



Performance, emissions and carbon deposit characteristics of diesel engine operating on emulsion fuel



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ABSTRACT

Little is known about the effects of using emulsion fuel for extended operation hours. Emulsion fuels comprise of water, low grade diesel fuel (D2) and surfactant in the ratio of 10:89:1 v/v% (E10) and 20:79:1 v/v% (E20). The characteristics of carbon deposits from an engine after a run of 200 h were examined. The carbon deposit analysis performed were macroscopic/microscopic photographs, thermogravimetric analysis (TGA), metal element analysis (MEA) and Fourier transform infrared (FTIR). Increasing water in emulsion fuel decreased particulate matter (PM) and nitrogen oxides (NO_x) altogether. TGA results observed that carbon deposit of E10 engine differed from E20 and D2 engines in terms of its characteristics, which includes darker colour of carbon deposit and the higher volatile content, while the MEA results observed that the elemental metal concentration in the carbon deposit was reduced with increasing water content. The intensity of the spectrum from C–H group for the carbon deposit E10 engine was higher compared to carbon deposit D2 and E20 engine respectively due to a complete combustion. Therefore, it was observed that 10% or less water content delivered better fuel consumption, emissions, and carbon deposit.

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1. Introduction

Global warming causes elevated global temperatures, rising ocean level and volatile storm occurrences. The phenomena mentioned above are the result of the substantial emission released by fossil fuel combustion from the industrial and transportation sectors. As diesel engines deliver the most efficient internal combustion; they generate a significant amount of particulate matter (PM) and nitrogen oxides (NO_x) emissions. A popular cylinder method to reduce the NO_x production rate is by injection of steam or water into the air intake/cylinder and in emulsion form with fuel. The intake steam or water injection uses the combination of a valve and flow meter to control the flow rate [1–3]. As for the cylinder

steam or water injection, the steam or water is injected into the combustion chamber in a separate unit or injector [4].

Ishida et al. observed an increase of 1% in the specific heat of the gases in the burned zone and a 50% reduction in NO_x emission with water injection in the intake [5]. Stanglmaier et al. claimed that water injection system improves the improvement in both NO_x and PM emissions, under steady-state and transient conditions [6]. Southwest Research Institute and Delphi Diesel Systems have developed a system which is integrated with electronic control unit and controls the pump that delivers metered volumes of water to an electronic injector. The method enables NO_x emission to be reduced by 42% [7]. Tauzia et al. concluded that higher water flow rate contributes to longer ignition delay, higher peak heat release, lower NO_x emission but deteriorated production of carbon monoxide (CO) and hydrocarbon (HC) [8]. Steam injection method (SIM) with exhaust gas recirculation (EGR) was performed using 20% steam and 10% EGR ratios of fuel mass injected per cycle. This

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method yielded nitrogen monoxide (NO) emissions reduction of up to 48.3% and an increase of 3.5% in specific fuel consumption [9]. Another setup with a combination of SIM, turbocharging and Miller cycle was also carried out and at the optimum condition resulted in the reduction of NO, HC, CO and carbon dioxide (CO₂) by 48%, 35%, 64% and 8% respectively. With this combo, the brake power and thermal brake efficiency were increased by 17% and 11%, respectively [10]. A two-zone combustion model was performed on the application of SIM on a diesel engine fuelled with an ethanol-diesel blend for 15% ethanol content and 20% steam ratios. The model generated an increase in effective efficiency and effective power of maximum 12.5% and 4.1% respectively while the NO emission was reduced up to 34% [11].

Most researchers agree that emulsion fuel can reduce simultaneously the PM and NO_x emissions [12,13]. Bulent and Mudhafar investigated the effects of water (5, 10 and 15%) concentration in a biodiesel nanoemulsion. Biodiesel nanoemulsion produced lower NO_x emissions and soot opacity but increased the fuel consumption and CO emissions [14]. In 2013, Prakash et al. reported that emulsion fuel of bio-oil derived from the pyrolysis of waste wood increased the brake thermal efficiency (up to 7.4%) and decreased the smoke (up to 26.7%) [15]. Furthermore, in 2015, Utilisation of emulsions obtained from wood pyrolysis oil and jatropha methyl ester showed increase in brake thermal efficiency (up to 7.4%), decreased hydrocarbon (up to 37.9%) and smoke opacity (up to 27.8%) [16]. Basha and Anand investigated the effect of nanoparticles (alumina, carbon nanotubes (CNT), and cerium oxides) on emulsion fuel and noted encouraging improvements in combustion, performance, and emission characteristics [17–19]. Blending two nano particles namely alumina and CNT in Jatropha biodiesel gave a reduction of NO_x by 23%, increased the brake thermal efficiency and smoke opacity reduction by 1.5% [20]. There have been several studies on the characteristics of carbon deposit from engines running on emulsion fuel; however, more detailed analyses such as thermogravimetric analysis is needed to clarify these findings [21,22]. Carbon deposits can be defined as heterogeneous mixtures consisting of carbon residue, oxygenated resinous organic material and carbonaceous combinations [23], resulting from an incomplete combustion of fuel and thermal cracking of impurities in the lubricant oil [24]. The formation of carbon deposits may significantly affects the engine performance and drivability. It is formed on piston top and cylinder head surfaces, which in turn caused problems with the engine due to the significant increase in compression ratio and surface temperature [25].

Numerous studies have investigated carbon deposits generated from a range of conventional and alternative fuels, but only a few focused on emulsion fuel. Kweonha and Inseok in 2004 did the durability test using a six cylinders direct injection diesel engine with a turbocharger running on emulsion fuel with 15% water content [21]. After the durability test, the head was dismantled, and whitish deposits were found in what was supposed to be a black surface. But, there was no detailed analysis of the carbon deposits other than photographs to justify the result of the study. In 2006, Tzirakis et al. used emulsion fuel for buses travelling over 50,000 km. They observed normal engine operability and lubricant oil conditions; however, there is no analysis done regarding the carbon deposits [26]. The latest research on carbon deposits was performed in July 2010, where Kawasaki Heavy Industries Ltd. tested the performance and emissions of their ships. In January 2011 emulsion fuel was applied on their ships until recently [27]. However, the exhaustive results on the long term operation of these ships are still unpublished.

Although many works on the properties, formation, stability, combustion, performance and emissions of emulsion fuel were performed, there were still very limited detailed studies on the

carbon deposit characteristics related to water content. Two novelties were born from this study: Firstly, it is the use of emulsified diesel fuel with two different water concentrations (10% and 20%). Secondly, long-term operation of different engines is performed instead of a single engine with various fuel for short term operation. Furthermore, detailed analysis of carbon deposits was carried out which are macroscopic and microscopic photographs, thermogravimetric analysis (TGA), metal element analysis (MEA) and Fourier transform infrared (FTIR) analysis. The macroscopic and microscopic photographs were examined for the effect of SPAN 80 as the surfactant, as it produces an emulsion that is opaque and milky in colour. The TGA determined the details of carbon deposits that can be categorized by quantities of volatile and non-volatile fractions. This analysis helped to confirm which fuel delivers better combustion while explaining the micro-explosions phenomena too. MEA was carried out because emulsion fuel tends to reduce wear of the moving parts in the combustion chamber. The concentration of elemental metal on the carbon deposits helped to determine the wear of the moving parts. Meanwhile, the FTIR analysis could give light on the details of chemical functionality in the effects of water introduction in carbon deposits. Finally, the best water percentage is determined from the correlation of the performance, emissions and carbon deposit characteristics of a diesel engine.

2. Experiment details

Emulsion fuel with two different water content were used: 10% (E10) and 20% (E20) (Fig. 1). The fuels used diesel fuel (D2) as base fuel and tap water; they were prepared using a mixer at 2500 rpm for 5 min. The details of the D2 are shown in Table 1. To stabilise the emulsion fuel, 1 volumetric percentage of SPAN 80 was added as a surfactant. Firstly, a test run was done with the focus on fuel consumption, PM, NO_x, CO and exhaust temperature. The hydrocarbon emission was not observed due to the problems with its sensor. The engines were run at a constant maximum speed at low load (1 kW) and high load (5 kW). The schematics of the engine test setup are shown in Fig. 2. The specification of the Testo 350 emission analyser is provided in Table 2. Testo recorded the emission every 5-s for 2 min, and an average was considered for the discussion. A K-type thermocouple probe connected to a Kyowa data acquisition system was used to measure the exhaust gas temperature.

The PM emission was measured, conforming to the California Air Resources Board standards. Exhaust gas was diluted with heated air and led into a tunnel by suction of a compressor. The temperature of the diluting air was maintained at 50 °C by a heater, while the ratio of hot air to exhaust gas was set to 10:1. A Teflon filter (Millipore FHLP04700) was used to sieve the PM. The filter had a diameter of 47 mm and equipped with an orifice of 0.45 μm. PM formation was measured by weighing the filter before and after the experiment. Before the measurement, the filter was stored in a closed container equipped with silica gel for 12 h to control the moisture in the filter. The weighing device used was a Quartz Crystal Microbalance Mettler AE240 with an accuracy of 0.00001 g. Three new sets of 5 kW diesel engines generator without any modification were utilized for the three types of fuel based on works done in previous researches [28,29]. The alternator was calibrated, and all losses in the alternator such as armature current, copper, friction and windage were taken into consideration. The load applied to the engines was controlled by a voltage regulator (acting as a 5 kW of load bank) with a set of Philips QVF 137 Halolite lamps. The specifications of the engines are tabulated in Table 3. The tests were conducted for 200 h, with the first 100 h at a load of 3 kW and the remaining hours at 1 kW with a constant speed of 3000 rpm. The level of the lubricant was thoroughly monitored,

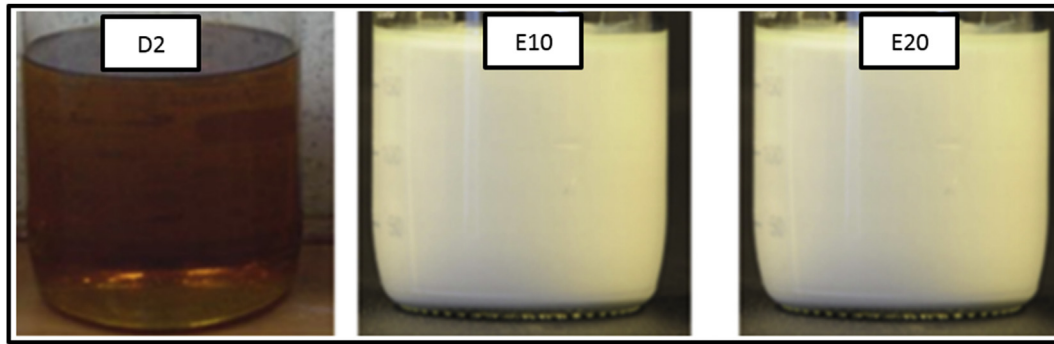


Fig. 1. Fuel samples used in the experiment.

Table 1
D2 fuel characteristic.

Properties	Unit	D2
Calorific value	MJ/kg	45.28
Cloud point	°C	18
Density @ 15 °C	kg/L	0.854
Total sulphur	mass%	0.28
Viscosity @ 40 °C	cSt	4.64
Distillation temperature, 90% recovery	°C	368
Flash point	°C	93
Pour point	°C	12
Cetane number	–	54.6
Carbon	wt%	84
Hydrogen	wt%	12.8
Sulphur	wt%	0.2
Nitrogen	wt%	<0.1
Oxygen	wt%	3.9

and a mixer at 60 rpm was equipped with the fuel tank to ensure the emulsion fuel was in a continuously homogenous state.

Before the engine tests were conducted, the fuel injector, cylinder head, and piston crown were thoroughly cleaned. After that, the engine was dismantled, and carbon deposits from the piston

were collected. The carbon deposits were stored overnight in a humidity box. Dried carbon deposits were milled and filtered to a size of 100 μm to ensure a good heat and mass transfer properties. A visual analysis on the carbon deposit was performed using KEYENCE VHX 2000 microscope, whereas a thermal analysis was conducted with a Q50 TGA. The weight of the carbon deposit was continuously recorded with each increasing temperature. Table 4 shows the test conditions for the TGA. The concentration of different metal elements in the carbon deposit samples from each engine was evaluated to understand the wear of various parts and material from the combustion chamber. Since many sliding parts were involved, it was expected that the debris in the carbon deposit would be generated from different components. A characteristic level of the metal element for diesel engine was advised by Haycock and Hillier [30], which can be seen in Table 5. Dried deposit samples were analysed for their elemental metal contents such as iron (Fe), copper (Cu), chromium (Cr) aluminium (Al) and lead (Pb) using NexION 350Q ICP-MS spectrometer. The infrared spectrum gave various details and proposed a range of chemical functionality. The chemically functional groups of the carbon deposit were determined using a Bruker Tensor II FTIR Spectrometer with a 4 cm^{-1} resolution in the 4000–650 cm^{-1} scan range with 16 scan numbers.

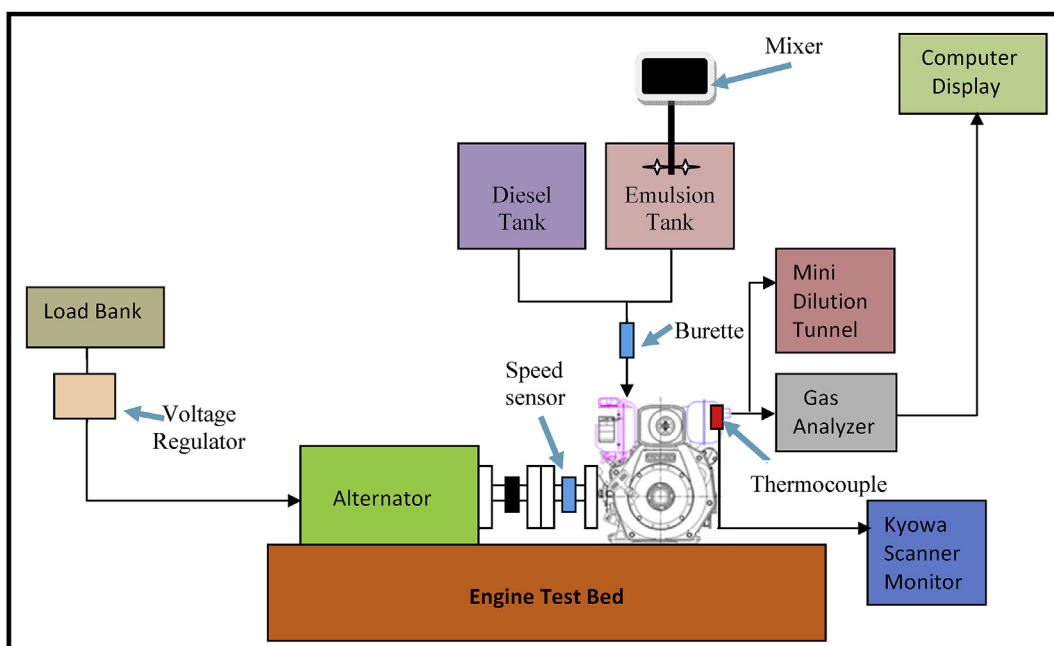


Fig. 2. Schematic diagram of the engine emission test setup.

Table 2
Specification of the Testo 350 emission analyser.

Measurement	Range	Accuracy	Resolution
CO (H ₂ compensated)	0–10,000 ppm CO	±5 ppm CO (0–199 ppm CO) ±5% of mv (200–2000–2000 ppm CO) ±10% of mv (2001–10,000 ppm CO)	1 ppm CO (0–10,000 ppm CO)
CO _{low} (H ₂ compensated)	0–500 ppm CO	±2 ppm CO (0–39.9 ppm CO) ±5% of mv (40–500 ppm CO)	0.1 ppm CO (0–500 ppm CO)
NO	0–4000 ppm NO	±5 ppm NO (0–99 ppm NO) ±5% of mv (100–1999.9 ppm NO) ±10% of mv (2000–4000 ppm NO)	1 ppm NO (0–3000 ppm NO)
NO _{low}	300–1500 ppm	±2 ppm NO (0–39.9 ppm NO) ±5% of mv (40–300 ppm NO)	1.1 ppm NO (0–300 ppm NO)
NO ₂	0–500 ppm NO ₂	±5 ppm NO ₂ (0–99.9 ppm NO ₂) ±5% of mv (100–500 ppm NO ₂)	0.1 ppm NO ₂ (0–500 ppm NO ₂)

Table 3
Test engine specifications.

Parameter	Specification
Model	Mr. Mark MC-D6500E diesel engine
Engine Type	One cylinder, air cooled, vertical engine
Bore/Stroke	86/72 mm
Maximum speed	3500 rpm
Compression ratio	18.7
Displacement	416 cc
Combustion chamber	Swirl chamber
Fuel system	Injection: Direct injection Pump: Mechanical pump Injection timing: 13° CA ± 1 BTDC Fuel injection pressure: 220 bar Fuel injection nozzle: Needle valve, 4 nozzle holes with hole diameter 0.2 mm Needle valve lifting pressure: 150 ± 0.5 bar Length of pressure pipe line: 43 cm

The samples were prepared using the KBr pellet technique, and the obtained spectrum for each carbon deposit sample was compared.

3. Results and discussion

Higher water content at 30% and 40% were used initially, but it was discontinued due to an intense vibration of the engine. Therefore, emulsion fuels with 10% and 20% water content were

Table 4
Test conditions for TGA.

Parameter	Unit	Characteristics
Sample size	mg	1–2
Weighing precision	%	±0.01
Isothermal temperature accuracy	°C	±1
Sensitivity	µg	0.1
Start temperature	°C	40
Final temperature	°C	1000
Heating rate	°C/min	20
Purge gas flow oxidative (O ₂)	ml/min	100
Non-oxidative (N ₂)	ml/min	100

Table 5
Trace element for medium/large diesel engines.

Element	Possible significance
Iron (Fe)	General wear, liner scuffing
Aluminum (Al)	Piston scuffing, ingested dust
Copper (Cu)	Cu/Pb bearings, bronze bushing
Lead (Pb)	Cu/Pb bearings
Chromium (Cr)	Chromed rings, possibly coolant

used in this experiment. Various other works explain in detail about the performance and emissions of emulsion fuel. However, in this study, the performance and emissions data were used to determine the correlation between emission and carbon deposit characteristics and consequently determined the optimum water content with the focus on fuel consumption.

3.1. Fuel consumption

Fig. 3 shows fuel consumption against the calorific value. Two methods were adopted for the fuel consumption; firstly by considering diesel + water as total fuel and secondly by considering diesel as total fuel. Considering the emulsion as total fuel, the fuel consumption was greater than D2, whereby the fuel consumption of E10 and E20 were higher by 14.28% and 25.73% respectively. The increase in water concentration increased the density, viscosity and cetane number, but it decreased the calorific value. Most of other works concluded that fuel consumption increases due to the lower calorific value of water and the increments are more noticeable at higher engine load. The water content reduces the diesel fraction, and hence the overall calorific value is reduced. This consecutively results in increased fuel consumption for an equal amount of desired power output. Currently, the addition of oxygenated additives (dimethyl ether, diethyl ether) increases the calorific value of the fuel and hence reduces the fuel consumption. In addition, presence of carbon nanotube in emulsion fuel reduces fuel consumption due to the high surface area to volume ratio and enhances the heat transfer rate and heat conduction properties [31].

Considering diesel fraction only as a fuel, the fuel consumption from E10 and E20 were lower than D2 by about 2.77% and 5.55% respectively. Abu-Zaid observed that the fuel consumption of emulsion fuel decreases to a maximum of 15% [32]. It means that as water quantity increases in an emulsion fuel, a higher amount of diesel fuel is replaced by the equal amount of water resulting in a lower amount of diesel fuel that remain in emulsion fuel. The micro-explosion causes secondary atomization of the initial spray; it makes better contact between the small fuel particles and air; it improves the combustion process. The combustion efficiency improves due to the air-entrainment in the spray, higher premixed combustion, the excess of air ratio and reduction in combustion temperature. A similar decreasing trend in fuel consumption was modelled and experimented in the works of Kannan [33,34]. Ignition delay causes the fuel to be injected when the piston is nearer to the top dead centre, thereby reducing the total volume in cylinder compared to the diesel setting, which increases the temperature due to higher compression inside the cylinder before the injection of fuel [35].

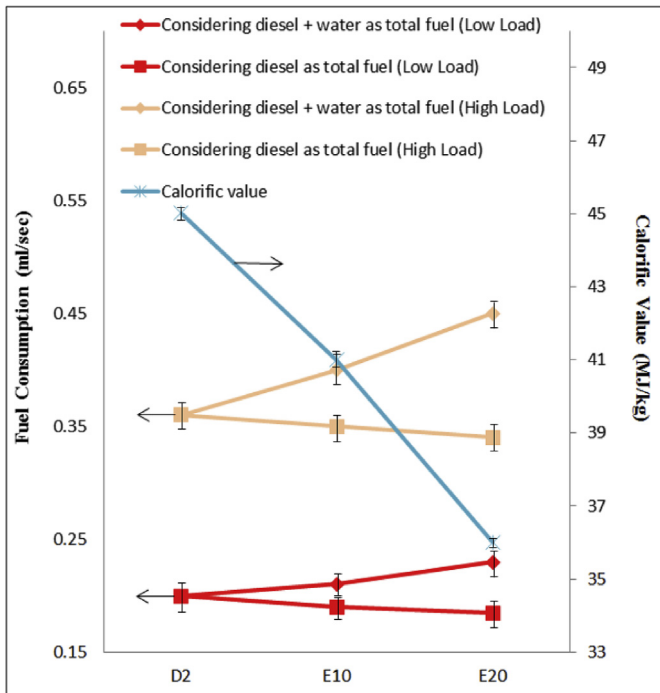


Fig. 3. Fuel consumption and calorific value.

3.2. Emissions

Fig. 4 shows the emission of NO_x , CO and the exhaust temperature. The fuel's oxygen and nitrogen contents together with the temperature affect the NO_x formation [36]. The higher temperature and presence of oxygen increased the NO_x emission with the increment in load as more energy was released. The higher content of water in emulsion fuel resulted in the lower NO_x and lower exhaust temperature by 43.33% and 40.10% respectively. The higher percentage of water resulted in higher NO_x reduction with E20 compared to E10. The lower NO_x emission was caused by the absorption of heat by the water content which caused a drop in the flame temperature. Also, the ignition delay caused reduced oxygen concentration, which in turn reduced NO_x emission [37]. The NO_x emission was defined by temperature to break the triple bond molecule of nitrogen gas. It followed the Zeldovich mechanism which states that the emission of NO is reinforced by high temperatures [38]. Here, the presence of water lowered the flame temperature and thus the NO emission decreased. Furthermore, by the ionization of water, oxygen atom was consumed during the formation of OH radicals and thus reducing the NO concentration even more [39].

Emulsion fuel tends to decrease NO_x while causing increment in CO emissions. This is due to the lower combustion temperature caused by the absorption of heat by water and the higher viscosity of the fuel. Higher water percentage also tends to reduce the exhaust temperature. The lower temperature of the combustion causes a reduction in the oxygenating time for the CO, hence the conversion reaction of CO to CO_2 becomes slower. When the temperature is lower than 1400 K due to the heat absorbed by the water, the oxidation process of CO will cease. In this experiment, emulsion fuels tended to increase CO emission up to 90.33%. Thus, the CO emission of the emulsion fuels was greater than D2. For emulsion fuel, CO_2 emission increases when CO decreases and vice versa. The cause for the increase in CO emission of emulsion fuels is not solely the unburned fuel resulting from the low combustion

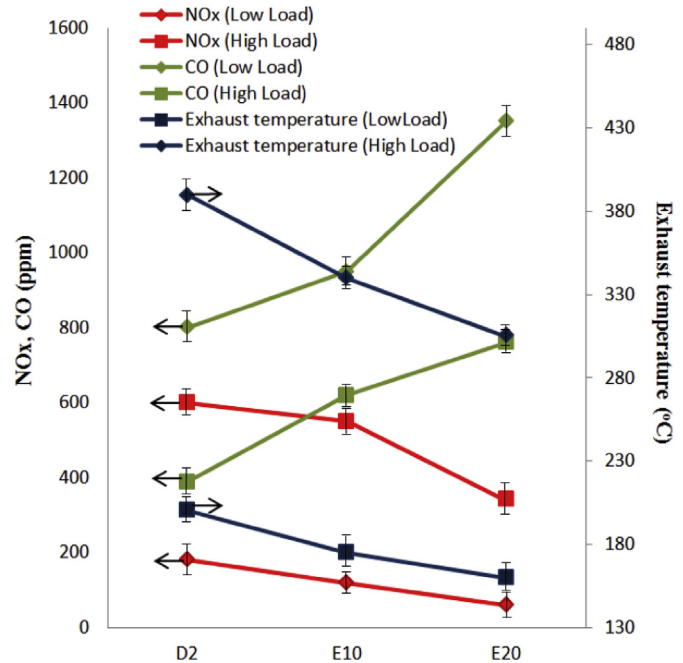


Fig. 4. Nitrogen oxides, carbon monoxide and exhaust temperature.

temperature but is also due to the increasing viscosity of the fuel, where it increases the fuel chance to hit the combustion chamber wall and left unburned [40]. The selection of water percentage should form a major criterion due to the proven improvement in fuel consumption and emissions reduction. Fig. 4 shows that the percentage of water below than 10% should be considered for emulsion fuel. The increase in CO emission should also be considered while reducing the NO_x . Also, the presence of oxygenated components such as diethyl ether, dimethyl ether and diethylene glycol dimethyl ether can help to reduce CO emission, which should be considered in forming the emulsion fuel [41].

Fig. 5 shows the relation of PM and NO_x emissions. Emulsion fuel proved to reduce both PM and NO_x emissions simultaneously, in contrast to other NO_x controlling methods. The PM emission from E10 and E20 decreased by 5.67% and 8.36% from D2 respectively. The fall in PM and NO_x emissions were determined by the increasing water content. The PM emission was lower because of the micro-explosions phenomenon causes a rise in OH radical concentration. Furthermore, the heat of evaporation absorbed by the water fraction lowers the temperature and reduces the creation of soot particles [42]. The water tends to weaken soot growth in gas phase species, retards the soot growth and improves the soot burnout by enhancing the value of oxidisation species [43]. For diesel engines, there is a trade-off between NO_x and PM production. The methods to reduce NO_x caused the PM to increase. Typical approaches include either exhaust gas recirculation (EGR) and diesel particulate filter (DPF) or a combination of both. However, those after-treatment systems for NO_x and PM reduction are expensive [44]. The addition of EGR leads to the formation of soot, increases reactivity and changes the oxidation mechanism from external to internal burning [45,46]. The incorporation of the DPF into the exhaust line implies an increase in the pumping work due to the additional backpressure introduced and the corresponding increase in the fuel consumption especially at a high load [47]. The lower NO_x emission is also observable in other studies that utilized water injection in the intake manifold. The reduction pattern of the PM emission is similar to water injection that tally with the

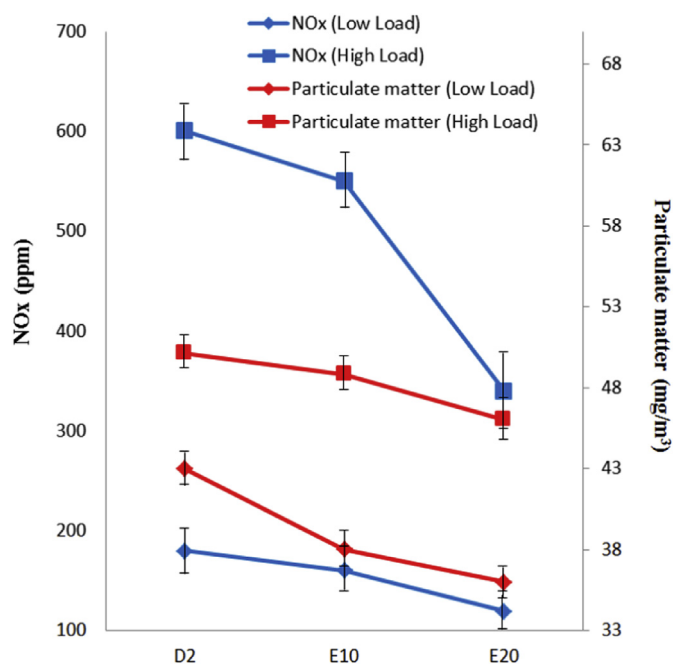


Fig. 5. Nitrogen oxides and particulate matter.

increasing water content. Thus, fuel emulsification is considered as one of the best technique to reduce the emissions of NO_x and PM altogether. Table 6 summarises the results of various studies on emulsion fuel in diesel engine on water percentage range, operating conditions, fuel consumption and emissions.

3.3. Carbon deposit

The major cause of carbon deposit is a complex reaction that occurs among the components, fuel, blow-by gases and lubricant oil. Most of carbon deposit originates from the fuel, while the remaining comes from the lubricant oil. Carbon deposit has a negative impact on the heat transfer process in the combustion chamber, emissions, combustion and maintenance costs. The analysis of carbon deposit in diesel engines is complex due various on engine sizes, technologies and test conditions. However, this study attempts to refer other researchers who have applied similar conditions to determine the best analysis on carbon deposit.

3.3.1. Macroscopic and microscopic analysis

Fig. 6 shows macroscopic and microscopic photographs of carbon deposit formation on piston crowns after the 200-h durability test. Carbon deposit can be defined as a heterogeneous mixture, which consists of carbon excess, carbonaceous combinations and oxygenated resinous organic material that stay together from incomplete combustion [23]. From the figure, it appears that there was some formation of white dusts on the piston from both carbon deposit E10 and E20 engines, and they were spread around the piston crown. Apparently, the white dust on the piston in the carbon deposit E10 engine was less than that of the carbon deposit E20 engine. It may be formed as a by-product of the oxidation of the surfactant [21]. Based on the microscopic observation, the carbon deposit structure of E10 engine was blacker and softer. In addition, there were some metals and other elements found in the carbon deposit of all engines, though it appears that they mostly found in the carbon deposit D2 engine. On the other hand, the amount of carbon deposit in the E10 engine was less than in the carbon deposit D2 and E20 engines. This reduction may be caused by a less

complete combustion of E20 as compared to E10. Based on the previous works, micro-explosions that occurred from E20 was not as efficient as E10 due to the different water droplet sizes [65].

3.3.2. Thermogravimetric analysis (TGA)

The carbon deposit can be categorized by the quantity of volatile and non-volatile fractions [37]. The non-volatile fraction can be separated into fixed carbon and ash. The quantity of each portion can be identified in the percentage weight loss from TGA as shown in Fig. 7. In temperature of $40\text{ }^\circ\text{C}$ – $550\text{ }^\circ\text{C}$ the volatile content was vaporized by thermal decay from carbon deposit samples, while for non-volatile fraction under oxidative environment is shown in $550\text{ }^\circ\text{C}$ – $650\text{ }^\circ\text{C}$. The non-volatile fraction was the remaining carbon deposit samples containing fixed carbon and ash, where the residual of non-volatile-non-oxidized fraction is called ash, and the evaporative section of the non-volatile fraction is known as fixed carbon. The trends of weight loss to the fixed carbon appeared to be constant after $650\text{ }^\circ\text{C}$ for all carbon deposits. The residual ash was measured when deducting the volatile fraction and fixed carbon from original carbon deposits at $1000\text{ }^\circ\text{C}$.

The carbon deposit derived from E10 engine showed the uppermost volatile content followed by carbon deposit D2 and E20 engines (Fig. 8). The carbon deposit derived from E20 engine was less volatile mostly because of the fuel dilution by a higher percentage of water in emulsion fuel. Furthermore, E20 was less effective micro-explosions as compared to E10 and has lower calorific value. The carbon deposit E20 engine contained similar fixed carbon as carbon deposit D2 engine and lowest in the volatile fraction as compared to other fuels. The carbon deposit that has higher amount of volatile matter is flammable and shows the ability to decay in the engine [66]. The creation of fixed carbon is due to the carbonization process, which is the advanced improvement of the solid carbon. Emulsion fuels reduce NO_x emissions caused by increasing ash values compared to the carbon deposit D2 engine. Consequently, the presence of a certain percentage of water in emulsion fuel would affect the carbon deposits on the volatile, fixed carbon and ash content. Based on the results, the water percentage of 10% and lower in the emulsion fuel is suitable due to micro-explosions phenomena and calorific value to maintain the performance and reduce the emission.

3.3.3. Metal element analysis (MEA)

MEA were obtained for Fe, Cu, Cr, Al and Pb. As illustrated in Fig. 9, the Fe found in the carbon deposit might be produced by the wear of cylinder wall, piston rings and valves. The carbon deposit D2 engine produced the highest level of Fe by 1.66 ppb than the carbon deposit E10 (1.2 ppb) and E20 engine (1.1 ppb). The low amount of Fe in emulsion fuel engines is related to less soot formation due to micro-explosions and thus there were less wear. The higher water content in emulsion fuel has lowered the metal element content in carbon deposit. Hence, it can be said that the emulsion fuel gives lower wear and friction. This reduction can be correlated due to presence of water which lowers the temperature of the combustion thus, decreases wear [67]. The Al indicates the wear on the piston or ingested dust. The values of Al for carbon deposit D2 engine was 0.41 ppb whereas carbon deposit E10 engine and E20 engine were 0.32 ppb and 0.1 ppb respectively. From this result, it is proven that emulsion fuels can decrease metal debris value of Cr, Cu and Pb better than D2.

3.3.4. Fourier transform infrared (FTIR) analysis

The infrared spectrum is designed based on the concentration of electromagnetic radiation at frequencies that related to the vibration of specific groups of chemical bonds from within a molecule. It displays a comprehensive range of chemical functionality. Fig. 10

Table 6
Various studies on emulsion fuel in diesel engine.

Type of emulsion	Ref. fuel	Engine tested	Operation conditions	Fuel consumption	Engine emission characteristics	References/Year
W/D, 10–40% water, injection timing	Diesel	Four stroke, WC, 6 cylinder, CR:17.6	700–2000 rpm	↓0.1–2.6%	CO: No effect ↓NO _x :2.6–29%	[48]/2001
W/D, 10 & 15% water	Diesel	4-cylinder, four stroke, AC, DI, 7188 cc (Automotive30 Test Bed)	1700 rpm 5,8 & 10 bar (Load)	No significant	In average- 10% water: ↓Soot:68% ↓HC:52% ↓NO _x :10% 15% water: ↓Soot:75% ↓HC:33% ↓NO _x :18%	[49]/2002
10% water, W/D two phase, D/W/D three phase, 5% oxygenated diglyme additive	Diesel euro 2	Four stroke, NA, WC, DI, V:3856 cc	1000–5000 rpm	↑4–15%	↑CO:15–95% ↓NO _x :6–17%	[50]/2004
W/D, 10% water	Diesel	4-cylinder, four stroke, WC, IDI, turbocharger, 1900 cc (Renault F8Q)	European Emission Directive 70/220, amendment 2001/C 240 E/01	↑2–15%	↑CO:7–270% ↓NO _x :42–63% ↓PM:4–20% ↓HC:24–66%	[51]/2005
W/D, 5–15% water	Diesel	4-cylinder, four stroke, WC, CR:21.50, V:1753 cc (FORD, XLD 418)	1000–5000 rpm	15% water is the highest by: ↑5–15%	15% water is the highest by: ↓CO:19–27% ↓NO _x :18–34% ↓PM: 64–70%	[52]/2006
15% water, W/D two phase, D/W/D three phase	Diesel	4-cylinder, four stroke, WC, CR:17, V:3856 cc (Isuzu UMBD1)	1600 rpm	↑2–15%	↑CO:75–100% ↓NO:5–23%	[53]/2006
W/D, 10% water	Ultra low sulphur diesel	1-cylinder, four stroke, NA, AC, DI, CR:15.5, 773 cc (Lister Petter TR1)	1200–1800 rpm 2 & 4 bar (IMEP) 0 & 20% EGR	↑5–17%	↑CO:61–150% ↓NO _x :26–42%	[54]/2009
W/D, 10–30% water,	Diesel	1-cylinder, four stroke, NA, IDI, CR:21.07 (Ricardo E6)	1080–2040 rpm 2–20 Nm injection timing, 20–45° BTDC compression ratio 14–22	30% water is the highest by: ↑32–79%	Not available	[55]/2009
W/D, 5–30% water	Diesel	4-cylinder, four stroke, WC, DI, CR:21.5, V:1450 cc	1000–5000 rpm	30% water is the highest by: ↑13–77%	30% water is the highest by: ↓NO _x :35–47% ↓ET:23–30%	[56]/2010
W/D, 20% water	Diesel	4-cylinder, four stroke, WC, DI, CR:17, V:1500 cc, VGT, DOC	1400–2100 rpm Injection strategy, EGR	No significant	↓NO _x :14–50% ↓PM: 69–91%	[57]/2011
W/D, 10–30% water	Diesel (Jordanian)	1-cylinder, four stroke, NA, AC, DI, CR:15.5, 1433 cc (Lister 81)	1000–1600 rpm	30% water is the highest by: ↑13–19%	30% water is the highest by: ↓PM:35–43% ↓ET:7–16%	[58]/2011
W/D, 10% water	Ultra-low sulphur diesel	4-cylinder, four stroke, WC, common rail, CR:18.5, V:2500 cc (Toyota 2KD-FTV)	800–3600 rpm (25%, 50%, 75% and 100% load)	↑15–28%	↑CO:20–440% ↓NO:7–25% ↓ET:6–18%	[59]/2013
W/D, 10% water, nano-organic additives	Diesel	4-cylinder, four stroke, WC, turbocharger common rail, CR:18.5, V:2500 cc	1000–4000 rpm	↑4–11%	CO: Not consistent ↓NO:7–25%	[60]/2013
W/D, 10–30% water	Diesel	4-cylinder, four stroke, WC, DI, 1450 cc (Automotive30 Test Bed)	1000–3000 rpm	30% water is the highest by: ↑19–70%	30% water is the highest by: ↓CO ₂ :28–38% ↓ET:23–30% ↓NO _x :62–71%	[61]/2013
W/D, 5–20% water,	Diesel (Euro 2)	1-cylinder, four stroke, NA, AC, DI, CR:19.03, 406 cc	3000 rpm 25–100% loads	20% water is the highest by: ↑15–25%	20% water is the highest by: ↑CO:20–166% ↓NO _x :19–40% ↓PM:27–50%	[62]/2015
W/D, 15% Glucose solution (20% glucose and 80% water)	Diesel	2-cylinder, four stroke, NA, AC, DI, CR:16.5, 1600 cc	1500 rpm 25–100% loads	Not available	↑CO:7–270% ↓NO _x :6–45% ↓Soot:12–63%	[63]/2015
W/D, 10% water, ZnO nanoparticles	Diesel	1-cylinder, four stroke, NA, AC, DI, VCR, 661.45 cc	25–100% loads	Not available	↑CO:50–60% ↓NO: 29–45%	[64]/2016

*The symbols ↑/↓ and value in % represents the trend and intensity of variations observed in each study compared to diesel fuel and cannot be used for comparison among different studies.

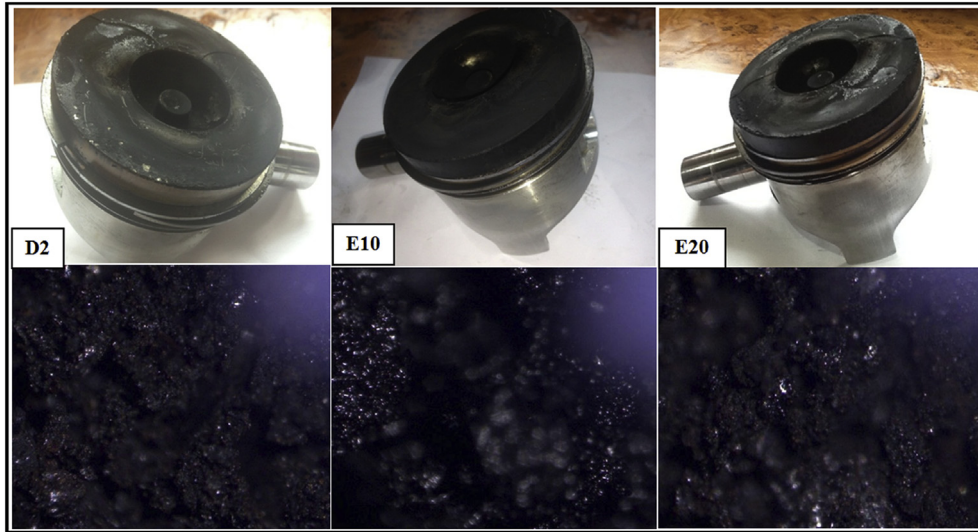


Fig. 6. Macroscopic and microscopic photographs of carbon deposit formation on piston crown after the durability test.

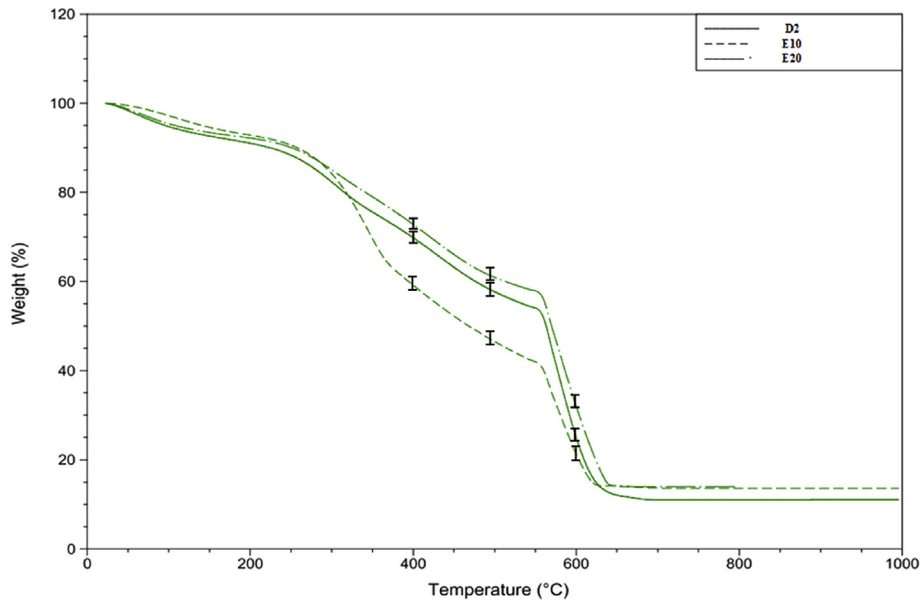


Fig. 7. Carbon deposit weight loss with temperature.

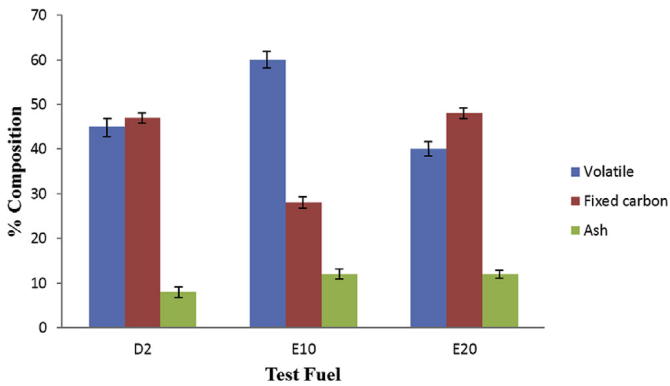


Fig. 8. Carbon deposit composition for test fuels.

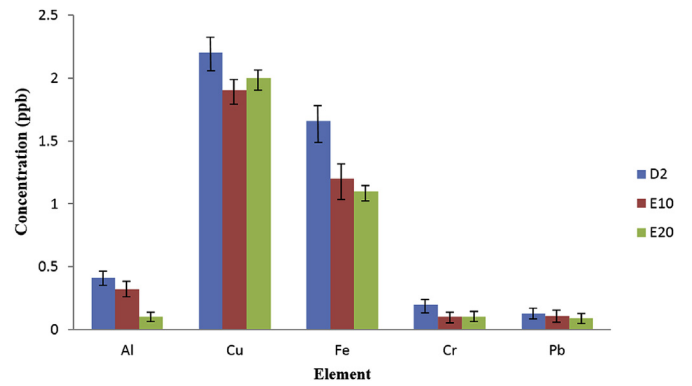


Fig. 9. Element metal concentration in carbon deposit sample.

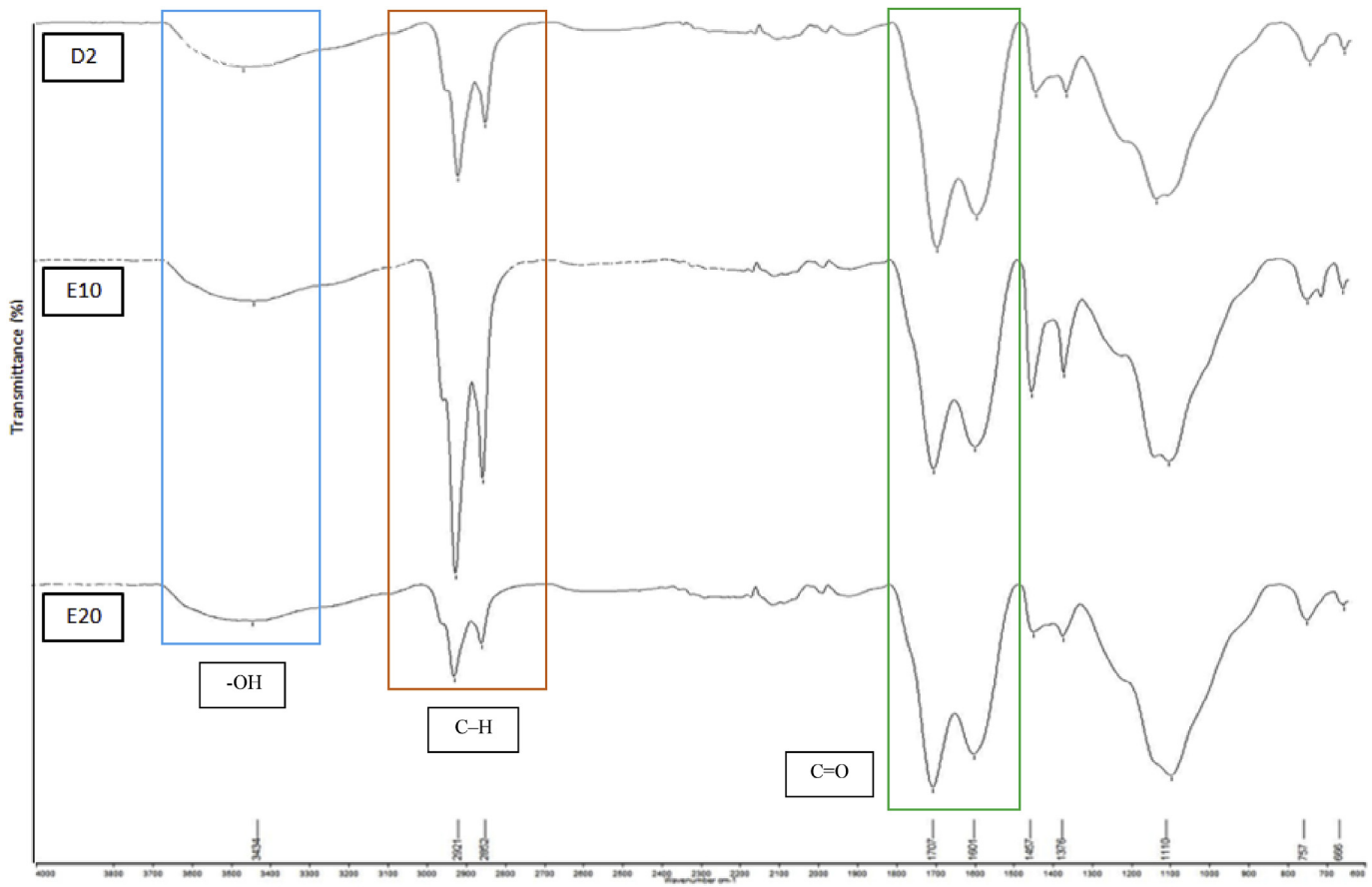


Fig. 10. FTIR spectrum of carbon deposit sample.

show the FTIR spectra of carbon deposit samples derived from D2, E10 and E20 as test fuels. For these three samples, the spectra were found at similar positions. The range of spectrum for oxygen functionality or $-OH$ can be found at $3500\text{--}3200\text{ cm}^{-1}$, whilst unsaturated aldehydes or $C=O$ at $1710\text{--}1665\text{ cm}^{-1}$ and for alcohols, carboxylic acids, esters, ethers or $C-O-C$, the spectrum was at $1320\text{--}1000\text{ cm}^{-1}$. The spectrum near $3000\text{--}2852\text{ cm}^{-1}$ was attributed to alkanes $C-H$. The occurrence of $-OH$ might be due to the water or the primary amine ($N-H$ bond) spectrum ($3467\text{--}3434\text{ cm}^{-1}$).

The amine functional group comes from nitrogen atom in the air which then combined in combustion and produced carbon deposit. The presence of water did not have any impact to the formation of carbon deposit due to the same spectrum intense of the carbon deposit D2 engine. Deposits obtained from each sample show the spectra intensity between 2920 and 2950 cm^{-1} and $1365\text{--}1467\text{ cm}^{-1}$. These spectra are attributed to the characteristics of vibration of $C-H$ group [25,68]. Evidently, the intensity of the spectrum of $C-H$ group for the carbon deposit E10 engine is higher than carbon deposit D2 and E20 engine. This might be attributed to some chemical changes due to the effectiveness of micro-explosions phenomena to produce a complete combustion. The spectrum in the region of 1706 cm^{-1} indicates ketones, aldehydes, carboxylic acids, lactones, acid halides, anhydride, amides and lactams that show a strong $C=O$ stretching absorption band.

4. Conclusions

All the results obtained from emulsion fuels had been compared

with D2. From these results, it can be concluded that:

1. Considering only the diesel fuel content in emulsion fuel, the fuel consumption of emulsion fuel is found to be improved.
2. Increasing water in emulsion fuel increases CO emission because of lower exhaust temperature and calorific value. However, emulsion fuel is the best method to decrease PM and NO_x altogether.
3. The macroscopic and microscopic result showed the presence of white dust in both emulsion fuel engines. It was apparent that the white dust in carbon deposit E10 engine was less than the carbon deposit E20 engine. The carbon deposit structure of E10 engine was less in amount, blacker, and softer compared to others. Furthermore, some metal and other elements can be easily identified for carbon deposit D2 and E20 engine.
4. TGA result showed that carbon deposit E10 engine gives (a) higher volatile fraction (b) less fraction of fixed carbon and (c) largest fraction of ash carbon in comparison to carbon deposit D2 and E20 engine.
5. Increasing water content has reduced the element metal concentration in carbon deposit, the most is by carbon deposit E20, about 66.26% from carbon deposit D2 due to lower combustion temperature.
6. FTIR analysis confirms the presence of alkyl groups, aromatic rings and the oxygen molecular inside carbon deposit. The presence of water did not impact to the formation of carbon deposit due to the same $-OH$ spectrum intense of carbon deposit D2 engine

7. The suitable range of water percentage to produce emulsion fuel is an important criterion to maintain the performance without degrading the emissions. The range 10% and lower can be considered as suitable water percentage as found in this study and other research findings.

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