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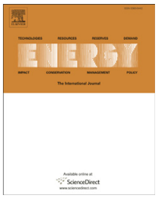

Investigation on the combustion characteristics and particulate emissions from a diesel engine fueled with diesel-biodiesel-ethanol blends

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ABSTRACT

This study investigated the influence on the combustion characteristics and particulate emissions of a diesel engine fueled with DBE (diesel-biodiesel-ethanol) blended fuels. The effects on in-cylinder pressure, heat release rate, combustion duration, diffusion fuel mass, BSPM (brake specific particulate mass) and BSPN (brake specific number concentrations) when diesel-biodiesel is blended with 0%, 5%, 10% and 20% ethanol were tested in a 4-cylinder naturally-aspirated direct-injection diesel engine at a steady state speed of 1800 rev/min under five engine loads. Overall, compared with ULSD (ultra-low-sulfur diesel), DBE blends can effectively reduce BSPM, BSPN and maintain a good trade-off relationship among PM-PN-NO_X. Compared with biodiesel, the blended fuels perform better in suppressing BSPN, leading to a reduction in the number of ultrafine and nano-particles.

1. Introduction

Diesel engines are widely used in commercial applications. However, there is serious concern on their emissions, in particular the nitrogen oxides (NO_x), PM (particulate matters) and carbon dioxide (CO_2). In the last few decades, the significant global warming problems caused by CO_2 have been magnified by the continued and increasing use of petroleum in diesel engines. Reducing CO_2 emission has become an explicit goal of policy measures to support the use of biofuels. For example, European Union mandates 10% share for biofuels in the EU (European Union) total energy mix by 2020 [1] and United States sets a total of 36 billion-gallon target for biofuel production by 2022 [2]. Therefore, alternative renewable biofuels have been investigated to partly or completely replace diesel fuel to overcome the emission problems. Of the alternative biofuels, the most widely investigated include biodiesel and ethanol [3–5]. These two fuels have clear emission advantages over diesel fuel. However, some studies have raised the concern of "food versus fuel" arising from plant-based biodiesel and ethanol, which might be the main hurdle for commercialization [6]. In fact, the economic consequences of these biofuel expansions are mixed and there are still some issues that will influence the actual impacts on food costs that have not been accounted for [7]. To counter the "food, energy and environment trilemma", the development of these biofuels from non-food sources (i.e. biodiesel from waste cooking oil, ethanol from cellulosic non-food crops, etc) can show great promise in reducing food commodities being utilized for biofuel production [8].

Different biodiesels, including those produced from low-cost waste cooking oil, have been investigated for application to diesel engines directly without the need to modify the engine. The direct use of biodiesel can reduce HC (hydrocarbon), CO (carbon monoxide) and particle-mass emissions but with technical constraints for increase in fuel consumption, particle-number and NOx emissions. Investigations have then been carried out for diesel-biodiesel blended fuels for improving the subject technical constraints brought from biodiesel [9–11]. More recently, Rakopoulos et al. [12] investigated influence of various common biofuels (including vegetable oil, biodiesel, ethanol, n-butanol, diethyl ether), blended with diesel, on the combustion and emissions of a diesel engine, with emphasize on the effect of fuel-bound oxygen contents. Ethanol is considered as a promising fuel oxygenate because its high heat of evaporation favors NOx reduction while its high oxygen content favors PM reduction. However, ethanol and diesel can only be mixed with the assistance of fuel stabilizer [10]. Biodiesel molecule is known to have a polar end with affinity for ethanol, which is also polar in nature, thus, biodiesel can be used as an effective stabilizer in preventing the separation of

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Nomenclature

BMEP	brake mean effective pressure
CO_2	carbon dioxide
CO	carbon monoxide
DBE	diesel-biodiesel-ethanol blends
HC	hydrocarbons
NO_X	nitrogen oxides
PM	particulate matters
PN	particle number concentrations
ULSD	ultra-low-sulfur diesel
SOC	start of combustion
EOC	end of combustion
TDC	top dead center
Øp	premixed combustion phase
Ød	diffusion combustion phase

ethanol from diesel fuel [13]. Investigations have therefore been carried out to investigate the combined use of biodiesel and ethanol in diesel fuel. As such, DBE (diesel-biodiesel-ethanol) blended fuel has been studied in recent years so that the disadvantages of either diesel-biodiesel or diesel-ethanol blended fuels can be overcome [13–17]. For example lubricity and cetane number of diesel fuel will be degraded by ethanol due to its lower density and viscosity while biodiesel has good lubricity and high cetane number which could enhance the lubricity and cetane number of diesel-ethanol blends [14,18]. Investigations on DBE for diesel engines can be traced back to as early as 1995. Ali et al. [19,20] investigated the effect of DBE on engine performance and gaseous emissions. Shi et al. [21] used DBE blends with 5% ethanol, 20% methyl soyate and 75% diesel fuel by volume. The DBE showed a significant reduction in PM emission but 2–14% increase in NO_X emission. Certain carbonyls were also measured and found to increase slightly with DBE. Guarieiro et al. [22] found that the combustion efficiency could be enhanced by the addition of ethanol and three kinds of biodiesels (methyl soybean ester, methyl castor ester and methyl residual oil ester) in diesel fuel which resulted in more complete combustion and reduced NOx emission in the ranges of 6.9%–7.5% at 1800 rev/min and 4%–85% at 2000 rev/min. 18 carbonyl compounds were also measured and the emission rate of total carbonyl compounds increased with DBE. Jha et al. [23] studied emissions from DBE blends with 5% diesel-70% biodiesel-25% ethanol, 10% diesel-70% biodiesel-20% ethanol and 15% diesel-70% biodiesel-15% ethanol on both new and used diesel engines. They found that DBE blends significantly reduce NOx emission in new engines with increase of ethanol fraction whereas the old engine showed increase in NOx emission. Moreover, CO emissions increased with increasing ethanol proportion in the blends in both new and old engines. Cheenkachorn et al. [24] studied the fuel properties and tested DBE blends with 84% diesel, 0.25% hydrous ethanol, 4.75% anhydrous ethanol and 11% biodiesel on a light-duty truck on a chassis dynamometer simulating the Bangkok driving cycle and found reduced PM and CO emissions as compared to diesel fuel. Hulwan et al. [25] reported that DBE blends with 20–40% ethanol attained significant smoke reduction and increased NO_X emission at high engine loads as compared with diesel fuel. They also measured the in-cylinder pressure and evaluated the heat release rate. Pidol et al. [26] tested three diesel-FAME-ethanol blends on a multi-cylinder DI (Direct Injection) diesel engine and a single cylinder diesel engine and found that smoke level was lower than using diesel fuel due to the presence of oxygen, decrease of soot precursors concentration and higher volatility of the blended fuel. Yilmaz et al. [15,17] have also investigated DBE on diesel engines with focus on the influence of ethanol concentration on engine performance and regulated gaseous emissions, with up to 25% ethanol in the fuel. Qi et al. [11,27] investigated the combustion and emissions characteristics of a diesel engine using different fuels including a DBE with 5% ethanol. The influence on in-cylinder pressure, rate of pressure rise and heat release rate were compared among the different fuels. Fang et al. [28] investigated effects of DBE on the combustion characteristics and emissions of a diesel engine in premixed low temperature combustion, however, particulate emission was not investigated. More recently, Lee et al. [29] investigated DBE with water and Chang et al. [30] investigated acetone-butanol-ethanol as blending additive in a diesel engine fueled with biodiesel and diesel for reducing NOx emissions. Previous works on DBE blends mainly focused either on reducing CO, HC, NO_X or PM mass concentration. However, due to the strong links between particle number concentrations and health effects, it is more important to have in-depth study on the particulate number-size distributions for better understanding about the potential use of DBE blends. Kim and Choi [31] investigated the effect of biodiesel and bioethanol blended diesel fuel on nanoparticle and exhaust emissions from a common-rail direct injection diesel engine. Their study involved a DBE blend with 80% diesel-15% biodiesel-5% ethanol and they found that the DBE blend was much more effective in reducing particle number and particle mass when compared with B20 (80% diesel-20% biodiesel). Muralidharan et al. [18] also investigated DBE blends with 5% ethanol. They concluded that the particle size and number reduced with DBE blends. Armas et al. [13] investigated the influence of a DBE blend with 10% ethanol on the emission of a bus. They found a slight increase in nuclei mode particles despite a reduction in total number concentration. In these studies, the influence of different concentrations of ethanol in the DBE has not been investigated.

The above review shows that very few studies on DBE blends are related to the combustion characteristics and particle number concentrations. A significant number of particles emitted by diesel engines are in the nano-size range with diameter less than 50 nm while most of the mass-based PM is in the accumulation mode with diameter in the range of 50 nm–1000 nm [17]. The smaller the emitted particles, the more harmful they are because smaller particles can more easily infiltrate into the respiratory organs of human body. On the other hand, ethanol has very low cetane number and hence the ethanol content in DBE would affect ignition delay and hence subsequent heat release characteristics as well as the emissions. Ignition delay will affect the start of combustion, combustion duration and diffusion burning thereby affecting the PM emissions. The correlation between these combustion characteristic parameters and the particulate emissions for DBE blends, over a range of ethanol content, has not been studied. The aim of this study is to fill in this knowledge gap. It aims at investigating the influence of DBE on the combustion characteristics and particulate emissions, both by mass and by number, of a diesel engine. The DBE used has ethanol content ranging at 0%, 5%, 10% and 20% while the biodiesel used is manufactured from waste cooking oil.

In this investigation, effects of DBE blends on HC and CO emissions have also been measured and published in Tse et al. [32]. The results are not repeated in this paper because they are mostly in-line with those published in the literatures.

2. Experimental investigation

The fuels used in this study include ULSD (ultralow-sulfur diesel fuel), biodiesel and ethanol. The major properties of them are shown in Table 1. Euro V diesel fuel contains less than 10 ppm sulfur by weight. The biodiesel, produced by Dynamic Progress from

Table 1
Properties of blending stocks.

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 Deg.C	840	871	786
Viscosity (mPa S) at 40 Deg.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

Calculated properties	DBE0	DBE5	DBE10	DBE20
Density (kg/m^3) at 20 Deg.C	845	842	839	833
Lower heating value (MJ/kg)	41.7	41.0	40.3	38.9
Oxygen content (% mass)	1.7	3.3	5.0	8.2

Table 2
Specifications of test diesel engine.

Model	Isuzu 4HF1
Engine type	In-line 4-cylinder DI
Combustion chamber shape	Omega
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)
Injection nozzle diameter	0.3 mm
Injection nozzle opening pressure	18.1 MPa

waste cooking oil collected from restaurants in Hong Kong, is in compliance with EN14214. Four blended fuels 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. The content of biodiesel in the DBE is held constant at 15% so that the effect of ethanol in replacing diesel fuel can be evaluated. Tests were firstly conducted with diesel fuel and biodiesel to obtain the baseline data. Engine performance and exhaust emissions from the DBE blends were compared with those obtained from diesel and biodiesel fuels.

Fig. 1 shows the schematics of the experimental system. All experiments were carried out on a natural-aspirated, water-cooled, 4-cylinder direct-injection diesel engine which was dismantled from a 1995 model year truck. Specifications of the engine are given in Table 2. The engine was coupled with an eddy-current dynamometer and its operation was controlled by the Ono Sokki diesel engine test system.

The raw exhaust gas was diluted with filtered air using a two-stage mini-dilutor (Dekati Ltd, Finland) for measurement of PM. The first stage was heated while the second stage was not. The sampled gas was drawn from the exhaust manifold through a heated and insulated sampling line to prevent deposition of solid particles and condensation of volatile materials on the interior wall. The sampled gas was then drawn into the first stage dilutor and diluted with hot air. Part of the diluted gas was passed to the second stage dilutor at atmospheric pressure and further diluted with cold air. The actual dilution ratio was evaluated based on measured CO$_2$ concentrations in the raw exhaust, the diluted exhaust and the background air. The primary diluted exhaust gas was measured with a tapered element oscillating microbalance (R&P TEOM 1105) for PM mass concentration. The diluted exhaust gas at the inlet of the TEOM (Tapered element oscillating microbalance) was held at 47 °C. The secondary diluted exhaust gas was measured with a scanning mobility particle sizer (SMPS (scanning mobility particle sizer), TSI, Inc 3071A) for particle size distribution and number concentration. The ratios for primary dilution and secondary dilution were 11 ± 2 and 88 ± 7 respectively. NOx was measured with a heated chemiluminescent analyzer (HCLA, CAI Inc.).

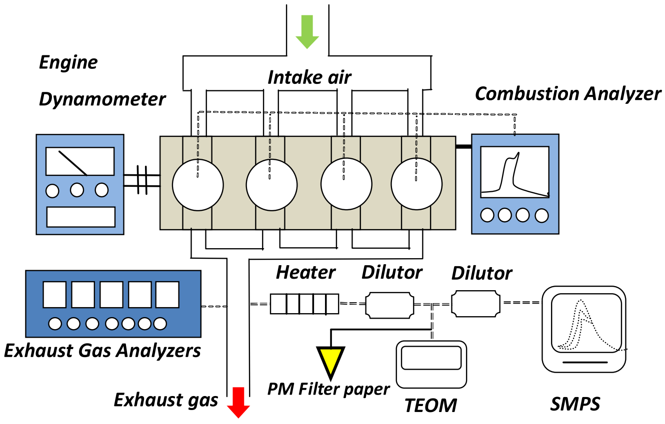

Fig. 1. Schematics of the experimental system.

A Kistler type 6056A piezoelectric pressure transducer was used to measure the in-cylinder pressure at 0.5 crank-angle interval. Crankshaft position was measured by a Kistler crank-angle encoder. The cylinder pressure was first averaged over 400 cycles to smooth any combustion cyclic irregularity which may appear in diesel engines fueled with low-ignition-quality biofuels [33]. The averaged cylinder pressure was analyzed with a combustion analyzer (DEWETRON, DEWE-ORION-0816-100X) to obtain the heat release rate. The methods of heat release rate analysis have been reported in detail in previous publications [34–36] Basically, the First Law of Thermodynamics is applied to obtain the heat released arising from the fuel burned per crank angle.

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 BMEP (brake mean effective pressures) of 0.09, 0.17, 0.35, 0.58 and 0.70 MPa. At each engine load, the engine was sufficiently warmed up for each test. The particulate mass concentrations were measured continuously for 5 min. Each steady state test was repeated three times for assessing experimental uncertainties. For particle number concentrations and size distributions, four measurements were recorded at each test. The averaged results are presented in this paper. Meanwhile, the engine oil temperature, mass flow rate of fuel and exhaust gas temperature were recorded during the experiments. The experimental uncertainty and standard errors in the measurements were determined based on the method of Moffat [37] and Ames et al. [38]. The maximum experimental standard errors in the measurements of mass of fuel, PM mass and PM number are 1.2%, 2.1% and 2.4% respectively. Student's t-test was employed to analyze whether the difference between the results obtained from ULSD and the blended fuels are statistically significant at 95% confidence level.

3. Results and discussions

3.1. Combustion characteristics

The variation of in-cylinder pressure and heat release rate are shown in Fig. 2 for different fuels at the low, medium and high engine loads of 0.09, 0.35 and 0.70 MPa, respectively. The peak

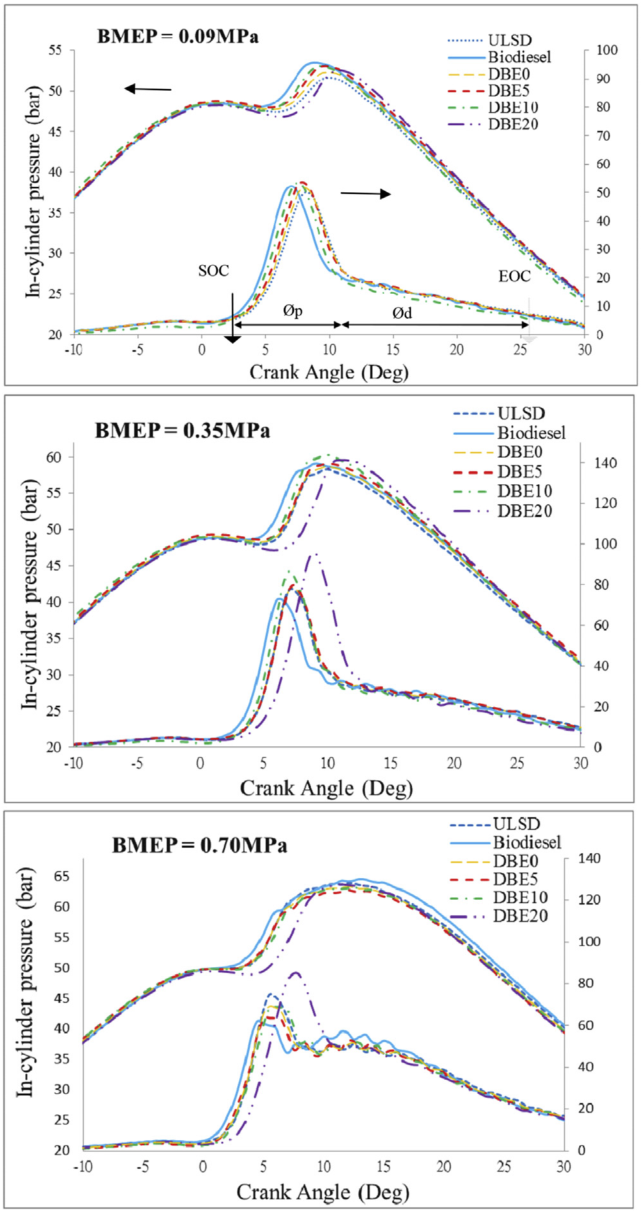

Fig. 2. Variation of in-cylinder pressure and heat release rate with engine load.

in-cylinder pressure occurs further away from the TDC (top dead center) in the expansion stroke with increase of engine load, which is similar to the results of Qi et al. [27]. 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. [39].

At the low engine load of 0.09 MPa, the fuel is burnt mainly in the premixed mode. Combustion occurs earlier for biodiesel than diesel fuel due to its earlier initiation of fuel injection arising from its higher bulk modulus of compressibility [40]. 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 affecting peak in-cylinder pressure and heat release rate [9,21,41]. 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 [40,41]. However, the peak in-cylinder pressure drops slightly because combustion occurs further away from the top dead center during the expansion stroke.

At the medium 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. 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 lowest.

At the high 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 for all the fuels tested. 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 has the highest heat release rate among all the tested fuels while biodiesel has the lowest.

The above observations show that the heat release characteristics of the DBE blends are significantly different from that of biodiesel but close to that of ULSD, except for DBE20. DBE0 is observed to have 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 heat release in the premixed mode and hence it has the highest peak heat release rate.

The start and duration of combustion for different fuels under different engine loads are shown in Fig. 3. SOC (start of combustion) is defined as the beginning of rapid pressure rise or the beginning of heat release. It is an indication of ignition delay; the later the combustion starts, the longer is the ignition delay. The EOC (end of combustion) is defined as the point with 95% accumulated heat release. Combustion duration is the time interval from the start to the end of combustion. The premixed combustion phase ($Ø_p$) and the diffusion combustion phase ($Ø_d$) are annotated in Fig. 2. From Fig. 3, it can be found that with increase of engine load, the start of combustion of all tested fuels advances while combustion duration increases. That is to say, the ignition delay decreases with increase of engine load. For the different fuels, the ignition delay increases in the order of biodiesel, ULSD, DBE0, DBE5, DBE10 and DBE20. The shorter ignition delay of biodiesel compared with ULSD is attributed to its higher density and bulk modulus of compressibility leading to advanced fuel dynamic injection timing [12,42,43]. Moreover, Sivalakshmi et al. [44] explained that gaseous compounds of low molecular weight, broken down from biodiesel during injection into the engine cylinder at high temperature, could ignite earlier thus reducing the ignition delay and advancing the start of combustion for biodiesel. As for the DBE blends, the increase of ethanol fractions from 0% to 20% increases the ignition delay thereby retarding the start of combustion.

The combustion duration in general increases in the order of DBE20, DBE10, DBE5, biodiesel, DBE0 and diesel. For a specific engine load, the volume of fuel consumed increases in the order of ULSD, DBE0, DBE5, DBE10, DBE20 and biodiesel due to the lower

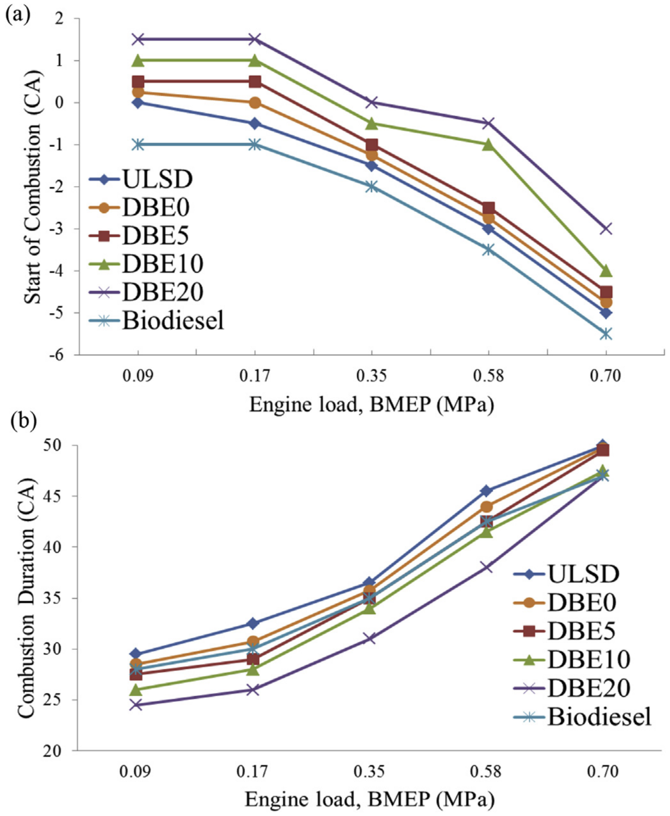

Fig. 3. Variation of start of combustion and combustion duration with engine load.

calorific values of biodiesel and ethanol compared with ULSD. DBE blends generally have longer ignition delay, larger amount of fuel burned in premixed mode, less burned in diffusion mode, resulting in shorter combustion period when compared with biodiesel and diesel fuel for all engine loads. At high engine load, the difference in combustion duration among the different fuels decreases as the ignition delay period decreases at high engine load.

Diesel particles are composed of soot, volatile organic fraction and sulfate while soot is mainly formed in diffusion combustion mode. In order to understand the effects of combustion characteristics of different fuels on particulate emission, it is essential to examine their respective mass of fuel burnt in the diffusion mode. The variations of total fuel mass consumption and diffusion fuel mass consumptions for different fuels with engine load are shown in Fig. 4. The total fuel mass refers to the mass of fuel consumed per engine cycle while the diffusion fuel mass refers to that part of the fuel consumed in the diffusion combustion mode. It can be generally observed that the total fuel mass consumed per cycle increases with the increase of engine load and mass fraction of oxygen in the fuel.

Biodiesel, with the lowest calorific value among the tested fuels, has the highest total fuel mass or the highest brake specific fuel consumption. DBE blends have higher total fuel mass than ULSD at all loads. Increasing ethanol concentrations from 0% to 20% in DBE blends increases the total fuel mass as well. As for the diffusion fuel mass, biodiesel has the highest value at all engine loads due to its highest total fuel mass and shortest ignition delay period. As for DBE blends, their longer ignition delay periods resulted in longer premixed combustion durations and shorter diffusive combustion durations. However, the diffusion fuel mass of the DBE blends is in the same order as that of ULSD at all engine loads. Increasing ethanol concentrations from 0% to 20% in DBE blends has little influence on the diffusion fuel mass.

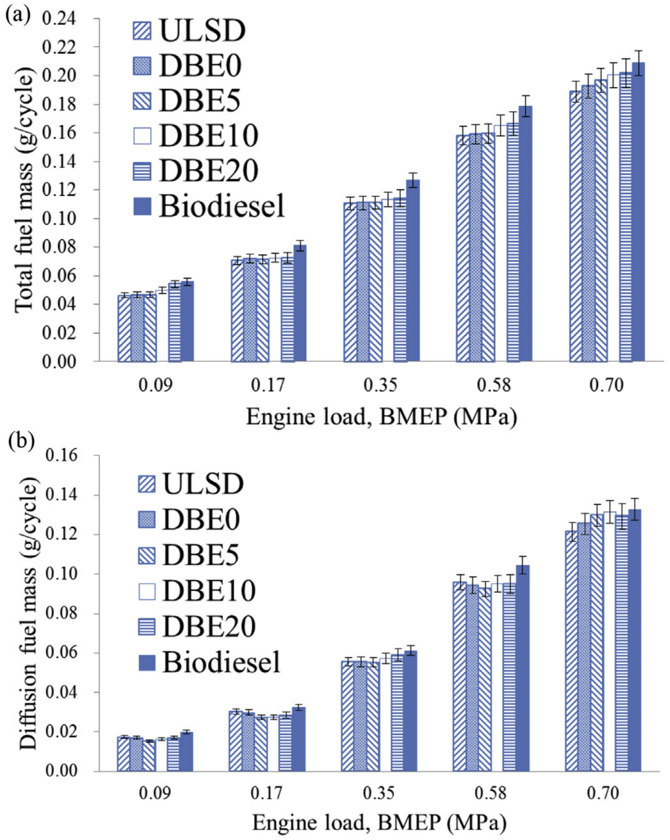

Fig. 4. Variation of total fuel mass and diffusion fuel mass with engine load.

3.2. Particulate mass concentration

Fig. 5 shows that the BSPM (brake specific particulate mass) emission of each tested fuel decreases with engine load from 0.09 to 0.35 MPa while increases from 0.58 to 0.70 MPa. At low engine loads, the fuel is burned mainly in the premixed mode and more time is available for soot oxidation, resulting in lower particulate formation. When engine load is increased, more fuel is injected into the combustion chamber and hence more fuel is burnt in the diffusion mode while less time is available for soot oxidation, leading to higher particulate formation at high engine load [40].

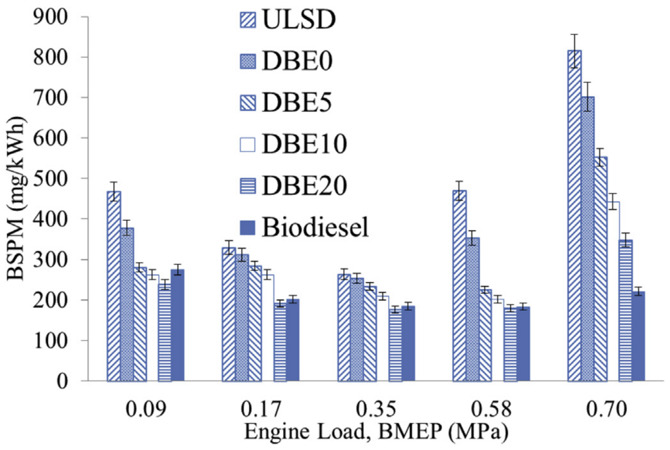

Fig. 5. Variation of BSPM with engine load.

However, the brake thermal efficiency increases with engine load, leading to the lowest BSPM emission at the engine load of 0.35 MPa.

ULSD, which has no oxygen in the fuel, has the highest BSPM among the tested fuels at all loads. 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 0.70 MPa for ethanol fractions of 0%–20%. The percentage reduction increases with increase of ethanol fractions in the blended fuels. Biodiesel has the highest oxygen contents in the fuel, has BSPM always lower than that of ULSD and DBE0; but its BSPM is close to that of DBE5 at 0.09 MPa, close to that of DBE20 at 0.17–0.58 MPa and is the lowest among all fuels at 0.79 MPa.

The reduction of BSPM is resulted from the reduction of soot and sulfate in particulate. Karavalakis et al. [9] found that the lower volatility and higher oxygen content of biodiesel could reduce PM emission significantly. The DBE blends have oxygen concentration ranging from 1.7% to 8.2%. They are also effective in reducing BSPM emissions, compared with ULSD, due to the increasing displacement of diesel fuel by ethanol which has higher oxygen content and lower fuel aromatics and fuel sulfur, all of which are favorable for reducing soot formation. The results are similar to the findings reported by Muralidaharan et al. [18] in their study of DBE blends on light commercial vehicle.

It is observed that the combustion duration and diffusive fuel mass of all tested fuels increase with engine load from 0.09 to 0.70 MPa. Compared with ULSD, at each engine load, the DBE blends have shorter combustion duration, as shown in Fig. 3(b), but comparable diffusion fuel mass. Since soot is mainly formed in the diffusion combustion period, the comparable diffusion fuel mass supports that DBE blends emit lower BSPM because of the change in fuel properties. Diesel fuel replacement by ethanol and biodiesel has more significant influence over the effect from its diffusion fuel mass on soot reduction. Di et al. [10] found that diesel-ethanol blends with oxygen concentration from 2 to 8% provided higher BSPM reduction than diesel-biodiesel blends, indicating that the ethanol structure is more effective in reducing soot precursors than the ester structure of biodiesel, leading to better particulate mass reduction [13]. Thus, the use of DBE, with biodiesel serving as the stabilizer between diesel and ethanol, has facilitated the effective use of diesel-ethanol blended fuel for improved particulate mass reduction.

3.3. Particulate number concentration

Influence of particles to the environment and human health depends not only on their mass concentration, but also on their number concentration and size distribution. It has been hypothesized that particle toxicity increases with decreasing size due to the higher specific surface area of smaller particles [23]. It is generally believed that nano-particles are more dangerous and hazardous to health. Therefore, the particles investigated by SMPS in this study are classified into three groups: (i) total number of particles, (ii) ultrafine particles with diameter less than 100 nm and (iii) nano-particles with diameter less than 50 nm. The results, including BSPN (brake specific particle number) concentration and percentages of both ultrafine and nano-particles evaluated based on the total particle numbers, are shown in Table 3.

For each fuel, total particle numbers, ultrafine particles and nano-particles increase with engine load, while BSPN is the highest at 0.09 MPa and lowest at 0.35 MPa. The increase in number concentration is associated with the increasing amount of fuel with engine load.

At each engine load, biodiesel is generally observed to achieve the highest in BSPN, total number, ultrafine and nano-particle emissions among the tested fuels although it has the lowest BSPM in most cases. Various reasons have been offered in the literature for increased particulate number concentration associated with biodiesel. Some researchers explained that biodiesel reduced soot emission due to the reduced soot surface growth rate weakening the ability of condensation and adsorption of volatile organic fractions on soot particle such that high super-saturation may lead to form more nuclei mode particles [45–47]. Tsolakis [48] reported that the higher production of smaller particles from biodiesel was due to its higher viscosity thereby increasing the fuel injection pressure for better fuel atomization and air fuel mixing. Pang [49] also found that the increased fuel injection pressure could affect particle size distribution and increase the number of nuclei mode particles during his study with a heavy-duty diesel engine.

DBE blends with ethanol could reduce BSPN, total particle numbers, ultrafine particles and nano-particles by 99% on average for all engine loads as compared with both biodiesel and ULSD. It is due to the combined effects of the presence of fuel-bound oxygen, reduced aromatics and sulfur compound and the alcohol structure in ethanol which are effective on reduction of soot precursors than methyl-ester structure [25] and the subsequent reduction in particle numbers. Di et al. [10] also reported that diesel-ethanol blends gave lower total number concentrations, ultrafine particles and nano-particles than ULSD while diesel-biodiesel blends showed the opposite trends. Thus, besides the particulate mass reduction, DBE also plays an important role in particle number reduction.

For each fuel, the percentages of both ultrafine and nano-particles in total particle numbers decrease with increasing engine load, implying that the emitted particles become larger in size. Biodiesel has the highest percentage of ultrafine and nano-particles because of its higher fuel viscosity which favors higher production of smaller particles. ULSD has the lowest percentage of ultrafine and nano-particles, implying that larger particles are emitted than biodiesel and DBE blends.

The variation of total particle number concentrations against combustion duration and diffusion fuel mass is shown in Fig. 6. DBE

Table 3
Particulate emissions for different test fuels.

1800 rev/min	Parameters	ULSD		Biodiesel		DBE0		DBE5		DBE10		DBE20	
0.09 MPa	BSPN (#/kWh)	1.61E+15		1.96E+15		8.07E+14		1.62E+13		1.38E+13		9.84E+12	
	Total number (#/cm^3)	3.05E+07		3.48E+07		1.54E+07		3.22E+05		2.65E+05		2.59E+05	
	Ultrafine particle (#/cm^3)	2.74E+07	89.8%	3.35E+07	96.3%	1.35E+07	90.3%	3.02E+05	93.7%	2.51E+05	94.7%	2.46E+05	95.3%
	Nano-particle (#/cm^3)	1.54E+07	50.5%	2.33E+07	67.0%	7.48E+06	55.2%	1.90E+05	59.0%	1.65E+05	62.3%	1.69E+05	65.2%
0.35 MPa	BSPN (#/kWh)	9.21E+14		9.96E+14		4.64E+14		8.86E+12		7.90E+12		6.46E+12	
	Total number (#/cm^3)	5.15E+07		5.40E+07		2.60E+07		5.18E+05		4.67E+05		3.77E+05	
	Ultrafine particle (#/cm^3)	4.39E+07	85.3%	4.97E+07	92.0%	1.96E+07	75.5%	4.09E+05	78.9%	4.16E+05	89.1%	3.43E+05	90.9%
	Nano-particle (#/cm^3)	2.17E+07	42.1%	2.90E+07	53.7%	8.87E+06	45.2%	2.52E+05	48.6%	2.27E+05	48.6%	1.95E+05	51.7%
0.70 MPa	BSPN (#/kWh)	1.53E+15		1.49E+15		7.88E+14		1.27E+13		1.22E+13		1.33E+13	
	Total number (#/cm^3)	1.25E+08		1.27E+08		6.30E+07		1.05E+06		1.03E+06		1.16E+06	
	Ultrafine particle (#/cm^3)	7.99E+07	63.9%	1.16E+08	91.2%	4.36E+07	69.2%	7.39E+05	70.3%	7.47E+05	72.5%	8.46E+05	72.9%
	Nano-particle (#/cm^3)	2.74E+07	21.9%	6.84E+07	53.8%	1.24E+07	28.5%	3.82E+05	36.3%	4.58E+05	44.5%	5.85E+05	50.4%

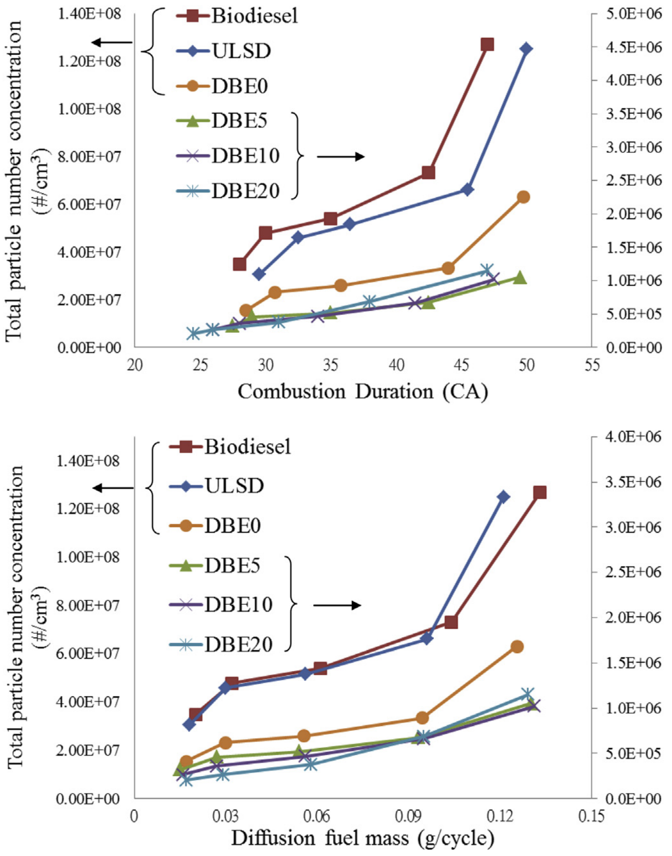

Fig. 6. Total particle number concentration against combustion duration and diffusion fuel mass of all test fuels at five engine loads.

blends on average having shorter combustion duration and comparable diffusion fuel mass achieve lower total particle concentration than ULSD at all engine loads.

Therefore, it appears that DBE blends can emit less total number of particles, ultrafine and nano-particles than both ULSD and biodiesel. On the contrary, biodiesel leads to the increase of these particles.

3.4. *Trade-off relations among PM, PN and NOx*

There is trade-off between PM and NOx emissions due to their contradictory responses to oxygen content in a fuel. It is well known that biodiesel could reduce PM emissions but lead to an increase in NOx emissions. Adding ethanol to a diesel fuel could reduce NOx emissions because of the cooling effect associated with the high latent heat of evaporation of ethanol. Fig. 7 and Fig. 8 show that increasing ethanol from 0% to 20% in the DBE blends gives lower BSPM, BSPN and BSNOx simultaneously than ULSD, weakening the PM-PN-NOx trade-off relationship, whilst compared with biodiesel, DBE blends give lower BSNOx and BSPN but higher BSPM.

The combustion behavior and emissions-wise performance is influenced by different fuel type characterized by its fuel-bound oxygen, injection characteristics, latent heat of evaporation, lower heating value, cetane number, etc. However, the fuel-bound oxygen in a fuel is a comparatively dominant parameter influencing the combustion behavior via local fuel-air ratios in combustion zones thereby affecting its emission characteristics [12].

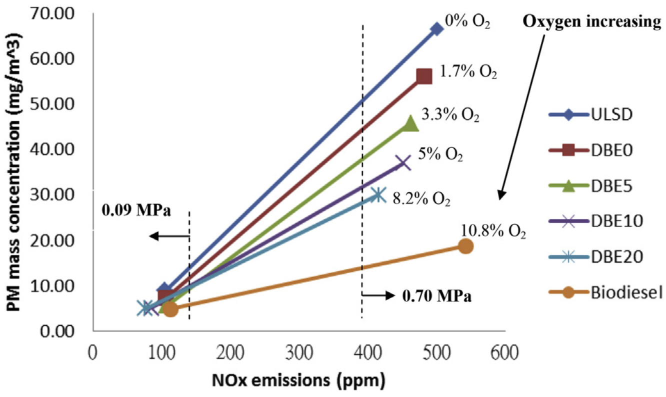

Fig. 7. PM-NOx trade-off curves for different fuels at loads of 0.09 MPa and 0.70 MPa.

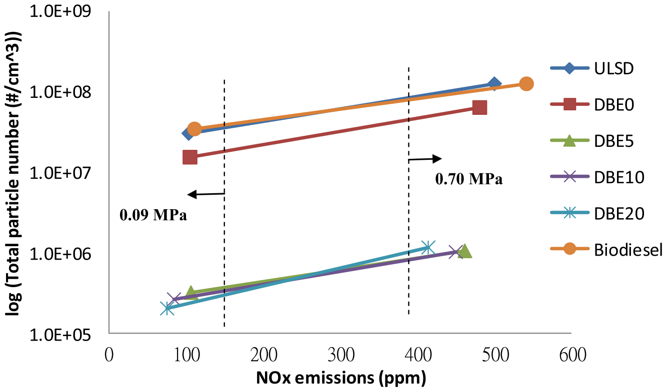

Fig. 8. PN-NOx trade-off curves for different fuels at loads of 0.09 MPa and 0.70 MPa.

4. Conclusions

In this study, the combustion characteristics and trade-off relations among PM (particulate mass), PN (number concentrations) and NOx from a diesel engine fueled with diesel, biodiesel and DBE blends with four ethanol blending ratios were investigated. The following main results are summarized:

(1) 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.

(2) The DBE blends retard the start of combustion and shorten the combustion duration resulting in longer premixed and shorter diffusive combustion duration when compared with biodiesel and ULSD. The higher the ethanol fraction in the blended fuel, the shorter the diffusion combustion duration and the lesser mass of fuel burned in the diffusion mode.

(3) DBE blends also lead to particulate reduction which is associated with shorter diffusive combustion in which less fuel mass is burnt as well as reduced aromatics and sulfur arising from partial replacement of diesel fuel with ethanol, favoring reduction in particulate by mass and by number. Biodiesel achieves the least BSPM but leads to increase of total particle, ultrafine and nano-particle concentrations. On the contrary, DBE blends could effectively attain lower BSPM and BSPN emissions in particular with lesser ultrafine and nano-particle concentrations than ULSD.

(4) The ethanol in DBE blends has an added advantage of reducing NOx emissions, leading to lower BSPM, BSPN and BSNOx than ULSD and lower BSPN and BSNOx but higher BSPM than biodiesel. The use of DBE blends can weaken the PM-PN-NOx trade-off relationship.

Therefore, the use of DBE blends can effectively reduce NOx, total ultrafine and nano-particle concentrations than ULSD and biodiesel except particle mass concentrations a bit higher than biodiesel. However, for better understanding the characteristics of DBE fuel, there is a need for further investigation on other DBE mixing ratios than those explored in this paper; furthermore investigation on the effects of DBE on particle volatility, oxidation properties, morphology and toxicity would widen our understanding on properties of DBE particles.

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