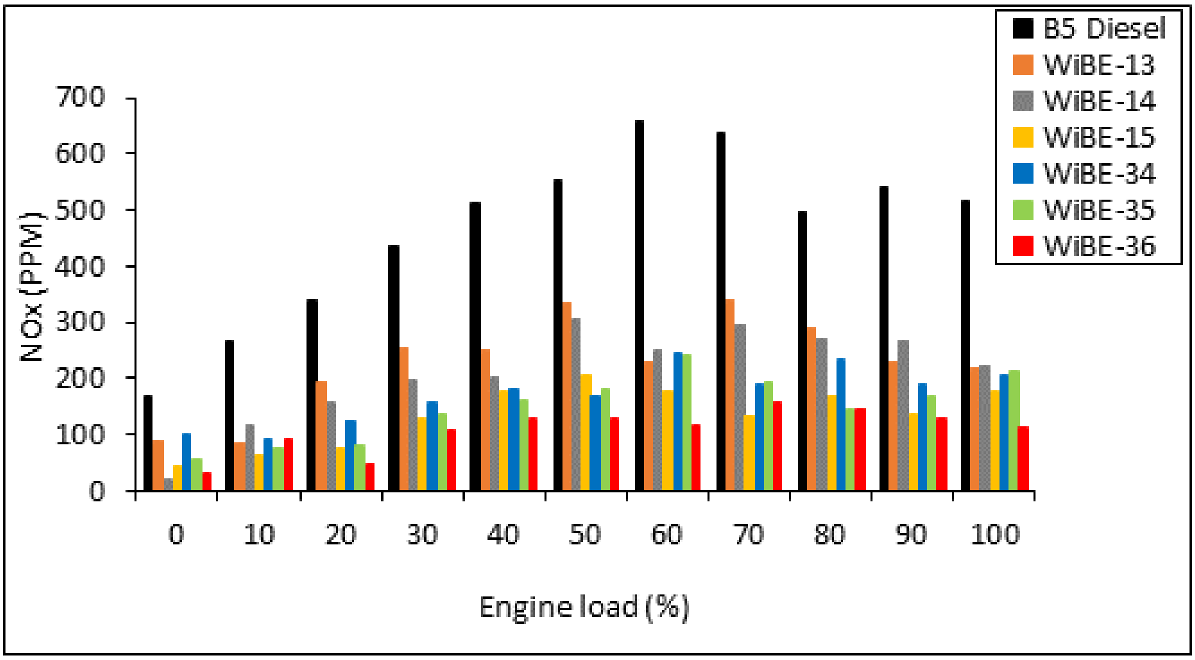

Figure 19 Emissions of NOx for B5 and WiBE

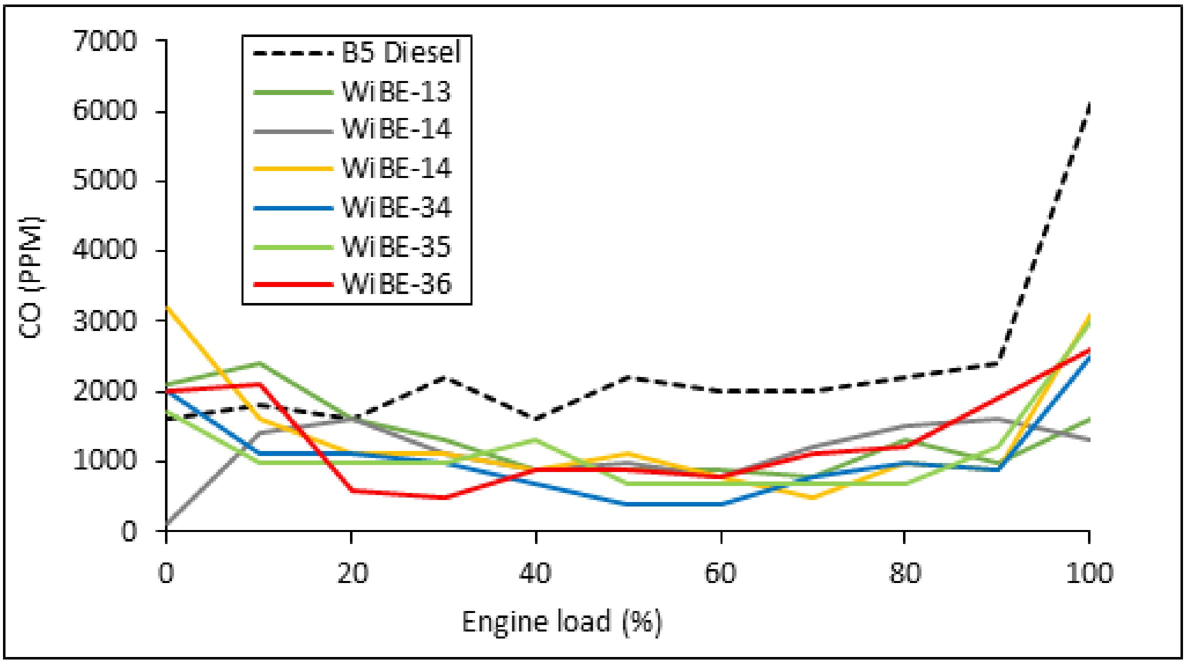

Figure 20 CO emissions for B5 and WiBE

increase after 60% load. The difference in CO among the emulsions were less significant. According to Lin et al. [17], the water-in-diesel emulsions produced lesser CO compared to diesel, because the emulsions undergo micro-explosion process resulting in more mixing of charge. The reduction in CO is an indication of improved combustion in terms of WiBE compared to the base fuel B5. A similar observation was mentioned by Nadeem et al. [15] when water in neat diesel emulsions was tested in a multi-cylinder diesel engine.

The effect of the WiBE on the oxygen generation is shown in Figure 21. It can be inferred from Figure 21 that, as the engine load is increased, there was a decrease in O_2 production. In general, the base fuel B5 diesel had lesser oxygen compared to all the emulsions. The O_2 percentages are higher than for the emulsions because of the presence of inherent oxygen in POME [24]. At the maximum load, base fuel B5 diesel has 8.6% of O_2 and it was 10-14% in case of emulsions stabilized with 10% surfactant dosage and 9 - 10.6% in the emulsions stabilized with 15% surfactant dosage.

CONCLUSIONS

Stabled water-in-biodiesel emulsions were prepared and tested in a single-cylinder DI diesel engine. From the experimental analysis and findings, the following conclusions can be made:

- The engine power produced by the WiBE were reduced between 6 to 11.7% compared to base fuel B5 diesel. The specific fuel consumption increased up to engine load of 70% and comparable with base fuel for engine load of 70% to 100%.
- The in-cylinder pressure traces and the heat release rate attained by WiBE were found to be higher than the base fuel at high engine loads. This can be attributed to the occurrences of micro-explosion during combustion.
- NO_X was reduced significantly with a reasonable reduction in CO with WiBE compared to base fuel B5 diesel. The exhaust gas temperature was slightly reduced while, relatively large reduction in smoke opacity especially at the intermedia load with WiBE.

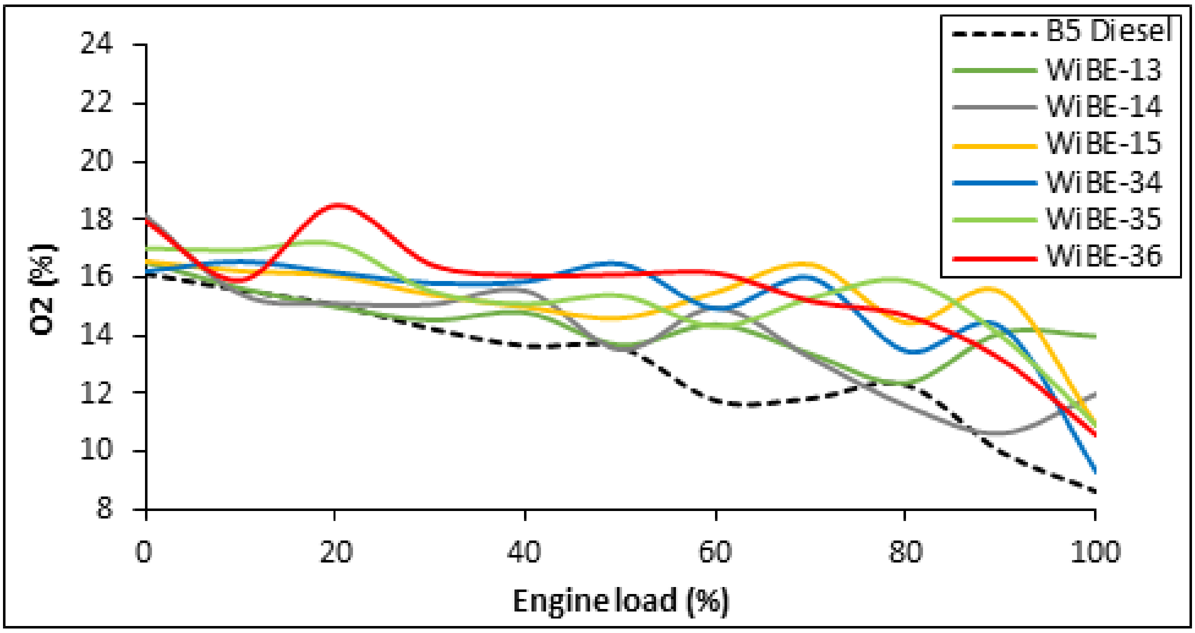

Figure 21 O_2 emissions for B5 and WiBE

- The amount of reduction for NO_X was found to be more for WiBE stabilized with 15% surfactant dosage with an HLB of 9 compared to the WiBE stabilized with 10% surfactant dosage with an HLB of 6.

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