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Performances, Emissions and Soot Properties from a Diesel-Biodiesel-Ethanol Blend Fuelled Engine

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Abstract

The aim of this study is to provide experimental results for assessing diesel-biodiesel-ethanol (DBE) blended fuels as future technology for efficiently using these three fuels and for reducing engine emissions. The results included engine performance, brake specific emissions and soot properties for diesel-biodiesel blended with 0%, 5%, 10% and 20% ethanol tested at steady speed of 1800 rev/min under different engine loads. It was found that DBE blends can reduce NOx, CO_2, volatile organic fractions and particulate mass-number concentration with improved thermal and combustion efficiency while slightly decreased the particle size.

Keywords: Diesel-biodiesel-ethanol; Diesel engine; Combustion characteristics; Emissions; Soot agglomerates

Introduction

The diesel vehicle industry is under pressure to find methods to meet the dual purpose of reducing reliance on fossil fuels and engine emissions. Vehicle emissions from current available diesel technologies are almost close to the statutory limits and those limits are expected to be more stringent in the near future. As such, many investigations have been carried out on using new fuels to reduce vehicle emissions without the need of modifying the engine [1].

Blending biodiesel in the base fuel of ULSD has the advantage of reducing HC, CO and PM emissions but biodiesel would increase NOx, number of nano-sized particles and other oxygenated compounds (such as aldehydes and ketones) which may serve as the major impediment to the application of diesel-biodiesel blends in motor vehicles [2]. Besides biodiesel, ethanol is one of the low-cost oxygenates for use as a blended fuel for effective reduction on thermal NOx due to its relatively higher latent heat of evaporation and effective reduction on PM due to its relatively high oxygen content. Diesel-ethanol blended fuel is more effective in reducing NOx emissions but the two fuels could not be mixed directly without the assistance of an additive [3]. Biodiesel can be used as an additive in preventing the separation of ethanol from diesel. As such, diesel-biodiesel-ethanol (DBE) blended fuel has been investigated in recent years so that the disadvantages of either diesel-biodiesel or diesel-ethanol blended fuels can be overcome while maintaining the engine performance close to standard diesel with reduced emissions [1,4]. Shi et al. [5] studied the emission characteristics of DBE (75% diesel, 20% methyl soyate and 5% ethanol) on a Cummins-4B diesel engine and found a significant reduction in PM emissions and 2-14% increase of NOx emissions. Kwanchareon et al. [1] studied the phase diagram of DBE at different purities of ethanol and different temperatures. They also examined the fuel properties of the selected blends and their emissions performance in a diesel engine. They concluded that a blend of 80% diesel, 15% biodiesel and 5% ethanol was the most suitable ratio because of the acceptable fuel properties and the reduction of emissions. Jha et al. [6] studied the emission characteristics of DBE on a new engine and a used engine and found a significant reduction in NOx emission in the new engine with increased ethanol while with the used engine under similar conditions, an increased NOx emission was observed. Barabas, et al. [7] studied the key properties of DBE and found that blends containing 5% ethanol had the same or very close density and viscosity to standard diesel.

Apart from the regulated gaseous emissions, numbers of particles emitted by diesel engines in nano-size range have become a significant health risk problem in many cities around the world. Kim, et al. [8] reported that a DBE of 80% diesel-15% biodiesel-5% ethanol was much more effective for the reduction of particle number and particle mass when compared with B20 (80%diesel-20%biodiesel), being the most popular biodiesel blend fuel studied in different countries. Armas, et al. [9] studied the particles emitted from an urban bus fueled with DBE of 60% diesel-30% biodiesel-10% ethanol and found that DBE blends achieved lower number concentration of small-sized particles than diesel-ethanol blends. Full comprehensive of different soot properties would help understand the source-related PM2.5 health mechanism. It is known that oxygenated fuels may result in lower PM emissions by producing soot with nanostructure possessing higher soot reactivity [10].

Up to present time, there are still few studies for comprehensively evaluating the potential use of low-cost oxygenated fuel – DBE blends. Therefore, the aim of this study is to evaluate the effects of DBE blended fuels on engine performance, combustion characteristic, gaseous emissions and soot properties for better understanding.

Experimental Investigation

Experimental set up and specifications of test engine are shown in Figure 1 and Table 1 respectively. The diesel engine was coupled with an eddy-current dynamometer. The engine is a 4334 c.c. ISUZU 4HF1 engine with a compression ratio of 19, having a maximum torque of 285 Nm at 1800 rpm.

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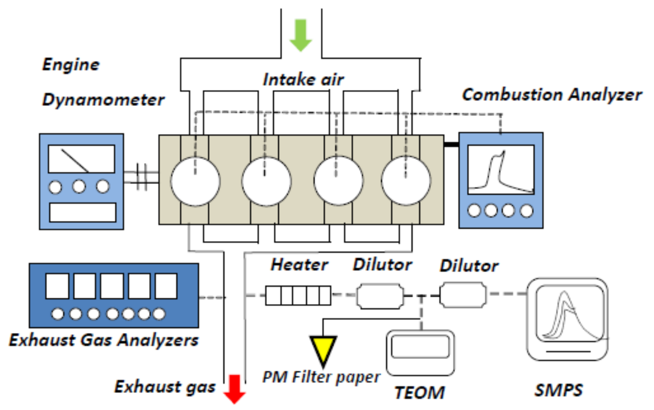

Figure 1: Schematics of the experimental system.

Model	Isuzu 4HF1
Engine type	In-line 4-cylinder DI
Max. power	88 kW/3200 RPM
Max. torque	285 Nm/1800 RPM
Bore x stroke	112 mm × 110 mm
Displacement	4334/cc
Compression ratio	19.0:1
Fuel injection timing	8° BTDC
Injection pump type	Bosch in-line type
Injection nozzle	Hole type (with 5 orifices)

Table 1: Specifications of test diesel engine.

A Kistler type 6056A piezoelectric pressure transducer was used to measure the in-cylinder pressure. Crankshaft position was measured by a Kistler crank angle encoder. The cylinder pressure, averaged over 400 cycles, was analyzed with a combustion analyzer (DEWETRON, DEWE-ORION-0816-100X) to obtain the heat release rate due to fuel combustion.

NOx emission in the engine exhaust was measured online using a heated chemiluminescent analyzer. CO_2 concentration was measured at the intake manifold by a non-dispersive infra-red analyzer. The exhaust gas temperature was measured with K-type thermocouple. The raw exhaust gas was diluted with filtered air using a two-stage mini-dilutor (Dekati Ltd, Finland) for measurement of PM. The primary diluted exhaust gas was measured with a tapered element oscillating microbalance (R and P TEOM 1105) for mass concentration while secondary diluted exhaust gas was measured with a scanning mobility particle sizer (SMPS, TSI, Inc 3071A) for particle size distribution and number concentration. The particulate nanostructure and morphology were analyzed by using a high-resolution transmission electronic microscopy (STEM, Jeol JEM-2100F). The maximum magnification was up to 910,000X with resolution of 0.2 nm. The soot samples were first collected in 47 mm-diameter quartz filter paper and the paper was cut into tiny pieces and mixed with ethanol in cylinder. Colloidal solution was then ultrasoniced for 15 minutes and droplets were dropped on a TEM grid by tweezer and left for drying till ethanol evaporation before arranging image processing. TEM images were taken from three to four locations with several aggregates surveyed at the same locations to maintain the consistency of examination.

Four DBE blends were prepared and denoted as DBE0 (85% diesel; 15% biodiesel; 0% ethanol, volume basis), DBE5 (80% diesel; 15% biodiesel; 5% ethanol), DBE10 (75% diesel; 15% biodiesel; 10% ethanol) and DBE20 (65% diesel; 15% biodiesel; 20% ethanol) for evaluation. In this paper, all tests were performed at the engine speed of 1800 rev/min and at five engine loads of 30, 60, 120, 200 and 240 Nm, corresponding to brake mean effective pressures (BMEP) of 0.09, 0.17, 0.35, 0.58 and 0.70 MPa. The gaseous and particulate mass concentrations were measured continuously for five minutes with three times. As for particle number concentrations and size distributions, four measurements were recorded. Tables 2a and 2b shows the basic properties of fuels used in this study. ULSD used has a sulfur content of less than 10-ppm-wt. Biodiesel was produced from waste cooking oil. Ethanol has a purity of over 99%.

Results and Discussions

Engine performance

For each test, the brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), in-cylinder pressure and heat release rate for each DBE blend were analyzed with comparison with base fuels of ULSD and biodiesel.

SFC defines the ratio of fuel mass consumption rate to the brake power. Figure 2 indicates that the BSFC of all test fuels decreases with an increase in engine load from 0.09 to 0.70 MPa with decreasing slope due to increase in brake thermal efficiency at higher engine loads. The results are similar to those reported in early works [3,11,12]. At each engine load, fuels having lower heating values require larger fuel mass

Properties	ULSD	Biodiesel	Ethanol
Cetane number	52	51	6
Lower heating value (MJ/kg)	42.5	37.5	28.4
Density (kg/m^3) at 20°C	840	871	786
Viscosity (mPa S) at 40°C	2.4	4.6	1.2
Heat of evaporation (kJ/kg)	250-290	300	840
Carbon content (% mass)	86.6	77.1	52.2
Hydrogen content (% mass)	13.4	12.1	13
Oxygen content (% mass)	0	10.8	34.8
Sulfur content (% mass)	<10	<10	0

Table 2(a): Properties of blending stocks.

Calculated properties	DBE0	DBE5	DBE10	DBE20
Density (kg/m^3) at 20°C	845	842	839	833
Lower heating value (MJ/kg)	41.7	41	40.3	38.9
Oxygen content (% mass)	1.7	3.3	5	8.2

Table 2(b): Calculated Properties of blending stocks.

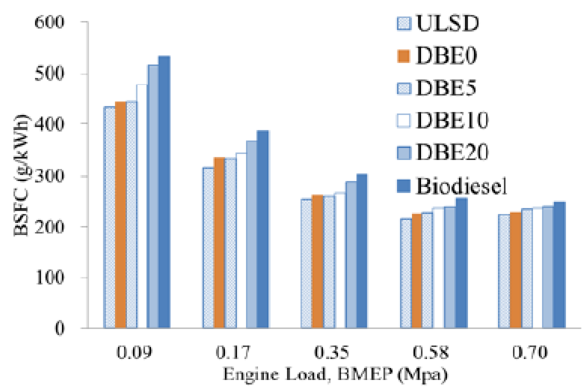

Figure 2: Comparison of BSFC.

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consumption rate to compensate its low energy content for generating the same engine power. As shown in Tables 2a and 2b the maximum LHV (42.5 MJ/kg) belongs to diesel, followed by DBE0 (41.7 MJ/kg), DBE5 (41.0 MJ/kg), DBE10 (40.3 MJ/kg), DBE20 (38.9 MJ/kg) and neat biodiesel (37.5 MJ/kg). At the highest test engine load of 0.70 MPa, the minimum BSFC is 225.3 g/kWh for ULSD, followed by, 230.0 g/kWh for DBE0, 234.8 g/kWh for DBE5, 239.1 g/kWh for DBE10, 240.5 g/kWh for DBE20 and 249.2 g/kWh for biodiesel. Therefore, the BSFC for biodiesel is the highest due to its lowest combustion energy content while that for diesel is the least among the test fuels. The higher the proportion of ethanol in the DBE blends, the higher the BSFC is. BTE defines the efficiency in which the chemical energy of a fuel is turned into useful work. BTE increases as a function of oxygen contents in the test fuels and increases with an increase in engine loads. For each engine load, the more the oxygenates are added in the fuels, the lower the heating value of the fuel blends and the higher the BSFC. However, the increase of oxygenates could provide additional lubricity, reduce fuel viscosity, improve atomization, and provide more oxygen contents for improving the combustion process in converting fuel chemical energy into useful engine work. Consequently, BTE is elevated. At the highest test engine load of 0.70 MPa, the maximum BTEs attained for attained for biodiesel, DBE20, DBE10, DBE5, DBE0 and ULSD are 38.53%, 37.95%, 37.82%, 37.36%, 37.32% and 37.10% respectively. Therefore, there is no obvious variation of BTE among diesel, biodiesel and the DBE fuels at the high engine load, which is similar to observations reported in the literature [3].

The variation of in-cylinder pressure and heat release rate are shown in Figure 3 for different fuels at the low, medium and high engine loads of 0.09, 0.35 and 0.70 MPa respectively. It is observed that the in-cylinder pressure curves of all test fuels increase with the increase of engine load. The peak in-cylinder pressure occurs further away from the top dead centre (TDC) in the expansion stroke with increase of engine load, which is similar to the results of Qi et al. [13]. The peak heat release rate increases with an increase in engine load from low to the medium, but decreases at the high engine load for all test fuels, which is similar to the results of Zhu, et al. [14].

The engine load of 0.09 MPa, the fuel is burnt mainly in the premixed mode. Combustion occurs earlier for biodiesel than diesel fuel. For the DBE fuels, ignition delay for DBE0 and DBE10 lies between those of biodiesel and ULSD while that of DBE20 is even longer than that of diesel fuel, indicating the influence of ethanol in increasing ignition delay. The peak in-cylinder pressures of DBE blends are observed to be lower than that of biodiesel, but higher than that of ULSD. The addition of ethanol leads to lower cetane number and higher latent heat of evaporation of the DBE blends thereby lowering the in-cylinder temperature during which injected fuel spray mixes with air, increasing the ignition delay as well as changing peak in-cylinder pressure and heat release rate [15-17]. The longer ignition delay, better volatility and lower viscosity contributed by the ethanol fraction in DBE blends cause more fuel accumulated in the ignition delay period to burn in the premixed burning phase and hence higher heat release rate [14,15].

At the engine load of 0.35 MPa, more fuel was injected into the engine. Compared with ULSD and biodiesel, the lower cetane number of the DBE blends causes longer ignition delay, compared with the case of 0.09 MPa, resulting in a stronger premixed burning phase. A larger amount of fuel is burned in the premixed mode, leading to higher peak in-cylinder pressure and heat release rate for DBE blends than ULSD and biodiesel. DBE20 gives the highest peak heat release rate while biodiesel gives the least.

At the engine load of 0.70 MPa, with further increase in the amount of fuel injected into the engine, the gas temperature inside the cylinder is higher thereby reducing the ignition delay period. However, the longer ignition delay associated with DBE blends can still be observed. There is no significant variation in in-cylinder pressure rise with increase of ethanol in the blended fuel because more fuel is burned in the expansion stroke. As for the heat release rate, the peak values of all the fuels are lower because, due to the shorter ignition delay period, less fuel is burned in the premixed phase. For the different fuels, the peak heat release rates of DBE blends are in general higher than that of biodiesel but lower than that of ULSD, except that DBE20 gives the highest heat release rate among all the test fuels while biodiesel is the lowest.

The above observations show that the heat release characteristics of the DBE blends are significantly different from those of biodiesel but close to that of ULSD, except for DBE20. DBE0 is observed to have

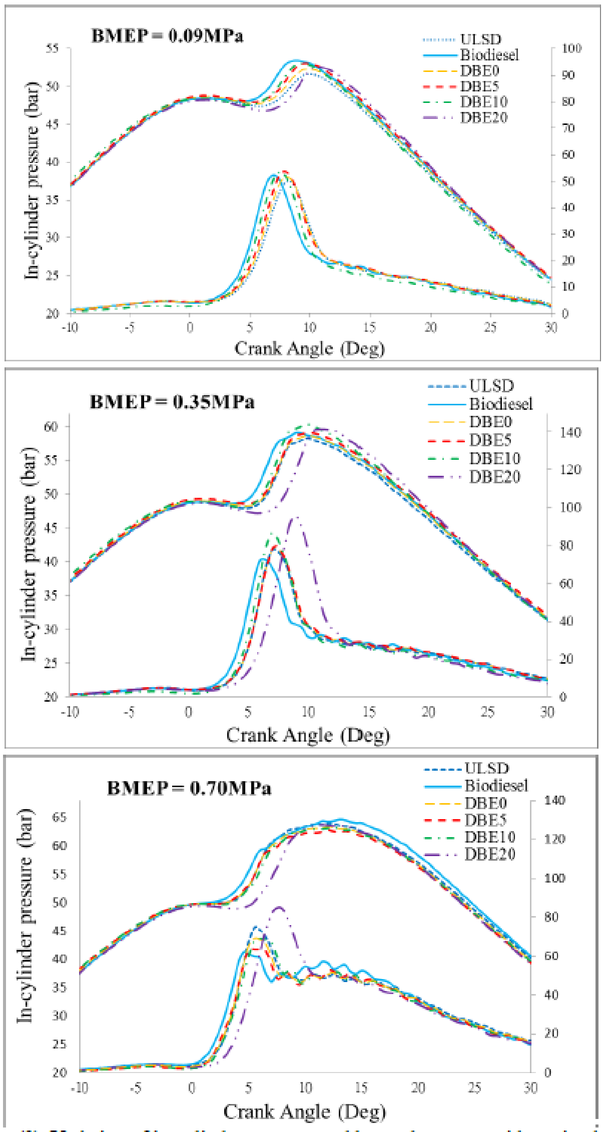

Figure 3: Variation of in-cylinder pressure and heat release rate with engine loads.

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the closest characteristics with ULSD among the DBE fuels. The large ethanol fraction in DBE20 leads to prolonged ignition delay, resulting in an increase of fuel released in the premixed mode and the highest peak heat release rate.

Gaseous and particulate emissions

The brake specific carbon dioxide ($BSCO_2$) emissions generally increases when the ethanol content is increased but the increment becomes less with increasing engine load as shown in Figure 4. Compared with ULSD, $BSCO_2$ emissions are decreased by 1.01% for DBE0, 4.41% for DBE5, 9.53% for DBE10 and 4.07% for DBE20 on arithmetic mean under five engine loads. Biodiesel has the highest $BSCO_2$ among all the test fuels in low and medium engine loads, but on similar level with other fuels at high loads.

The brake specific nitrogen dioxide (BSNOx) decreases with increase in engine load as shown in Figure 5. Biodiesel has the highest oxygen content among the test fuels thereby having the maximum temperature during the combustion and thus the highest BSNOx. The lower heating value (LHV) of ethanol is 1.3 times lower than biodiesel and 1.5 times lower than ULSD whereas the latent heat of evaporation of ethanol is about 2.8 times greater than biodiesel and ULSD, which decreases the peak temperature in the cylinder. The BSNOx thus decreases when ethanol content is increased in the DBE blends from 0 to 20%. In comparison with ULSD, the BSNOx are reduced by 0.01% for DBE0, 2.47% for DBE5, 5.30% for DBE10 and 29.56% for DBE20 on arithmetic mean under five engine loads.

The brake specific particulate mass (BSPM) emission of each test fuel decreases with engine load from 0.09 to 0.35 MPa while increases from 0.58 to 0.70 MPa as shown in Figure 6. ULSD has the highest BSPM among the test fuels at each engine load while biodiesel has the least. For each engine load, with increasing oxygen contents in the test fuel, the BSPM in general decreases. The oxygen concentration in the DBE blends ranges from 1.7% to 8.2% which is much lower than that of 10.8% in biodiesel. As such, DBE blends have comparatively higher BSPM than biodiesel. When compared with ULSD, the DBE blends could effectively reduce BSPM by 19-49% at 0.09 MPa, 5-42% at 0.17 MPa, 4-33% at 0.35 MPa, 25-61% at 0.58 MPa and 14-57% at 0.7 MPa for ethanol fractions of 0%-20%. For each engine load, increasing ethanol concentrations in DBE blends enhances the oxygen contents and diesel fuel replacement favoring BSPM reduction.

Regarding the particle number concentration (PN) for each fuel shown in Figure 7, it increases with engine loads when amount of fuel and carbon mass are increased. At each engine load, biodiesel

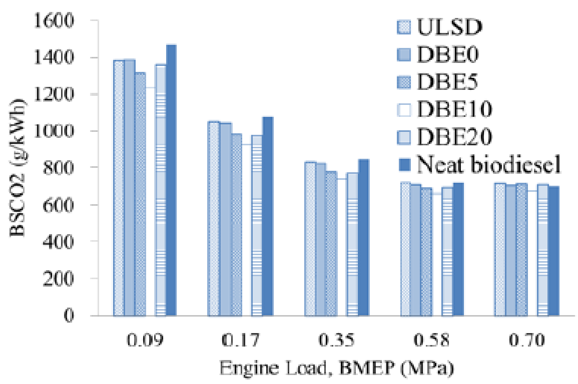

Figure 4: Variation of BSCO2 emissions with engine loads.

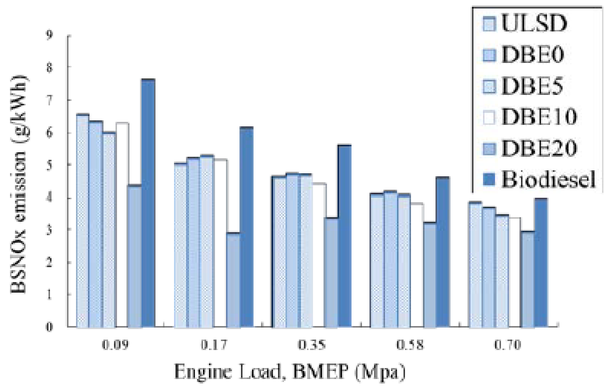

Figure 5: Variation of BSNOx with engine loads.

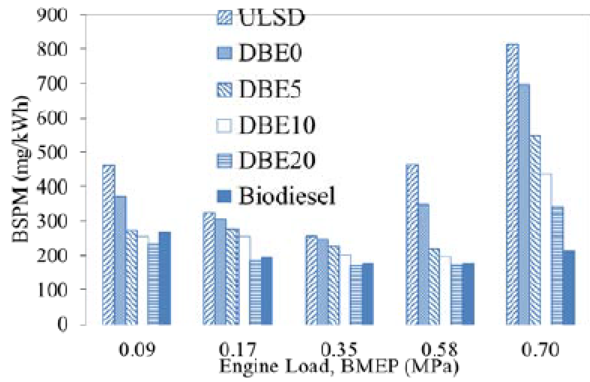

Figure 6: Variation of BSPM emissions with engine loads.

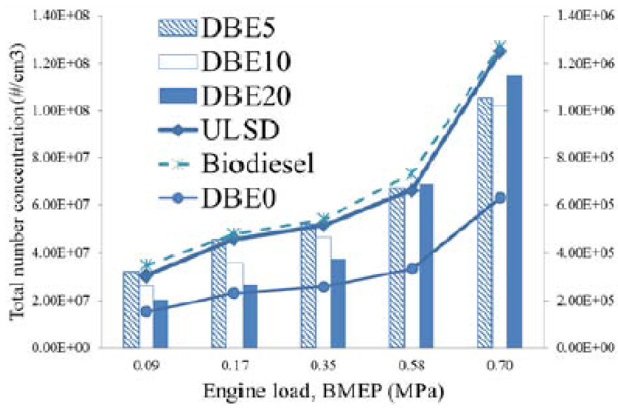

Figure 7: Variation of PN emissions with engine loads.

is generally observed to achieve the highest PN because of its higher fuel viscosity favoring higher production of smaller particles. The DBE blends with ethanol could reduce PN by 99% on average for all engine loads as compared with both biodiesel and ULSD. It is due to the combined effect of the oxygen content and the alcohol structure in ethanol which is effective in reducing soot precursors.

Figures 8 and 9 show the effect of fuel type and engine load on the proportion of volatile organic fractions (VOF) in PM and brake specific volatile organic fraction (BSVOF) emissions. For each fuel,

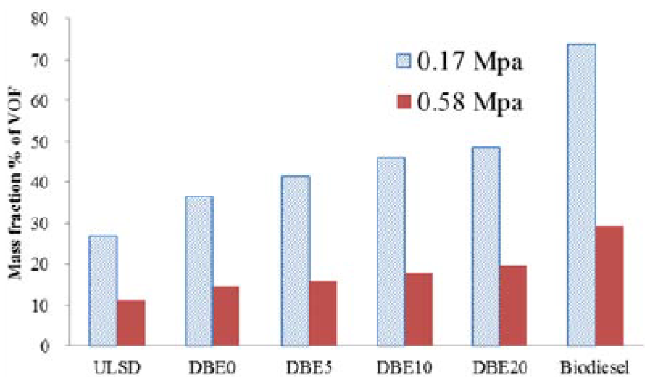

Figure 8: Mass fraction % of VOF with different fuels at two different engine loads.

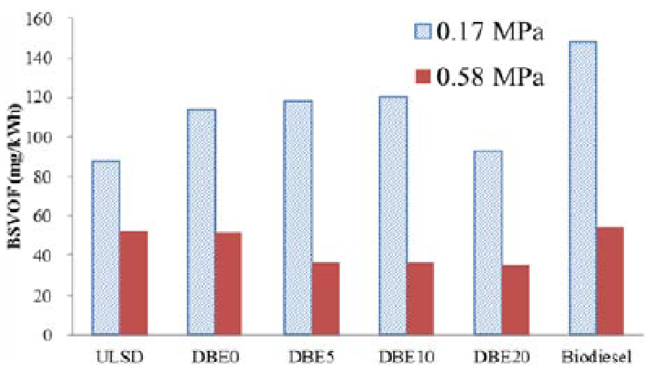

Figure 9: Variation of BSVOF with different fuels at two different engine loads.

with an increase in the engine load from 0.17 MPa to 0.58 MPa, the mass fraction of VOF and brake specific VOF (BSVOF) emission decrease. For each engine load, mass fraction increases with an increase in oxygen content in fuel in order of ULSD, DBE0, DBE5, DBE10, DBE20 and biodiesel, corresponding to oxygen content of 0%, 1.7%, 3.3%, 5.0%, 8.2% and 10.8% as shown in Figure 9. Increasing the engine load from 0.17MPa to 0.58MPa resulted in a decrease from 27.78 to 11.16% for ULSD, 36.60 to 14.64% for DBE0, 41.5 to 15.96% for DBE5, 46.02 to 17.70 % for DBE10, 48.65 to 19.46% for DBE20 and 73.75 to 29.50% for biodiesel. For the BSVOF emission, it increases in order of DBE20, DBE10, DBE5, DBE0, ULSD and biodiesel. Since VOF is a major constituent of PM [9], reducing the BSVOF would help decrease the total PM emission.

Soot properties

Figures 10 and 11 show the soot agglomerates produced from ULSD, biodiesel and DBE blends at low (0.17 MPa) and high (0.58 MPa) engine loads. Agglomerates from different fuels at different loads were found to be composed of fine primary particles forming a mixture of chain-like structures and clusters of spherules. Figure 12 illustrates the sample measurement of agglomerates including maximum projected length (L) and maximum projected width normal to length (W) and fine primary particles including projected primary particle diameter (D) and primary particle area (A). Table 3 summarizes the above measurements of the soot agglomerates and its respective primary particles shown in Figures 10 and 11.

For each test fuel, the projected diameter and area of fine primary particles increase with engine load because more fuel is burned at higher load resulting in the growth of soot nuclei. Increasing the engine load from 0.17 to 0.58 MPa, the projected diameter increases in order of DBE20 from 15 nm to 18 nm, DBE10 from 17 nm to 20 nm, DBE5 from 19 nm to 23 nm, DBE0 from 20 nm to 24 nm, biodiesel from 24 nm to 31 nm and ULSD from 34 nm and 41 nm. As for the projected area, it follows the same trend with projected diameter with increasing order of DBE20, DBE10, DBE5, DBE0, biodiesel and ULSD.

The use of DBE blends, compared with biodiesel and diesel, produce smaller projected diameter and area of fine particles. Increasing the proportion of ethanol from DBE5 to DBE20, the carbon content of the blend fuels decreases and the oxygen content increases leading to the reduction of nuclei particles. The possibility of agglomeration and condensation of smaller particles to form larger ones is then reduced. As for the projected length of agglomerates from DBE blends, it decreases from 448 nm to 419 nm at 0.17 MPa and 508 nm to 449 nm at

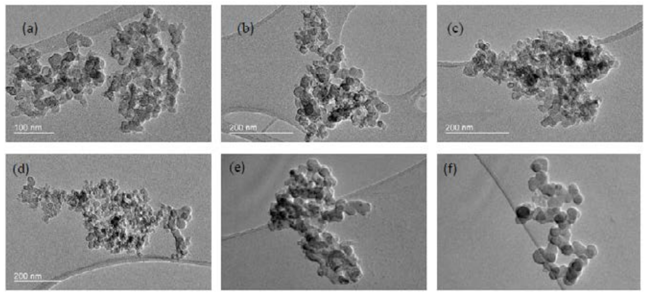

Figure 10: TEM pictures of soot particles from (a) ULSD, (b) biodiesel, (c) DBE0, (d) DBE5, (e) DBE10 and (f) DBE20 at engine load of 0.17 MPa.

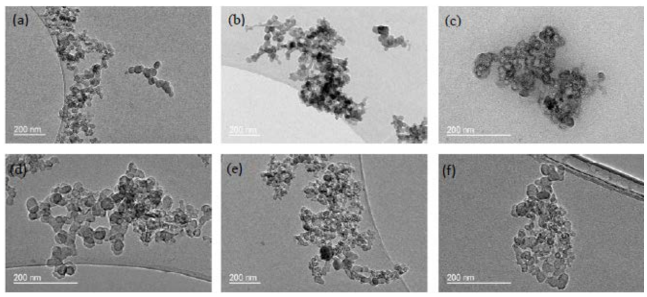

Figure 11: TEM pictures of soot particles from (a) ULSD, (b) biodiesel, (c) DBE0, (d) DBE5, (e) DBE10 and (f) DBE20 at engine load of 0.58MPa.

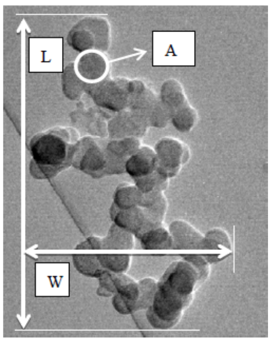

Figure 12: Measurement of agglomerates and fine primary particles.

Fuels	Load (MPa)	Figures	Nos. agglomerates	L average (nm)	W average (nm)	(L/W) average	Nos. particles	D average (nm)	A average (nm^2)
ULSD	0.17	Fig. 10a	4	241 ± 23	303 ± 45	0.8 ± 0.3	39	34 ± 4	942 ± 29
Biodiese	0.17	Fig. 10b	4	488 ± 48	424 ± 56	1.3 ± 0.4	35	24 ± 4	485 ± 32
l DBE0	0.17	Fig. 10c	4	360 ± 23	363 ± 20	0.9 ± 0.3	43	20 ± 3	332 ± 27
DBE5	0.17	Fig. 10d	4	448 ± 75	562 ± 52	0.9 ± 0.4	52	19 ± 3	300 ± 24
DBE10	0.17	Fig. 10e	4	434 ± 54	417 ± 23	1.0 ± 0.2	47	17 ± 5	224 ± 15
DBE20	0.17	Fig. 10f	4	419 ± 68	387 ± 41	1.1 ± 0.3	46	15 ± 4	172 ± 17

Table (3a): Measurement of the soot agglomerates and its respective primary particles at engine load of 0.17 MPa.

Fuels	Load (MPa)	Figures	Nos. agglomerates	L average (nm)	W average (nm)	(L/W) average	Nos. particles	D average (nm)	A average (nm2)
ULSD	0.58	Fig. 11a	4	275 ± 50	373 ± 33	1.0 ± 0.4	29	41 ± 7	1332 ± 12
Biodiesel	0.58	Fig. 11b	4	735 ± 57	790 ± 81	0.9 ± 0.3	45	31 ± 3	749 ± 21
DBE0	0.58	Fig. 11c	4	459 ± 74	690 ± 65	0.7 ± 0.2	33	24 ± 3	471 ± 13
DBE5	0.58	Fig. 11d	4	508 ± 76	625 ± 51	0.8 ± 0.2	49	23 ± 3	417 ± 15
DBE10	0.58	Fig. 11e	4	506 ± 61	487 ± 38	1.1 ± 0.1	44	20 ± 4	343 ± 20
DBE20	0.58	Fig. 11f	4	449 ± 98	415 ± 41	1.2 ± 0.4	42	18 ± 2	244 ± 19

Table (3b): Measurement of the soot agglomerates and its respective primary particles at engine load of 0.58MPa.

0.58 MPa while the projected width decreases from 562 nm to 387 nm at 0.17 MPa and 625 nm to 415 nm at 0.58 MPa when ethanol blending ratio increases from 5% to 20%.

It is generally found that high-engine-load particulate samples for each test fuel exhibit comparatively more ordered and clear graphitic structures when compared with low-engine-load particles. At low engine load, particulate samples examined under TEM micrographs are amorphous and disordered due to its high content of VOCs in samples. While increasing engine load with higher exhaust temperature, VOCs in samples are burnt out and particles are then distinct and graphitic in morphology. Zhu, et al. [18] also reported similar trend that crystallite dimension of diesel particulate increases with engine load and exhaust temperature in their study in light-duty diesel engine [19].

Conclusions

The engine performance, brake specific emissions and soot properties of a 4-cylinder direct-injection diesel engine fuelled with ULSD, biodiesel and diesel-biodiesel blended with 0%, 5%, 10% and 20% by volume of ethanol were investigated. The following conclusions can be drawn.

1. On engine performance, the higher the proportion of ethanol in the DBE blends at each engine load, the higher the BSFC is. DBE0 has very close BSFC to diesel while pure biodiesel has higher BSFC than DBE10 and DBE20. At high engine loads, there is no obvious variation of BTE between diesel and different oxygenate test fuels.

2. The in-cylinder pressure and peak heat release rate of DBE blends are comparatively higher than that of ULSD and biodiesel. With the increase of ethanol in the blended fuels, the ignition delay becomes longer. The in-cylinder pressure and peak heat release becomes higher and retarded due to more fuel burned in the premixed burning phase.

3. DBE blends can reduce brake specific emissions of NOx, CO_2, volatile organic fractions and particulate mass-number concentration with slightly decreased the particle size.

4. Agglomerates from different fuels were found to be composed of fine primary particles forming a mixture of chain-like structures and clusters of spherules. Increasing the fuel oxygenation leads to the increase of amorphous nanostructure characterized by smaller particle size.

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Conflicts of Interest

The authors declare that they have no conflicts of interest in this work.

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