Experiment of Oxygenated Fuel on Diesel Engine: Performance, Emission and Particulate Matter

Hazman Abu Hassan[1], Rizalman Mamat[2*], Ftwi Y. Hagos[2] and Gholamhassan Najafi[3]

[1]Department of Chemical Petrol Engineering, Polytechnic Tun Syed Nasir (PTSN) 84600 Pagoh, Johor Malaysia.
[2]Faculty of Mechanical Engineering Universiti Malaysia Pahang (UMP) 26600 Pekan, Pahang Malaysia.
[3]Department of Mechanics of Biosystem Engineering, Tarbiat Modares University, Tehran, Iran.

ABSTRACT

The main purpose of the study is to characterise the effects of diesel, biodiesel blends B5M10 and B10M10 and emulsion fuels B5M10E3 and B10M10E3 as fuels for the impact on particulate matter emission. Engine tests have been performed to obtain results of engine performance, gas emission and particulate matter with various cycles. Excel analysis methods were used to analyse the data obtained. The B5M10E3 produces lower NO_x emission results than B10M10E3 as biodiesel fuel increases the combustion temperature. In conclusion, biodiesel blends able to reduce emissions of particulate matter and gas emissions compared to diesel but increase NO_x emissions. Therefore, emulsion fuels B5M10E3 and B10M10E3 can be the best alternative fuel for the future.

Keywords: Biodiesel, Emulsion Fuels, Emission.

1. INTRODUCTION

Diesel engine technology may soon phase out from the market unless particulate matter (PM) and nitrogen oxides (NO_x) emissions are dealt with as per the standard requirements. The current study is an extension of previous research works where diesel and biodiesel blends are modified to emulsify and oxygenate through water and alcohol, to reduce emissions from the exhaust. Emulsion of fuel is convenient due to the secondary atomization from micro-explosion and droplet breakdown of emulsion fuel, which is responsible for the reduction in PM emissions. The morphology of PM demonstrates that emulsion fuel produces lower soot concentration compared to biodiesel blends and diesel. The diesel engine is a notably important contributor to the advancement of the global economy and wellbeing of society while not neglecting its impacts on pollutants from the combustion of diesel fuel [1]. Naturally, diesel fuel emits PM, total gaseous hydrocarbon (THC), sulphur oxides (SO_x), carbon dioxides (CO_2), NO_x and carbon monoxide (CO). Moreover, diesel also emits acidic gaseous that combines with water droplets in the air and turn into acid rain and causing global warming [2]. The causes for major emissions—mainly PM and THC—are the deficiency of oxygen in the combustion process and the presence of aromatics in diesel fuel [3]. In recent years, there has been increased attention on oxygenated fuels because oxygen helps in deep-burning and reduces emissions [4]. Challenges and pollution threats caused by diesel fuels are anticipated to be handled by producing alternative fuels that contain oxygen and that can facilitate the diffusion process [5, 6]. As such, oxygenated fuel is a fuel that contains oxygen in its chemical structure [7, 8], where it can reduce carbon monoxide and soot due to complete combustion [9, 10]. Blending of two or more fuels is the process of mixing diesel fuel with other naturally miscible liquid fuels to produce a new fuel with a different fuel property than its parent fuels that can provide better engine performance, reduce pollution and cost-efficient [11-14].

Corresponding Author: rizalman@ump.edu.my

Many researchers have been carried out on the blend of diesel with biodiesel [11-13], diesel with alcohols [6, 15-17] and three blends of diesel, biodiesel and alcohols [18, 19]. Biodiesel has many advantages in which the plant does not contain sulphur and has a high oxygen content [20]. Song et al. [17] demonstrated that the experiments on blended fuel for investigation of fuel extraction characteristics from ethanol-aviation kerosene revealed a positive outcome. Mainly, spray tip penetration, spray cone angle and spray area injection increased the performance [17]. Another study has shown that the blended fuel had better performance compared to a triple mixture of diesel/butanol/biodiesel blend, where there was an improvement in a flame tube boiler [21]. On the other hand, Ali Keskin et al. [22] indicated that mixing of diesel fuel-biodiesel blends with palladium and acetylferrocene has resulted in the reduction of pollution such as particulate matter. There have been recent efforts to extend the intervention of fuel blends in tackling all the emissions while not affecting the performance of the engine. This was further intensified through the recent discovery of the micro-explosion phenomenon in the combustion chamber through the emulsification of different boiling temperature liquid fuels [23, 24]. Addition of alcohols or water to diesel and biodiesel blends has shown improvements through an emulsification technique on emissions of both PM and NO_x while improving the performance of the engine [25-27]. Therefore, the primary aim of this study is to investigate the PM of diesel, biodiesel and water in biodiesel. Furthermore, the study is aimed to characterize the PM oxygenated fuel through the observation of particulate matter morphology and to formulate the relationship between engine performance and PM of oxygenated fuels. The goal is to investigate four new alternative fuels that can produce minimum hazardous smoke and PM emission.

2. MATERIAL AND METHODS

The biodiesel used in the current study is palm oil-based biodiesel also known as POME that was supplied by a local industrial supplier from Selangor, Malaysia. A commercial fuel supplier provided the diesel fuel which is 100% pure diesel unlike the 7% biodiesel blended fuels available in stations. Methanol, Span 80 and Tween 80 were obtained from the chemistry laboratory, University Malaysia Pahang. The blending of the biodiesel and the fossil-based mineral diesel were prepared using an electrical magnetic stirrer. The diesel and biodiesel mixtures were stirred continuously for 25 min and left for 30 min at room temperature to reach equilibrium before subjected to the emulsification process. The emulsification process was conducted by the use of an ultrasonic emulsifier in the presence of surfactant. In addition to the based diesel fuel (DIESEL), a methanol emulsion of 10% by volume was added into both palm oil biodiesel and mineral diesel fuel, which correspond to B5M10 and B10M10 fuels, respectively.

Besides that, two emulsions of water were prepared which corresponded to B5M10E3 and B10M10E3 fuels. The emulsion mixtures require the use of a mechanical stirrer and ultrasonic horn agitators to obtain the naturally immiscible liquid by using a surfactant. This method produces stable fuel and can produce micro-emulsion. When a micro-emulsion mixture is formed, it is expected that a micro-explosion phenomenon will occur in the combustion. Consequently, there will be an increase in the performance and reduction of emission [28]. B5M10E3 is also known as an emulsion fuel as it contains 5% biodiesel oil, 10% methanol, 3% water, 80% diesel and 2% surfactant. The emulsifying agent or surfactant forms a thin interfacial film between two liquids to decrease water or oil surface tension and decrease contact, coalescence and aggregation of internal dispersed phase [29]. The surfactants are required to undergo hydrophilic-lipophilic balance (HLB) balance processing before the use. Non-ionic surfactants of span 80 with HLB value 4.3 and Tween 80 with an HLB value of 15 are preferred. American Society Testing Material (ASTM) suggests that HLB 0.5 – 16% is suitable for fuel, hence 2% of surfactant is considered as an option [12, 30]. The direct mixing of oil and water will deteriorate the function of the engine. This is due to the nature of the water that interacts with the iron, which will cause rust on the engine portion of the iron component [12]. This problem can be solved by ensuring the water is encapsulated in the oil employing an emulsification process called water in W/O and oil in water

and water in oil called O/W/O. Oil in water and water in oil (O/W/O) has shown to be a more stable emulsion and suitable for micro-explosion phenomenon in the diesel engine. The first stage of oil in water (O/W) is a process where oil is blended into the water with a surfactant of HLB 13 to stabilize the emulsion as expressed in Equation (1) and (2) as follows:

$$\% \, (A) \;\; = \;\; \frac{100(\, x - HLB_{(B)})}{HLB_{(A)} - HLB_{(B)}} \tag{1}$$

$$\% \, (B) = \;\; 100 - \% \, (A) \tag{2}$$

Based on Equations (1) and (2), the percentage of mixtures of Tween 80 and Span 80 surfactant were included in B5M10E3 fuel and mixed with a mechanical stirrer for 28 minutes at 25°C. The time interval for mixing was between 25 to 30 minutes. According to the ASTM standard, the ideal room temperature for the coolant material is at 25°C. All experiments were conducted under controlled room temperature, pressure and relative humidity to eliminate the effect of environmental error. The mechanical stirrer with a power of 80 to 100 hertz and with a speed of 600 to 620 rpm was employed for the first stage surfactant to produce O/W. The power of 80 hertz is essential for creating a strong force for the molecular mixture, while 600 rpm was ideal to cause the stirring of the water in a simple state according to the size and volume of the 500 ml jar. The second stage process involved using HLB 6 O/W, which was formed to be used with O/W/O to obtain better fuel emulsion stability.

The mixture of the surfactant percentage was added into B5M10E3 fuel gradually during the fuel recovery process using an ultrasonic emulsifier machine. It should be noted that the ultrasonic emulsifier machine has a power of up to 24 kHz to break the surface tension molecules to ensure optimum mixing of water and oil. Table 1 shows the Ultrasonic Emulsifier specification and cycle 0.6 was selected as it provides the appropriate mix of impact. Moreover, an amplitude of 70 was selected due to the medium strength of the medium-sized power 500 ml jar, which incorporated O/W into O/W/O with 10 minutes of operation time. The temperature of the oil sample increases with the increase in the duration of ultrasonic emulsification process. Furthermore, the recommended loading time was between 5 to 20 minutes depending on the size of the jar and the requirements for the sample rate. After the emulsification process, the fuel was processed slowly under the stirrer mechanical gauze for 10 minutes for gentle mixing of the molecular composition. It should be noted that B10M10E3 emulsion fuel requires similar processing to B5M10E3.

Table 1 Ultrasonic Emulsifier specification

Detail	Specification
Ultrasonic processors	UP400S
Efficiency	>90%
Working frequency	24kHz
Control range	±1kHz
Output control	20% … 100% step-less adjusted
Pulse-pulse mode factor	10% …100% per second, step-less adjusted

The investigation engine used in this study is a YANMAR TF120M, which is a four-stroke engine with a single-cylinder, water-cooled and direct fuel injection. The specifications are provided in Figure 1 while Table 2 that shows the engine test rig. A total of two base fuels were used for engine testing. The first fuel was mineral diesel, which was procured from supplier, and the second fuel was biodiesel, which was the palm-diesel provided by Mission Biotechnologies Sdn. Bhd. All fuels provided by the respective companies comply with EN14214. The DELTA SUPER HD40 German Technology was the engine lubrication oil used throughout the research as recommended by the manufacturer. It has a capacity of 4 litres.
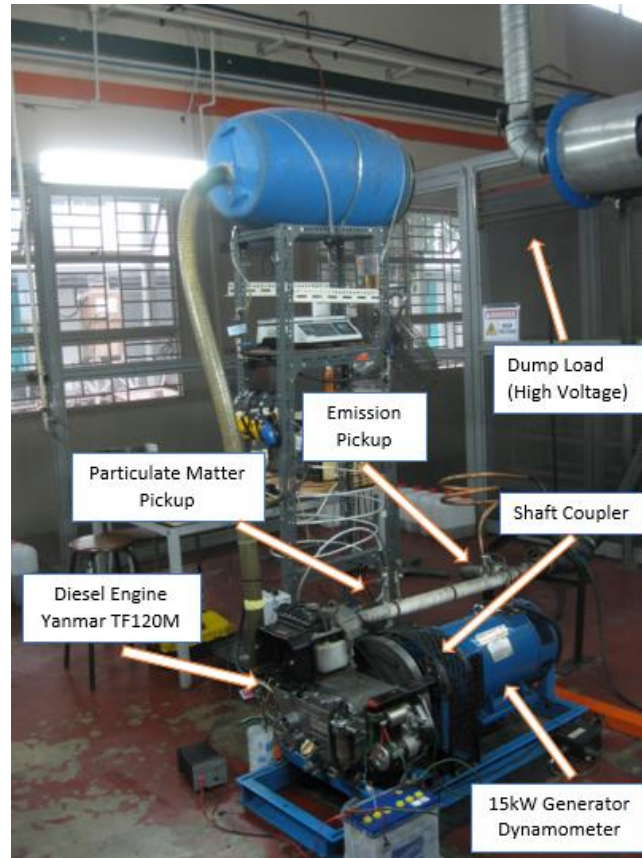
Figure 1. Engine test rig.

Table 2 Test engine specification

An example of a column heading	Column A (*t*)
Engine type	Diesel 1-cylinder
Stroke type	Four-stroke
Cylinder bore x stroke (mm)	92 x 96
Injection timing (deg.)	btdc 17°
Compression ratio	17.7
Displacement (lit.)	0.638
Maximum torque (kgf.m / rpm)	4.42 / 1800
Specific fuel consumption (g /kWh)	229.77
Fuel injection pump	Bosch Type
Injection pressure (Pa)	19.61×10^6

The engine performance is called the maximum brake output power of an engine. Engine torque was measured by a dynamometer rotor with clamp on a testbed and the shaft connected to the dynamometer rotor. The dynamometer operates to break the engine into certain loads and speeds. The dynamometer is a generator-type 'eddy current dynamometer'. Power from the engine rotates the rotor of the generator. The rotor field is controlled by dynamometer current. More current gives a stronger rotor magnetic field, inducing more power in the stator coils. Power from the stator coil is sent to the dump load located at a distance from the dynamometer. The dynamometer is suspended on bearings, and the torque is read by a load cell.

The rotor is coupled electromagnetically and hydraulically to a stator with supported low friction bearings. Figure 2 illustrates the principle of dynamometer operation where the torque exerted by the engine is *T*:

$T = Fb$ (3)

The formula of power P delivered from the engine and absorbed by the dynamometer is produced by torque with the angular speed as shown in Equation (4).

$P = 2\pi NT$ (4)

where, N is the crankshaft rotational speed. The formula in SI units is given in Equation (5):

$P(\text{kW}) = 2\pi N(\text{rev/s})T(\text{N.m}) \times 10^{-3}$ (5)

Brake power is the function of torque, T (Nm) and speed (rpm). T represents torque in the formula which is a measure of the engine's ability to do work, and P is the brake power which means the rate at which work is done.
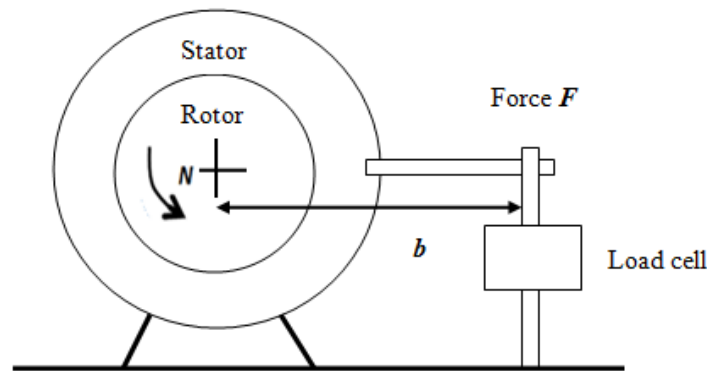

Figure 2. Principle of dynamometer operation [1].

A 15-kW eddy-current with a controller was used to load the engine. The main specifications for the dynamometer are listed in Table 3. The operating conditions of the engine and the dynamometer brake are characterized by speed and torque. In addition, the engine speed is controlled by the throttle engine position lever to increase or decrease the engine speed when operating the dynamometer. The operation of the test rig is more stable if the brake is more powerful than the engine at above the selected speeds. Before performing experimentation, the dynamometer was calibrated using levers and weights that allow clear and precise adjustments. After the engine are combusted in different loads, exhaust gases came out from the cylinder's flow through the exhaust extractors with extremely high temperatures and high pressures and harmful contents. Basically, the measurement of exhaust gas emission concentrated on the temperature, pressure and the content itself. As for the temperature measurement, there were two K-type thermocouples attached to the exhaust extractors, mounted to the engine. The QRO-401 gas analyser was incorporated together with signal instrument gas analyser for the calibration to assure the reliability of the exhaust gas measurement, the specifications for a QRO-401 gas analyser is shown in Table 4.

Table 3 A Dynamometer power BD-15kW specification

Detail	Specification
Mechanical Power	15 kW maximum
Torque	60Nm maximum
Speed	2400 rpm maximum (direct coupling)
Electrical Power	7,500W maximum
Voltage output	300V maximum
Current	40A maximum

Table 4 Accuracy measurement for QRO - 401 gas analyser

Gas Measurement	Resolution	Range
Oxygen (O_2)	0.01 %	0 – 25 %
Carbon monoxide (CO)	0.01 %	0 – 9.99 %
Carbon Dioxide (CO_2)	0.1%	0 – 20 %
Nitrogen (NO_x)	1 ppm	0 ~ 5000 ppm
Hydrocarbon (HC)	1 ppm	0~ 9999 ppm

3. RESULTS AND DISCUSSION

3.1 Fuel Properties and Analysis

Many studies have shown that the performance and emissions improvement with different alternative fuels is directly linked to the change in the physicochemical properties of the modified fuels [46]. Table 5 demonstrates the results of fuel properties obtained from different experiments. The properties considered in the current study are cetane number, calorific value, density at 25°C, kinematic viscosity at 40°C, flashpoint and boiling point. There are five test samples; diesel is taken as reference base fuel. The experiment was conducted three times on average and tabulated. Each fuel characteristic affects the combustion behaviour in the combustion chamber, which consequently influences particulate emission and performance.

Table 5 The fuel properties result from five different fuels

		Fuel				
Cetane Number	-	50	51.6	51.9	52.3	53.9
Calorific Value	MJ/kg	42.7	34.22	35.27	41.69	42.74
Density at 25 °C	g/cm^3	0.84	0.86	0.84	0.92	0.83
Kinematic Viscosity at 40 °C	mm^2/s	5	5.69	5.71	5.25	5.25
Flashpoint	°C	80	100-105	95-100	90-95	105-110
Boiling Point	°C	149	268.2	191.7	105.2	73

3.2 Engine Performance Analysis

The brake power at the output shaft is a relation of torque, and angular velocity (BP=Tω). The rates of change at the same angular velocity for brake power and torque shows a similar pattern. Figure 3 shows that at partial load conditions, the brake power for diesel fuel was higher when the engine is fuelled by pure diesel, biodiesel blend and emulsion fuels at different engine speeds. The brake power for diesel fuel was higher than B5M10, B10M10, B5M10E3 and B10M10E3 fuels at 1800 rpm speed in percentages of 5.31%, 3.74%, 1.87% and 1.73%, respectively. The lower brake power output for biodiesel blended fuel was due to their lower heating values and result in ignition delay during the combustion. Higher density and lower heating value in biodiesel blended fuels cause lower atomization ratio. This will cause a decrease in the air-fuel mixing rate which reduce the combustion efficiency and improper atomization. The diesel engines can run smoothly with all the prepared emulsion fuels with no engine modification. The emulsion fuels show lower brake power compared to diesel fuel but better than biodiesel blended fuel; this was due to micro explosion phenomenon which produced more atomization ratio and increased combustion efficiency. Ithnin [32] mentioned that emulsion fuel benefits the environment as energy usage of NO_x and PM is reduced to 31.67% and 16.33% respectively and improve the combustion efficiency with 3.89% fuel saving and 3.59% increased thermal efficiency compared to neat diesel [32]. Pullen and Saeed [33] concluded that biodiesel's higher density and oxygenated structure results in proportionally lower energy content. Higher engine power usually decreases according to the lower volumetric energy content of biodiesel and fuel

consumption is expected to increase by 14%. Shahabuddin [34] reported that in comparison to diesel, biodiesel has an early start of combustion and shorter ignition delay of between 1–5° and 0.25–1.0°, respectively [34]. Higher cetane number, lower compressibility and fatty acid composition of biodiesel have been identified as the cause elements for early start of combustion and shorter ignition delay. Biodiesel was also found to have a low heat release rate than diesel owing to its lower calorific value, lower volatility, shorter ignition delay and higher viscosity.
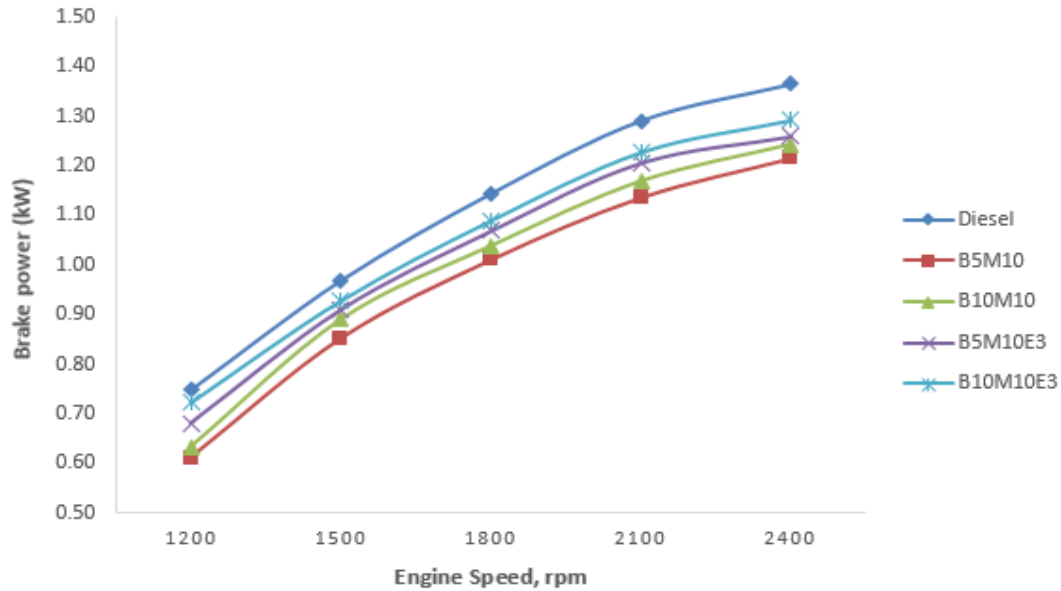
**Figure 3**. Variation of brake power vs. engine speed at partial load.

Low brake specific fuel consumption (BSFC) is always desirable because it is an important parameter that reflects the engine performance. The BSFC is an indicator that determines engine efficiency; it is a measure of utilization of the amount of fuel supplied to an engine to generate a certain brake power. Figure 4 shows that at partial load conditions, the BSFC for diesel fuel is still lower than biodiesel blend and emulsion fuels at different engine speeds. The BSFC for diesel fuel is lower compared to B5M10, B10M10, B5M10E3 and B10M10E3 fuels at 1800 rpm speed in percentages of 6.21%, 5.24%, 2.74% and 1.74%, respectively. BSFC was initially reduced to 1800 rpm and then the increased along with increasing engine speed for all the tested fuels. At high speed, the BSFC increases due to the increased friction while at lower speeds, the BSFC increase due to increased time for heat losses from the gas to cylinder and piston wall. The BSFC of the emulsion fuels is higher than that of diesel fuel because of their lower heating value which causes lower combustion temperature. Mosarof [35] explained that compared with other vegetable oils and petroleum diesel fuels, palm oil is associated with better engine performance, higher specific fuel consumption, and shorter ignition delay. Palm oil also has advantages such as reduced exhaust emission of hydrocarbon, carbon monoxide, carbon dioxide and smoke, but not oxide of nitrogen emission. The higher viscosity of palm oil improves its lubricating properties and anti-wear characteristics, which secures various engine components. Hasannuddin [36] mentioned that the fuel consumption was up to 33.33% including water and lower by 9.57% without water using emulsion. The NO_x and PM were reduced by 51% and 14% respectively by using emulsion. Emulsion fuel offers beneficial properties in terms of lower wear and friction as the water content in emulsion fuel absorbs the heat of combustion and produces a lower exhaust gas temperature to reduce wear. The average percentage of wear debris concentration reduction by emulsion fuel is 8.2%, 9.1%, 16.3% and 21.0% for Iron (Fe), Aluminium (Al), Copper (Cu) and Lead (Pb) as compared to diesel fuel, respectively.
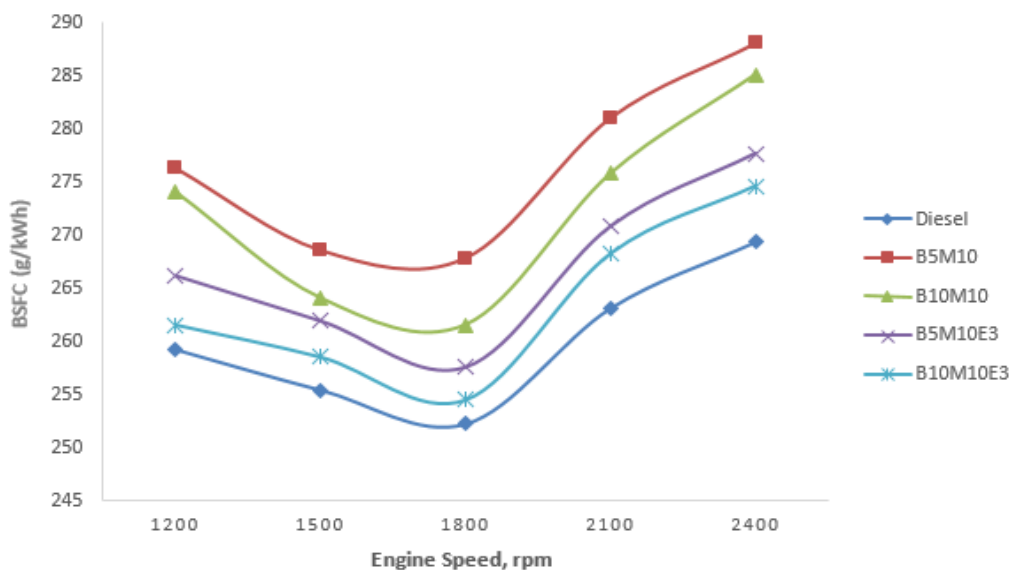
Figure 4. Change of BSFC according to variation engine speed at partial load .

Brake thermal efficiency (BTE) is important to gauge the ability of the engine to operate by using the tested fuels. BTE is defined as the ratio of brake power and total energy supplied by injected fuel, which is the product of fuel heating value and fuel flow rate. Different rates for BTE of each fuel will affect the ratio of thermal power inside the fuel that is transferred to the crankshaft. The BTE value was obtained by calculating the brake power at a certain speed and the calorific value of the tested fuel. Figure 5 represents the BTE percentage values obtained for different test fuels operating at engine speeds of 1200–2400 rpm at partial load. The BTE for diesel fuel is higher compared to B5M10, B10M10, B5M10E3 and B10M10E3 fuels at 1800 rpm speed in percentages of 11.27%, 9.86%, 9.85%, and 7.04%, respectively. The BTE for the emulsion fuels is lower than the standard diesel. This is due to the lower heating value of the emulsion fuels compared to that of diesel, thereafter affects the spray formation and results in poor atomization during the premixed combustion phase, hence increasing the fuel consumption. Zhang and Balasubramanian [5] proved that alcohol increase BTE compared to biodiesel and butanol-biodiesel blends that lead to a maximum of 1.6% increase in the BTE.
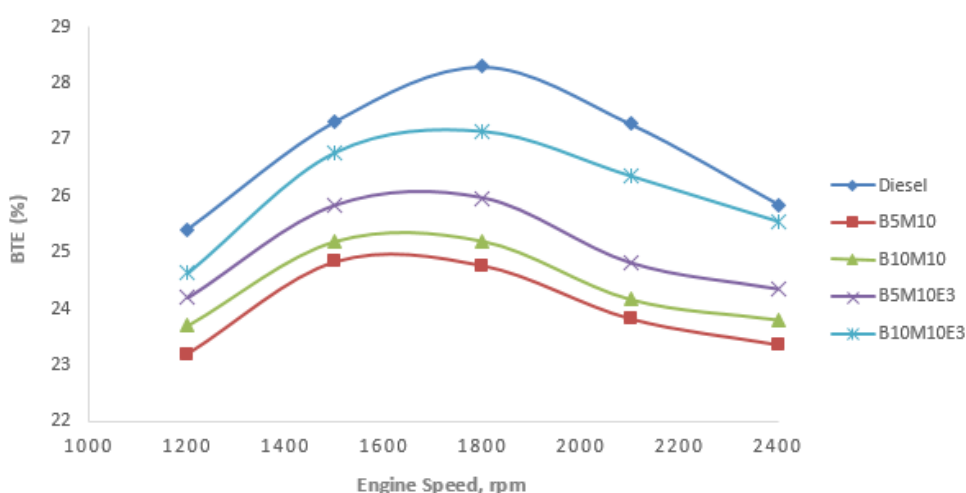

Figure 5. Change of BTE according to variation engine speed at partial load.

The NO_x is composed of nitric oxide (NO) and nitrogen dioxide (NO_2). The formation of NO_x is closely related to the temperature generated in the combustion chamber. The concentration of oxygen and the way the fuel is injected also affects the production of NO_x out of the exhaust.

Liaquat (2013) explained that the presence of oxygen in the combustion chamber will increase combustion activity and increase temperature and produce high NO_x formation. Figure 6 shows that at partial load conditions with an engine speed of 2400 rpm, diesel fuel produces 75 ppm compared with other fuels B5M10, B10M10, B5M10E3 and B10M10E3 with percentages of 8%, 5.33%, 13.33% and 10.67% lower, respectively. This is due to the addition of 10% methanol for B5M10 and B10M10 which reduces the temperature in the chamber burning. Figure 6 shows the same trends in the plot where, at 1200–1800 rpm, the formation of NO_x slowly increased, yet it gradually decreased at high engine speeds. Around 5.4%–15% reduction in NO_x emissions were noticed for emulsion fuels compared to diesel at the lower speed range of 1200–1800 rpm. This observation is because the emulsion fuel was enhanced thus reducing the combustion temperature inside the combustion cylinder. The principal mechanism for NO_x emission formation is controlled by peak temperatures occurring in the cylinder. Reducing in-cylinder temperatures will lower NO_x emissions. During evaporation of water, in the emulsion fuel delivered into the cylinder, heat is absorbed from the cylinder charge. This will cause cylinder temperature to reduce due to the high specific heat capacity of water. Beyond 1800 rpm, there was an increase in the NO_x emission for all tested fuels. Adding biodiesel blended fuels and emulsion fuels result in greater fuel consumption at higher engine speeds. The emulsion fuels were burning faster in the combustion chamber with a higher combustion temperature. More specifically, NO_x emission is mainly caused by high temperature developed by flame and water, owing to its cooling effects. Many researchers have previously reported that NO_x emissions increase the use of biodiesel fuels for all fractions, compared to diesel [43, 50, 51]. Among biodiesel blended fuel and emulsion fuel samples, B5M10E3 provides the lowest NO emissions, followed by B10M10E3, B5M10, B10M10 and diesel. As the biodiesel fraction in blend fuel increases, the amount of increase in NO_x emission increases. The increasing number of unsaturated fatty acid methyl ester in biodiesel, especially poly-unsaturated esters such as linoleic acid, require higher combustion temperature. Another method to reduce NO_x emission is the use of exhaust gas recirculation (EGR) but it would increase the PM emission. By increasing ignition delay, PM emissions can be reduced which enhances premixed combustion. These strategies may increase in-cylinder temperature resulting in higher NO_x emissions. Mondal and Mandal [52] concluded that there is a 41% reduction in NO_x emissions while using emulsion fuel compared to mineral diesel. This is attributed to the heat sink effect which tends to reduce temperature and NO_x formation. Varuvel et al. [53] observed that by adding small quantities of diesel with biofuel, the NO_x emissions decrease significantly and approach the performance of neat biofuel.
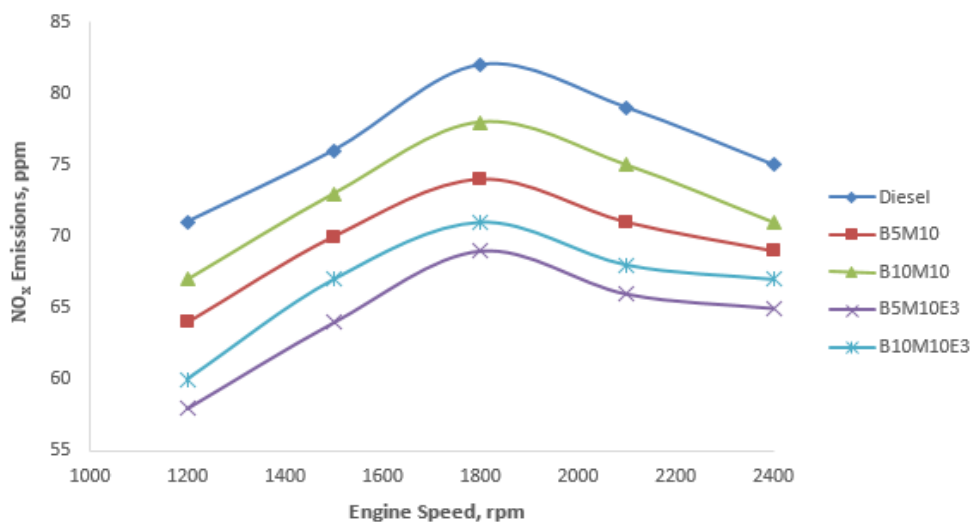
Figure 6. Measured NO_x emission at partial load and at various engine speeds for using diesel, B5M10, B10M10, B5M10E3 and B10M10E3 and the deviations in NO_x emission compared to the diesel engine data.

Carbon monoxide (CO) is the result of the combustion of hydrocarbons, in which less efficient internal combustion will produce CO. Figure 7 shows that at partial load with an engine speed of 2400 rpm, diesel fuel produces the highest CO of 0.34 compared to B5M10, B10M10, B5M10E3 and B10M10E3 with percentages of 14.7%, 29.41%, 38.24% and 44.12% lower, respectively. This matter is assisted by the oxygen content in biodiesel fuel, oxygen in water and methanol which also contributes oxygen to enable more complete combustion and reduce the harmful gases polluted by diesel engine combustion. As an overall conclusion, B10M10E3 produces lower CO emissions with 47.05% lower. Emulsion fuels will cause an increase in oxygen content and influence micro-explosions in the combustion chamber. Overall, at high air/fuel ratios due to low cylinder temperature during combustion, CO is not efficiently oxidized to CO_2. The real process at high loads and when richer fuel/air mixtures are used, the existing carbon in each fuel is not exposed to sufficient levels of oxygen to burn into CO_2. In this study, using B5M10 and B10M10 led to the decrease of CO emissions possibly due to combustion improvements. This is attributed to biodiesel's oxygen content particularly in the fuel-rich zones of the combustion cylinder. Addition of water into B5M10 and B10M10 decreased the CO emission during the combustion of water-containing B5M10 and B10M10 emulsions; the water encapsulated by the fuel droplets vaporized the earliest due to its low boiling point. The fact is that the latent heat of vaporization of water is 2260 kJ/kg is significantly higher than those of diesel (250) and biodiesel (200). Increasing the engine speed led to an increase in emitted CO because there is limited time available for cylinder filling in an intake stroke resulting in less oxygen availability [42, 54, 55]. Most researchers agreed on the benefits of oxygenated fuel on emissions such as Manigandan et al. [56] who had observed that by using corn biodiesel blends in a diesel engine at partial load, the CO concentration of the diesel is 40% higher than biodiesel blends. Vigneswaran et al. [57] reported a 15% reduction in CO emissions during the ideal mix of DWS (89% diesel + 10% water + 0.2% surfactant). This caused secondary atomization because micro-explosions increase the fuel surface area by forming tinier droplets of fuel. The impact for combustion of fuel is the process of surface reaction thus better combustion and fewer emissions of CO was found in case of emulsified diesel.
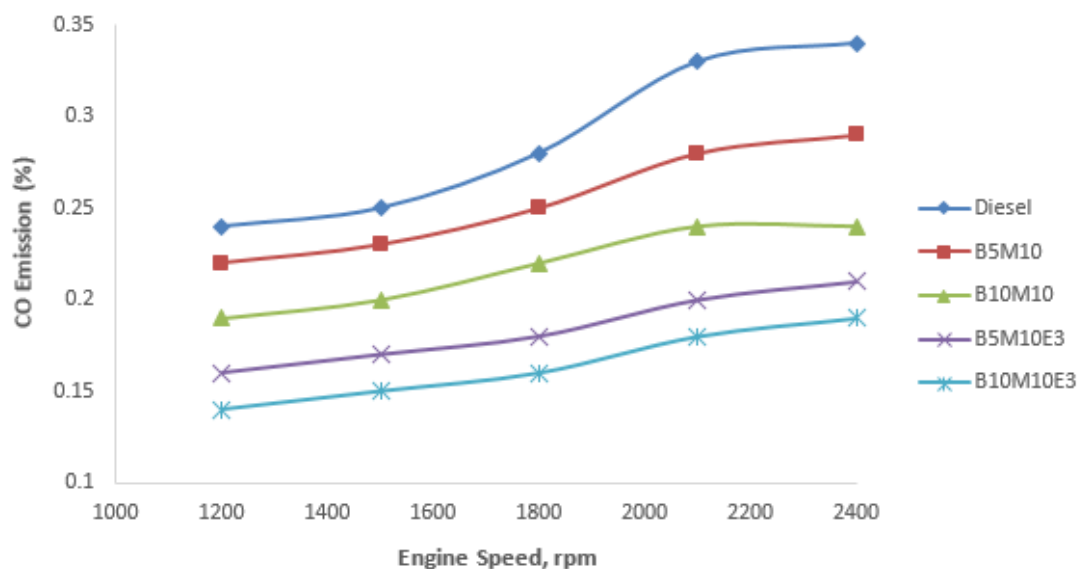

Figure 7. Measured CO emission at partial load and at various engine speeds for using diesel, B5M10, B10M10, B5M10E3 and B10M10E3 and the deviations in CO emission compared to the diesel engine data.

3.3 Engine Particulate Matter Analysis

The investigation method is to identify the increase or decrease of PM concentration with speed change. Increase in PM occurs due to the following two reasons: i) higher temperature in the

cylinder during main injection event that leads to a reduction of lift‑off length, thereby reducing charge air entrained into the main injection event, and ii) product releases from the pilot injection event have high temperatures and contain reduced oxygen content [37]. Figure 8 shows that at the partial load position, diesel fuels overall alternative fuels and gave the highest result for particulate matter concentrations. Meanwhile, B5M10E3 and B10M10E3 fuels show a reduction of PM of 62.96% and 59.26% compared to diesel at 1200 rpm. This may be due to the dispersed water droplets found in the water in the biodiesel blend fuel that has resulted in the occurrence of micro‑explosions and can assist in more complete combustion [38]. This happens because 1800 rpm speed is the ideal speed for this diesel engine, and thus leading to the most complete combustion. The amount of PM concentration is also low compared to other speeds at high load positions. At this high load position, it can be concluded that PM concentration is low for water in biodiesel blend fuel compared to biodiesel blend fuels only. The excellent potential of water in biodiesel blend fuel is because it shows a pro‑environment fuel compared with diesel fuels and biodiesel blend fuels when the percentage for PM reduces [39].
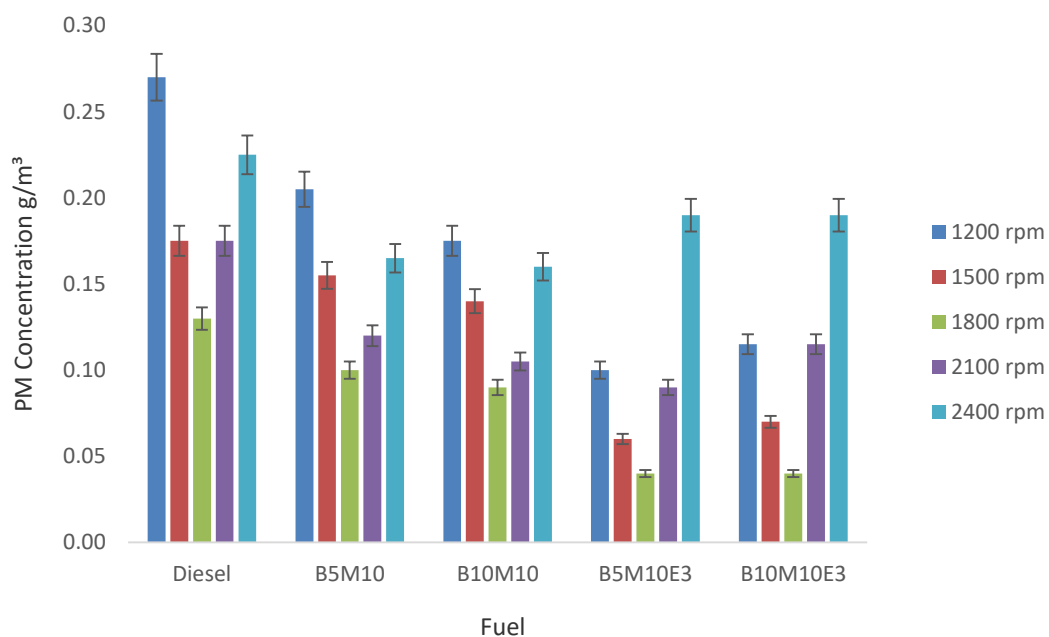

Figure 8. Particulate matter at partial load (50%).

The results showed that PM was reduced by using alternative oxygenized fuel compared to diesel fuel. The oxygen barrier of biodiesel fuel has activated the combustion process in the combustion chamber. It is renewable, biodegradable and oxygenated fuel consisting of triglycerides of long-chain saturated and unsaturated fatty acids. It is converted into monoglycerides by transesterification process. Fuel has low sulphur and aromatic content and contains nearly 10% oxygen which helps it to burn completely. It has been confirmed that the usage of biodiesel as a fuel reduces PM to a greater value [40, 41]. Meanwhile, the PM for emulsion fuel is lower than biodiesel blend fuels. The occurrence of micro‑explosion may have helped to complete the combustion and reduce PM. This eventually increased premixed combustion duration and more ignition delay period which then creates more time for fuel‑air mixing leading to a reduction in PM formation. Similarly, water droplet evaporation reduces peak cycle temperatures. This leads to the reduction of NO_x emissions [42, 43]. Oxygenated fuel additives like methanol is a fuel that has a chemical compound containing oxygen. These oxygenated additives simply enhance combustion and the ignition quality of fuel by improving the cetane number, thereby reducing the ignition temperature of particulate [44]. It is concluded from the above work that biodiesel blends, emulsified and additive fuels greatly reduced both PM and NO_x emission. The

combination of diesel, alcohol and biodiesel could be a promising fuel to reduce PM to a great extent and improve the thermal efficiency of the diesel engine satisfactorily.

Particulate surface morphology is a method of identifying the particulate accumulation rate tested with the eyes on five types of test fuels namely diesel, B5M10, B10M10, B5M10E3 and B10M10E3. Particulate matter is collected using a fibre filter placed on the exhaust part. All samples of diesel, B5M10, B10M10, B5M10E3 and B10M10E3 were collected at 1800 rpm speed and partial load. Scanning Electron Microscope (SEM) was used to view PM morphology. Figure 9 demonstrates the particulate surface morphology for diesel, B5M10, B10M10, B5M10E3 and B10M10E3 at 1800 rpm and 50% load. There was a particle state that was ripped and stacked to illustrate many of the collected particles for diesel sample. For the morphology of B5M10 (b), the PM collected was slightly lower than diesel at 1800 rpm speed and partial load conditions. The B5M10 sample had no particle conditions that were split and overlapped, where the collected particles were less than the diesel. B10M10 (c) was found to have no ripped particle, and the cylinder fibre shape indicates that the particles collected were less than the diesel and B5M10 samples. Particulate surface morphology for B5M10E3 (d) was found to have less PM compared to the other three samples namely diesel, B5M10 and B10M10. The shape of the cylinder fibre was visible, and there was a space between the cylinders, which demonstrated that the particles collected were lower than diesel, B5M10 and B10M10. Particulate surface morphology for B10M10E3 (e) was found to collect the least PM as compared to the other four samples. The form of cylinder fibre was visible, and there was a black space between the cylinders indicating the particles collected were lower than the others. The attributes are higher fuel oxygen content and the occurrence of micro-explosion phenomenon with emulsion fuels [43, 45].
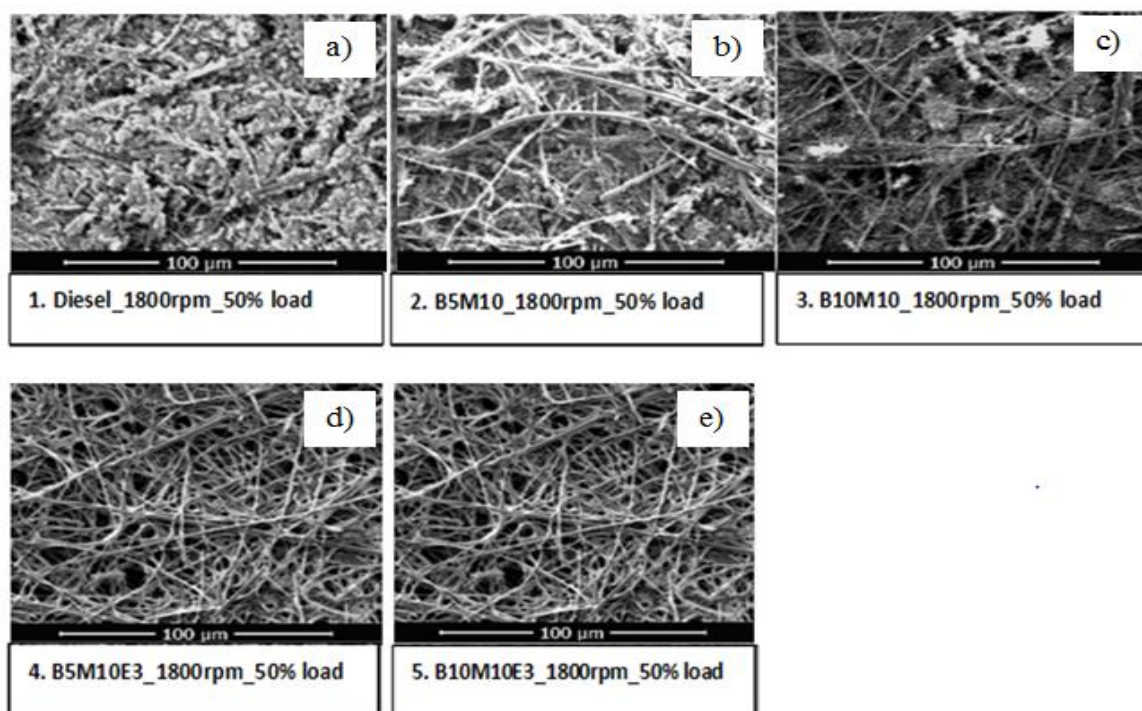
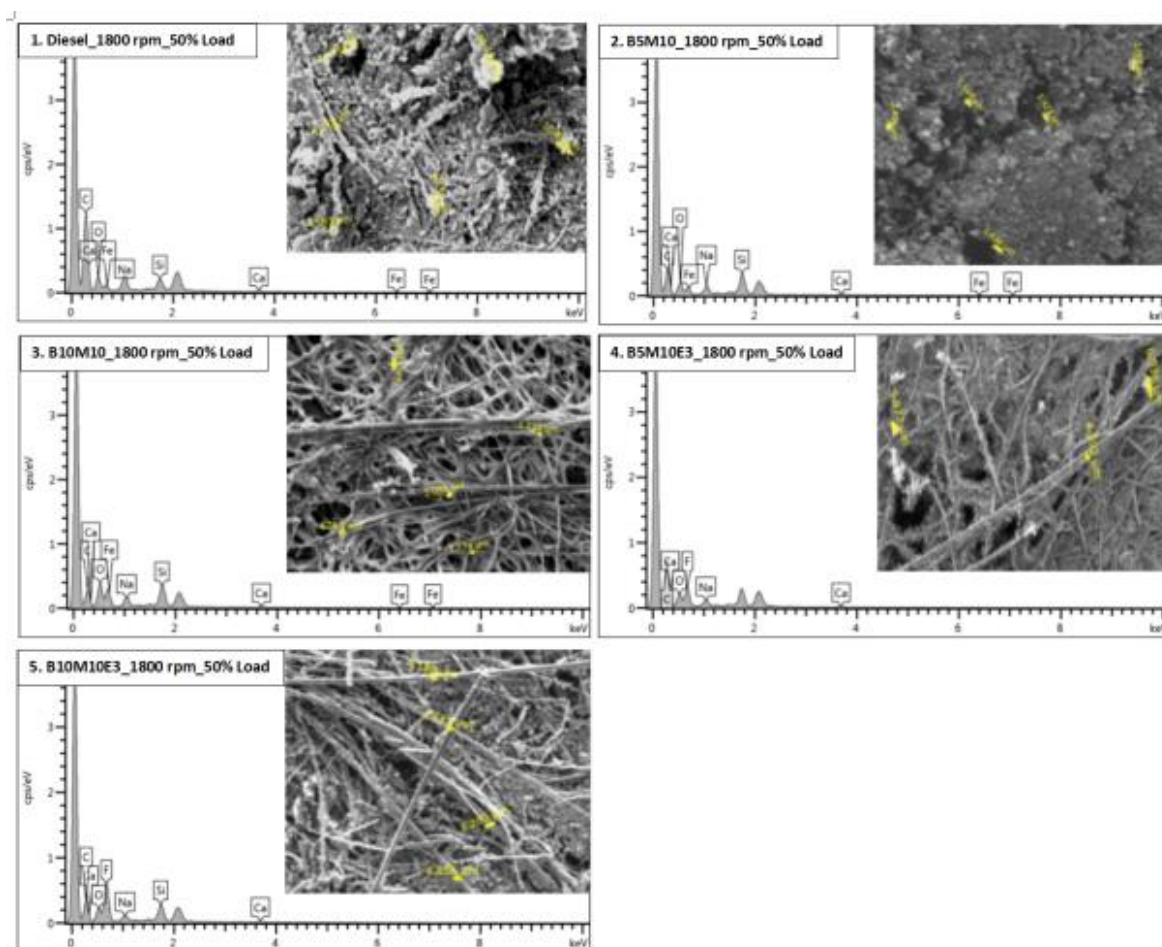**Figure 9**. Particulate surface morphology at partial load with speed 1800 rpm.

The modes of nucleation and aggregation are two crucial concepts of particle size distribution grouped by the particle's diameter. The particle size distributions with the diameter of 3–30 nm are particles which are grouped in nucleation mode. They are composed of SOF and sulphates. Moreover, these particles are mainly formed during the condensation (cooling), generally through homogeneous and heterogeneous nucleation mechanisms whereas the accumulation (aggregation) mode includes the particles with the diameter size of 30–1000 nm, where it

corresponded to the agglomerated soot and adsorbed volatile material. The agglomeration of nucleation mode particles, which are formed by the condensation of volatile material, can be changed to the formation of accumulation mode particles [46]. Table 5 also demonstrates the particulate composition and size for diesel, B5M10, B10M10, B5M10E3 and B10M10E3 at 1800 rpm and 50% load. There are trace metals present in the PM when they are analysed in elemental composition. While friction and wear take the major contribution, fuel and lubricating oil additives are some of the other primary sources of these trace metals. The trace metal concentration per unit mass of particulate decreased with the increase of engine load despite evidence to the contrary with PM mass emission. This finding could be correlated to the source of the trace metals. The decrease in trace metal concentration per unit mass of particulate matter with an increase in engine load is due to the higher engine friction at lower engine loads and more fuel burning with more engine load. Crust metals (Ca, Fe, Mg and Al) were generally in higher trace concentrations in particulates emitted by a mineral diesel engine. Nevertheless, anthropogenic metal (Pb, Cr, Zn, Na) were generally in mineral diesel at higher engine loads. Benzene soluble organic fraction (BSOF) is a marker of particulate toxicity [47].

SEM analysis reveals the various components of the diesel comprising C, O, Ca, Fe, Na and Si of particulates collected from the exhaust of a YANMAR TF120 diesel engine. Carbon has shown the highest accumulation of 1.2 cps/eV with diesel compared to other elements Ca, O, Fe, Na, Si and Ca. The samples consist of collections of primary particles agglomerated into aggregates. Individual particles range in appearance from clusters of spherules to chains of spherules. The diameter of spherules resulting from combustion in diesel forming soot particles was between 10 μm and 20 μm. The B5M10 and B10M10 samples have indicated a reduction in carbon accumulation of 0.2 cps/eV and 0.15 cps/eV, respectively as compared to diesel. This result might be due to the complete combustion efficiency as the consequence of the higher oxygen content of biodiesel and oxygenated fuel [9]. The B10M10 demonstrated an increase in oxygen composition of 0.2 cps/eV compared to 0.1 cps/eV for diesel. Various elements, including Ca, Fe, Na and Si had no significant changes in the amount detected for diesel, B5M10 and B10M10. The B5M10 and B10M10 produced smaller particle size compared to diesel in which the diameters are from 1.5 μm to 7 μm. The B5M10E3 and B10M10E3 samples have indicated a reduction in carbon accumulation of 0.6 cps/eV and 0.3 cps/eV, respectively as compared to diesel. Similarly, this outcome is due to the ultrasonic emulsification that caused the decrease in the total burning charge of the foam in turn leading to a micro-explosion. The presence of oil drops in the emulsion demonstrates a heterogeneous nucleation centre.

Hence, their size and number density are the main factors for successful explosive boiling. More importantly, the flame speed should exceed a certain critical value to induce the explosive boiling of the liquid phase. Moreover, the foam would decay in a 'smooth' regime due to fluctuations in capillary pressure [48]. The addition of water decreases the combustion temperature due to higher latent heat of vaporization which further lead to an increase in the ignition delay of the combustion. The in-cylinder pressure and heat release rate also decreased with the presence of water. The energy content per mass for the fuel charge also decreases [49]. The B5M10E3 and B10M10E3 fuels have shown the same reading for oxygen which was 0.2 cps/eV. Various elements, including Ca, Na and Si, were found to have no significant changes in the amount detected for diesel, B5M10, B10M10, B5M10E3 and B10M10E3 except Fe. The B5M10E3 and B10M10E3 were found to produce a slight increase in the size of particle compared to B5M10 and B10M10 diesel in which the diameters are 3 μm to 7 μm.

Figure 10. Particulate surface morphology, particulate composition and size at partial load with a speed of 1800 rpm.

4. CONCLUSION

In the present study, successful analysis of biodiesel blends, emulsion fuel and diesel on test rig are studied for all engine speeds and partial loads. The study is performed to measure the properties (density, viscosity, cetane number, calorific value and stability period of emulsion), performance (torque, brake power, brake specific fuel consumption, brake thermal efficiency, and emission (particulate matter, nitrogen oxides, carbon monoxide, and carbon dioxide) of biodiesel blends, emulsion fuel and diesel. Results from tests are concluded as follows:

Testing various biodiesel blended fuels, B5M10 and B10M10 the optimal result for performance are obtained using B10M10 fuel. Testing various emulsion fuels, B5M10E3 and B10M10E3 the best results for performance and emissions are given by B10M10E3. Testing stabilized emulsion fuels, the optimal fraction is obtained for B5M10E3, with surfactant 2%, biodiesel 5%, methanol 10% and water content 3%. Using B10M10E3, a slight decrease in engine torque and brake power, 1.74% increase in SFC, 7.04% decrease in brake thermal efficiency, 10.67% reduction in NO emission and 44.12% reduction in CO emissions were obtained compared to diesel. From the particulate test and results, the best results for lower particulate concentrations are shown by B5M10E3. However, particulate surface morphology for B5M10E3 was found to have less PM compared to the other three samples namely diesel, B5M10 and B10M10. Evaluating the test results, the best results for lower soluble organic and dry soot are given by B5M10E3. Methanol was used in the dispersed phase; vegetable oils were used in the continuous phase and sorbitan

monooleate 'Span 80 and Tween 80' was used as a surfactant. The emulsion destabilized with time due to agglomeration, sedimentation and rapid coalescence of methanol droplet. The phenomenon of micro-explosion resulted in secondary atomization thus better combustion of emulsion fuel than pure diesel. The premixed combustion due to the ignition delay enhanced the combustion efficiency and thus increase of heat release rate resulting in higher brake thermal efficiency. Other impressions shown are for better combustion of emulsion due to longer spray penetration, larger spray angle, larger fuel-specific area and air-entraining in fuel spray due to higher momentum of emulsion than those of pure diesel. Lastly, it can be concluded that more experimental work is needed for the optimization of the emulsion fuel specification as well as engine operating conditions. An organized method of emulsion fuel in internal combustion engines will be cost-effective as well as environmentally friendly. As the reserved fossil fuel is limited, the successful use of emulsified diesel fuel may extend the dependency of market demand on fossil fuel for years to come.

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