Fuel 90 (2011) 1743–1750

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Combustion, performance and emission characteristics of a DI diesel engine fueled with ethanol–biodiesel blends

Lei Zhu [a,b], C.S. Cheung [b,*], W.G. Zhang [a], Zhen Huang [a]

[a] Key Laboratory for Power Machinery and Engineering of M.O.E., Shanghai Jiaotong University, PR China
[b] Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, PR China

ARTICLE INFO

Article history:
Received 7 April 2010
Received in revised form 17 January 2011
Accepted 19 January 2011
Available online 2 February 2011

Keywords:
Biodiesel
Euro V diesel fuel
Ethanol
Combustion
Emission

ABSTRACT

In this study, Euro V diesel fuel, biodiesel, and ethanol–biodiesel blends (BE) were tested in a 4-cylinder direct-injection diesel engine to investigate the combustion, performance and emission characteristics of the engine under five engine loads at the maximum torque engine speed of 1800 rpm. The results indicate that when compared with biodiesel, the combustion characteristics of ethanol–biodiesel blends changed; the engine performance has improved slightly with 5% ethanol in biodiesel (BE5). In comparison with Euro V diesel fuel, the biodiesel and BE blends have higher brake thermal efficiency. On the whole, compared with Euro V diesel fuel, the BE blends could lead to reduction of both NO_x and particulate emissions of the diesel engine. The effectiveness of NO_x and particulate reductions increases with increasing ethanol in the blends. With high percentage of ethanol in the BE blends, the HC, CO emissions could increase. But the use of BE5 could reduce the HC and CO emissions as well.

1. Introduction

The demand for energy around the world is increasing, specifically the demand for petroleum fuels. World energy consumption is expected to increase to 180,000 GWh/year by 2020 [1]. Facing the increasing consumption of petroleum fuels and the increasingly stringent emission regulations, biofuels, such as ethanol and biodiesel, have been explored to reduce fuel consumption and engine emissions. Biodiesel is an alternative diesel fuel consisting of alkyl monoesters of fatty acids derived from vegetable oil or animal fats. Because of its reproducibility, nontoxicity, and sulfur-free property, a considerable amount of recent research has focused on the use of biodiesel on diesel engines. Furthermore, due to its similar physical properties to diesel fuel, there is no need to modify the engine when the engine is fueled with its blends [2,3].

In comparison with conventional diesel fuels, the fuel-borne oxygen in biodiesel may promote more complete combustion and thus reduce particulate matter (PM), carbon monoxide (CO) and total hydrocarbons (THC) in compression-ignition engine, while increase nitrogen oxides (NO_x) [4]. According to a review on emission data for heavy-duty engines published by EPA (Environmental Protection Agency of USA) [5], from diesel to B20 (20% biodiesel by volume), CO, HC, and PM decreased by 13%, 20% and 20% respectively, while NO_x emission increased by 4% on average. The same trends are obtained in the review paper published by Lapuerta et al. [6]. Thus, the higher NO_x emission arising from the use of biodiesel might be considered as an obstacle of biodiesel application. However, there are also opposite trends of NO_x emission in the literature. The results of Rakopoulos et al. [7] showed a slight decrease in NO_x emission.

Ethanol, with a high oxygen content of 35%, has been used in compression-ignition engine as ethanol–diesel blends. Lapuerta et al. [8] studied the emissions of diesel–bioethanol blends in a diesel engine and concluded that the use of ethanol–diesel blends provided a significant reduction on PM emissions, with no substantial increase in other gaseous emissions (NO_x, HC, CO). Ahmed [9] compared a 10% ethanol–diesel blend and a 15% ethanol–diesel blend with baseline diesel fuel when applied to a compression-ignition engine. They found 27% and 41% reduction in PM respectively for 10% and 15% ethanol–diesel blends, while an increase of 4% and 5% in NO_x respectively for 10% and 15% ethanol–diesel blends. Moreover, the use of ethanol–diesel blends has some disadvantages; for instance, an additive is required for ensuring good mixing of the two fuels and the blended fuel has poor lubricity. Biodiesel could be served as a good additive in stabilizing ethanol in diesel blends. Kwanchareon et al. [10] studied the solubility and emission characteristics of diesel–biodiesel–ethanol blends. They found that CO and HC reduced significantly at high engine load, whereas NO_x increased, when compared with those of diesel fuel. Chen et al. [11] reported that increasing ethanol in ester–ethanol–diesel blended fuel, the dry soot emission in PM was reduced significantly, the sulfate emission hardly changed, and the SOF emission in PM decreased when the ethanol percentage

* Corresponding author. Tel.: +852 2766 7819; fax: +852 2365 4703.
E-mail address: mmcsc@polyu.edu.hk (C.S. Cheung).

0016-2361/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.fuel.2011.01.024

was less than 20%. However, biodiesel and ethanol can be mixed without phase separation while the potential of the ethanol in reducing NO_x emission is an added advantage. Ren et al. [12] and Hansen et al. [13] showed that the drop of combustion temperature due to the higher heat of evaporation could suppress NO_x emissions and concluded that ethanol could act as an effective NO_x emissions reducing additive.

There are limited literatures focused on the application of ethanol–biodiesel blends to diesel engine. Kumar et al. [14] applied ethanol in animal fat to a diesel engine. They found that NO_x emission decreased, while HC and CO emissions increased at low loads but decreased at high loads. Lebedevas et al. [15] reported that CO and NO_x emissions decreased up to 10–12% for every 10% increase of ethanol blended with rapeseed oil methyl esters. Bhale et al. [16] studied the performance and emissions on Mahua biodiesel blended with ethanol. In their study, they found reduction of CO and NO_x emissions using 20% blended fuel but an increase in HC emission. However, there is lack of detailed data on combustion and emission of ethanol blended with biodiesel produced from waste cooking oil. Thus, the aim of this study is to investigate the combustion, performance and emissions of a diesel engine operating on ethanol–biodiesel blends, using biodiesel produced from waste cooking oil, and to compare these results with those obtained from neat biodiesel and Euro V diesel fuel.

2. Test engine and fuel properties

The experiments were carried out on a naturally aspirated, water-cooled, 4-cylinder, direct-injection diesel engine. The specifications of the engine are shown in Table 1. The engine was connected to an eddy-current dynamometer, and a control system was used for adjusting its speed and torque. The fuels used in this study include Euro V diesel fuel, biodiesel and biodiesel–ethanol blends. The blended fuels contain 5%, 10% and 15% by volume of ethanol, and are identified as BE5, BE10, and BE15 fuels. The biodiesel was produced from waste cooking oil by Dunwell Petro-Chemical Ltd. The major properties of the fuels are shown in Table 2. In Table 2 the lower heating values of Euro V diesel fuel and biodiesel were determined with bomb calorimeter while the lower heating value of ethanol was obtained with the Mendeleyev's formula [17]. The densities of the three fuels were measured in situ at 20 °C. Other properties of the fuels were obtained either from the literature or from fuel specifications. For example, the properties of biodiesel follow those in Utlu [18] while the percentage of C/H/O was evaluated by assuming a typical biodiesel composition of $C_{18.96}H_{35.64}O_2$ [19]. The latent heat of evaporation and lower heating value of each blended fuels were calculated based on the mass fraction of each chemical in the blended fuel.

3. Experimental setup and measurements

The experimental system is shown in Fig. 1. The cylinder pressure was measured by a Kistler piezoelectric sensor (Type 6056A). The pressure signals were amplified with a Kistler charge amplifier (Type 5011B) and analyzed with a combustion analyzer (DEWETRON, DEWE-ORION-0816-100×) to obtain the heat release rate. A crank angle encoder was employed for crank-angle signal acquisition. CO and CO_2 concentrations were measured with non-dispersive infra-red analyzers (NDIR, CAI 300). NO_x emission and THC emission were measured with a heated chemiluminescent analyzer (HCLD, CAI 400) and a heated flame ionization detector (HFID, CAI 300) respectively. The gas analyzers were calibrated with standard gases and zero gas before each test. Particulate mass concentration was measured with a tapered element oscillating microbalance (TEOM, Series 1105, Rupprecht & Patashnick Co., Inc.). Before passing through the TEOM, the exhaust gas was diluted with a Dekati mini-diluter. The dilution ratio (DR) was calculated based on the following equation:

$$DR = \frac{[CO_2]_{exhaust} - [CO_2]_{background}}{[CO_2]_{diluted} - [CO_2]_{background}}$$

where $[CO_2]_{exhaust}$, $[CO_2]_{diluted}$ and $CO_2]_{background}$ represents respectively the undiluted, the diluted and the background CO_2 concentration.

Experiments were conducted at a steady engine speed of 1800 r/min and at five engine loads, corresponding to the brake mean effective pressures of 0.08 MPa, 0.2 MPa, 0.38 MPa, 0.55 MPa, and 0.70 MPa. The maximum engine torque attainable with the test engine was around 240 Nm, corresponding to the engine load of 0.70 MPa. Engine performance deteriorated significantly beyond this engine load. At each engine operating mode, experiments were carried out for the diesel fuel, biodiesel and each of the BE blends. To ensure the repeatability and comparability of the measurements, the cooling water temperature was automatically controlled by a temperature controller to 80 °C, and held to within ±2 °C, while the lubricating oil temperature varied from 90 to 100 °C, depending on the engine load. Data were recorded after the engine has reached the steady state, as indicated by the lubricating oil temperature and the cooling water temperature. In this study, the diesel engine was not modified during all the tests. Moreover, for minimizing the cross contamination of different fuels with each other, before each test, the engine was allowed to operate with the new fuel for thirty minutes to clean the fuel system. The data were recorded continuously for 5 min to reduce experimental uncertainties, and average values were presented. Each test was repeated twice to ensure that the results are repeatable within the experimental uncertainties. The standard errors have been calculated by the method of Kline and McClintock [20]

Table 1
Engine specifications.

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

Table 2
Properties of Euro V diesel fuel, biodiesel, ethanol and blended fuel.

Property	EuroV diesel	Biodiesel	Ethanol	BE5	BE10	BE15
Cetane number	>51	51	6	–	–	–
Lower heating value (MJ/kg)	42.5	37.5	28.4	37.1	36.7	36.2
Density (kg/m^3) @ 20 °C	840	871	786	867	862	858
Viscosity (mm^2/s) @ 40 °C	2.86	5.28	1.2	–	–	–
Heat of evaporation (kJ/kg)	250–290	300	840	324.5	349.2	374.2
Carbon content (% mass)	86.6	77.1	52.2	76.0	74.8	73.7
Hydrogen content (% mass)	13.4	12.1	13	12.1	12.2	12.2
Oxygen content (% mass)	0	10.8	34.8	11.9	13.0	14.1
Sulfur content (mg/kg)	<10	<10	0	–	–	–

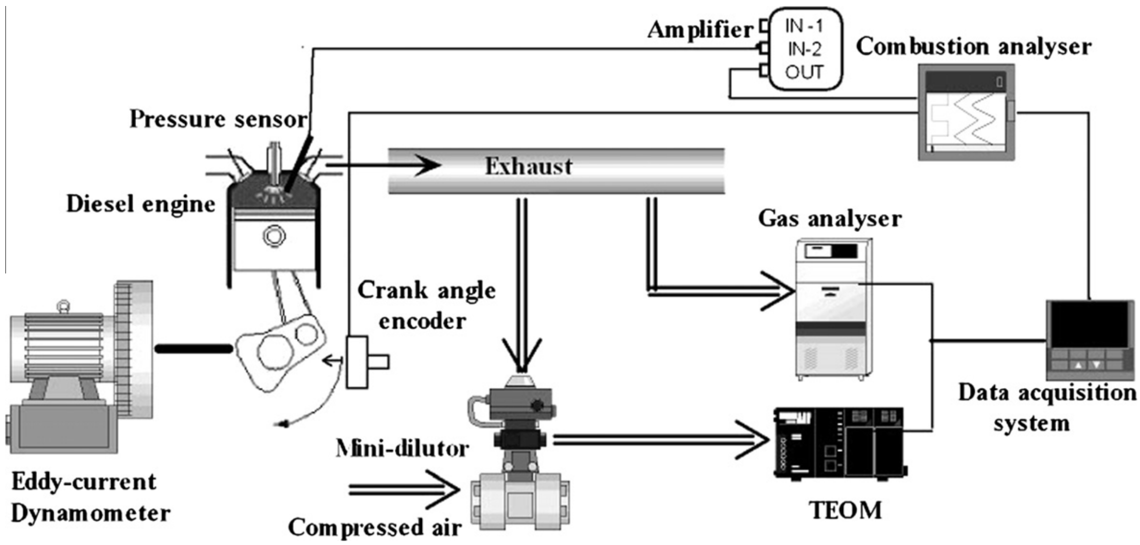

Fig. 1. Schematic diagram of experimental system.

and Ames et al. [21]. The standard errors are 8.6%, 2.9%, 5.2% and 1.3%, for THC, NO_x, CO, and mass fuel consumption respectively.

4. Result and discussion

4.1. Combustion characteristics

The in-cylinder pressure and heat release rate, averaged over 400 cycles, for the different fuels, are compared in Fig. 2 for the engine loads of 0.20 MPa, 0.38 MPa, and 0.70 MPa respectively. It can be seen from the figure that, at the same operating condition, the in-cylinder pressure curves of biodiesel and the BE blends are similar to that of Euro V diesel fuel. With increase in engine load, there is a corresponding increase in the maximum in-cylinder pressure, while the maximum pressure occurs further away from the top dead center (TDC) with increase in engine load. Also, the heat release rates of all the fuels have similar shape; having a premixed combustion phase followed by a diffusion combustion phase. It can be found that the premixed combustion phase for all the fuels is shortened, while the diffusion combustion phase is lengthened, with the increase of engine load. The maximum heat release rate increases with an increase in engine load from the low to the medium, but decreases at high engine load for all fuels, which is similar to the results of Lu et al. [22]. Moreover, with increase of engine load, the maximum heat release rate occurs slightly closer to the TDC, which is opposite to that of the in-cylinder pressure.

Compared with Euro V diesel fuel, biodiesel gives almost the same level of maximum pressure at low and medium engine loads, but higher maximum pressure at the high engine load. For biodiesel, the maximum heat release rate at the premixed combustion phase is lower than that of Euro V diesel fuel in all test modes, and occurs earlier, while the heat release rate of diffusion combustion phase is higher for biodiesel, in comparison with that of Euro V diesel fuel, especially at the high engine load. This trend is similar to that of Yu et al. [23].

Biodiesel vaporizes more slowly than Euro V diesel fuel and contributes to less air–fuel mixture prepared for combustion in the premixed phase [24]. In addition, biodiesel injected into the engine cylinder could form gaseous compounds of low molecular weight through thermal cracking [23]. The gaseous compounds could be ignited earlier, leading to earlier ignition timing. Moreover, the higher bulk modulus of compressibility of methyl esters lead to advanced injection timing with in-line pump-line-nozzle fuel injection system [25,26]. The earlier injection timing of biodiesel contributed to the advance of the peak cylinder pressure and the maximum heat release rate [24,27].

For the BE blends, the maximum pressure and the heat release rate increase with the increase of ethanol fraction in the blended fuel and occur further away from the TDC in comparison with biodiesel, indicating that there is a delay in the start of combustion. Because of the lower cetane number of ethanol, the start of combustion is retarded, leading to more fuel combusted in the premixed phase, resulting in the higher maximum pressure and higher premixed heat release rate [8,28]. Also, the increase in ignition delay with the BE blends could be explained by the higher latent heat of vaporization of ethanol which causes lower in-cylinder temperature and hence increase in ignition delay [22]. Moreover, due to the lower density and viscosity of ethanol [29], the BE blends could improve the spray characteristics and enhance the mixing of fuel and air, and hence increase the premixed heat release rate and the maximum pressure. At the diffusion combustion phase, the BE blends give higher heat release rate than that of biodiesel and Euro V diesel fuel, indicating that the diffusive combustion phase is improved due to the higher oxygen content of the BE blends, which also leads to reduction of the combustion duration.

Detailed information of the start of combustion and the combustion duration are shown in Fig. 3. The start of combustion is defined as the beginning of heat release, and the end of combustion is defined as the crank angle where the summated heat release is 95% of the total heat release. The combustion duration is the time interval from the start of combustion to the end of combustion. With increase of engine load, the start of combustion is advanced, while the combustion duration is prolonged. Compared with Euro V diesel fuel, biodiesel gives earlier start of combustion and shorter combustion duration. While for the BE blends, the start of combustion is retarded and the combustion duration is shortened, in comparison with biodiesel. Donahue and Foster [30] showed that higher oxygen content in the spray (from oxygen enriched air or oxygenated fuel) reduced pyrolysis and increased oxidation, thus shortening the combustion duration.

In order to better understand the effect of ethanol on the combustion characteristics, another combustion parameter is obtained based on the heat release analysis. Fig. 4 shows the effect of different fuels and engine loads on the crank angles corresponding to 10%, 50%

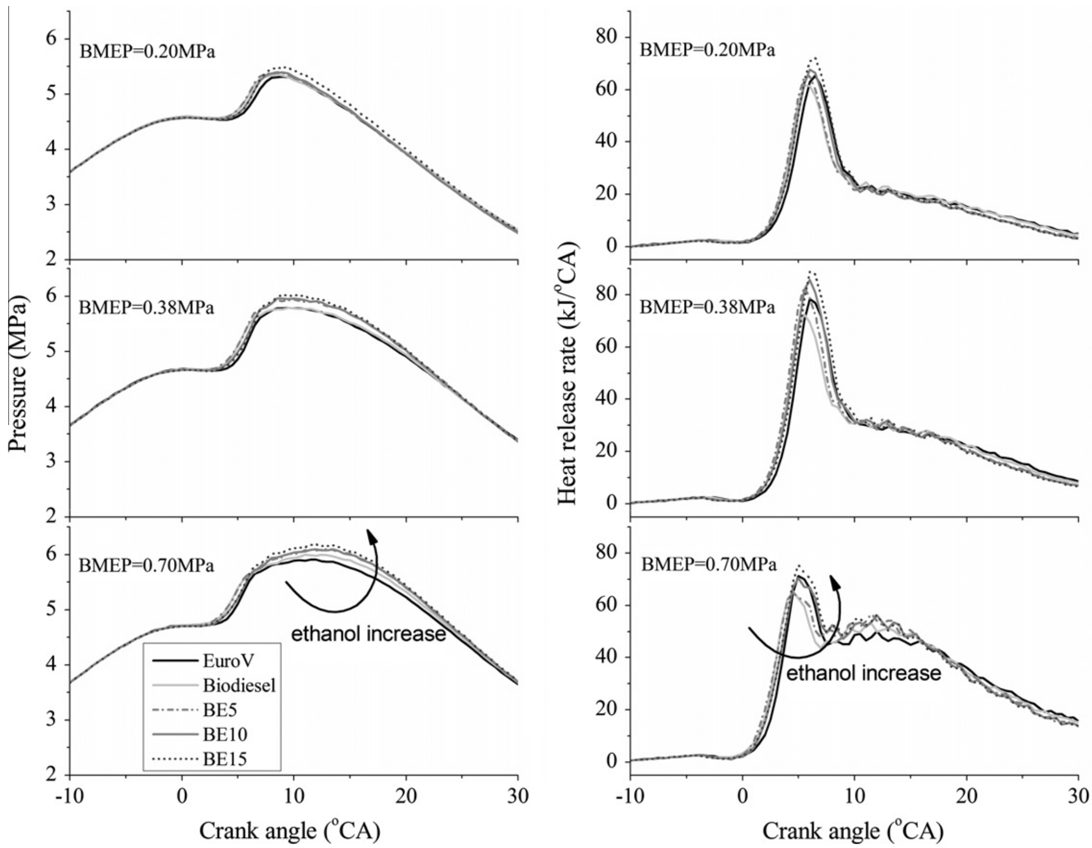

Fig. 2. In-cylinder pressure and heat release rate.

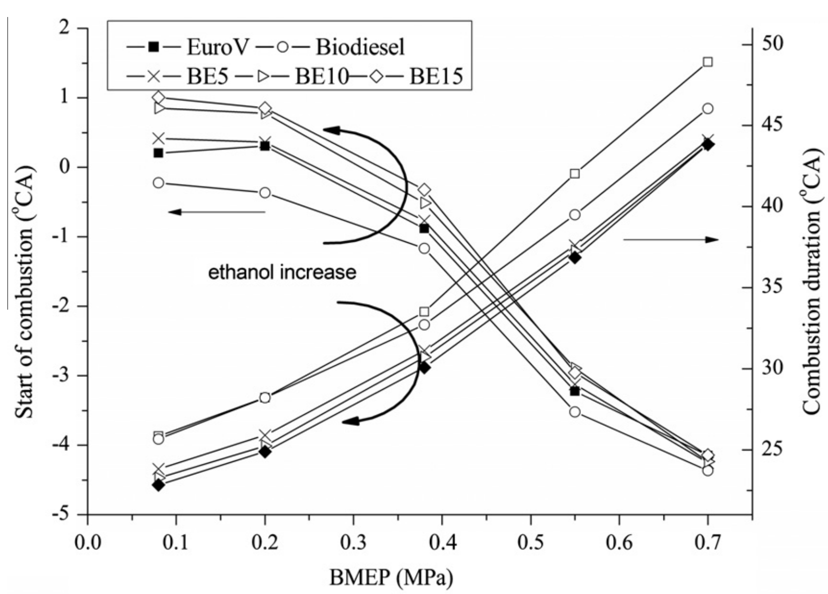

Fig. 3. Start of combustion and combustion duration.

and 90% of the total heat release. As seen in the figure, all the BE blends give faster combustion in all test modes than biodiesel and Euro V diesel fuel, which could compensate the initial ignition delay in start of combustion [8]. Also, the faster combustion process in each stage could lead to the increase in brake thermal efficiency (BTE). Information on BTE is discussed in the next section.

4.2. Brake specific fuel consumption and thermal efficiency

The brake power, the brake specific fuel consumption (BSFC), and the brake thermal efficiency (BTE) have been calculated from the engine torque, engine speed and fuel consumption rate and shown in Fig. 5.

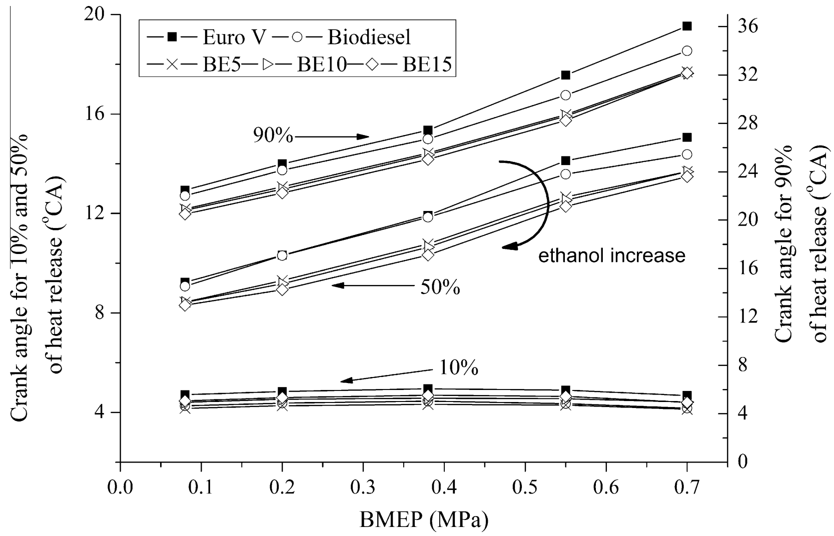

Fig. 4. Crank angle for 10%, 50% and 90% of heat release.

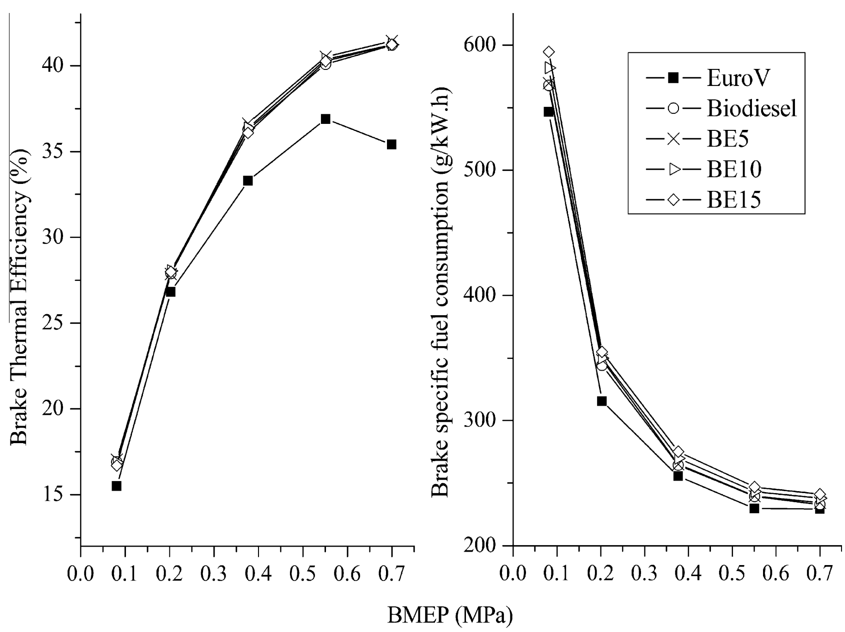

Fig. 5. Brake thermal efficiency and brake specific fuel consumption.

The BSFC decreases with an increase in engine load. For biodiesel and the BE blends, the BSFC are higher than that of Euro V diesel fuel. For each engine load, the BSFC increases with the proportion of ethanol in the blended fuel. The increase of BSFC is due mainly to the lower calorific values of biodiesel and ethanol compared with that of Euro V diesel fuel.

The variation of brake thermal efficiency (BTE) is also shown in Fig. 5. The BTE increases with an increase in engine load. However, the BTE of Euro V diesel fuel decreases at 0.70 MPa, indicating deterioration in engine performance at this engine load. The BTE of biodiesel is higher than that of Euro V diesel fuel and it increases with engine load, even at 0.70 MPa. Thus, the difference in BTE between the diesel fuel and biodiesel is very significant at 0.70 MPa. Compared with biodiesel, the blended fuels have almost the same BTE, except for BE5, which has slightly higher BTE than biodiesel. The increase of BTE is due to the improvement of the combustion process on account of increased oxygen content in the fuels. According to Fig. 4, the faster combustion process of the blended fuels and biodiesel in all modes could be a contributor of the increase in BTE. Moreover, based on the heat release rate analysis, the crank angle at which 50% of biodiesel or the blended fuels are burned is closer to the top dead center, leading to higher positive work done on the piston and hence higher BTE than that of Euro V diesel fuel.

Ethanol has lower stoichiometric air/fuel ratios than biodiesel and diesel fuel, thus blending ethanol into biodiesel leads to leaner combustion. The calculated equivalence ratios for different fuels are shown in Fig. 6. It is obvious that the equivalence ratio of the air and Euro V diesel fuel mixture is higher than those of the other fuels. With increase in the proportion of ethanol, the equivalence ratio decreases. However, this effect is slight, especially at light load.

4.3. Emission characteristics

The brake specific CO emissions (BSCO) are shown in Fig. 7a. As seen in the figure, the BSCO emissions decrease with increase of

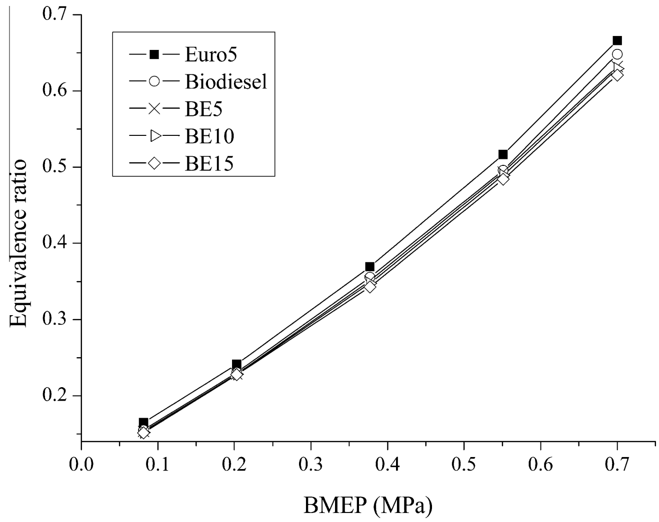

Fig. 6. Equivalence ratio.

engine load, due to the increase of in-cylinder gas temperature. Compared with the diesel fuel, the BSCO emissions of biodiesel are lower, because of the higher oxygen content of biodiesel, which could improve the combustion process. As seen in Fig. 2, biodiesel gives a faster combustion process in all modes, which could contribute to the reduction of CO emission. For BE5, the BSCO emission is even lower than that of biodiesel in all test modes. Bhale et al. [16] also reported that CO emissions decreased when operated with Mahua biodiesel blended with ethanol. Thus, for BE5, the higher oxygen content may be the major factor, leading to the reduction of CO emission. However, for BE10 and BE15, compared with biodiesel, the BSCO emissions are higher at light and medium engine loads, while on the same level at high engine load. The higher the proportion of ethanol in the blended fuel is, the higher the BSCO emissions are. From pure biodiesel to BE15, the increases are 79.6%, 45.6%, and 6.1%, respectively for the engine loads of 0.08 MPa, 0.20 MPa and 0.38 MPa. For BE10 and BE15, the cooling effect is the dominant factor at light engine loads. Nevertheless, statistical treatment of data shows that at high engine loads of 0.55 MPa and 0.70 MPa, there is no significance difference in the BSCO emissions at the 95% confidence level ($P < 0.05$) among the different fuels.

Fig. 7b shows the variation of brake specific HC (BSHC) emissions. Similar to the BSCO emissions, with an increase in the engine load, the BSHC emissions decrease. Compared with Euro V diesel fuel, biodiesel and the BE blends give lower BSHC emissions. The BSHC emissions of biodiesel decrease 60%, 38%, 32%, 40% and 30% at the engine loads of 0.08 MPa, 0.20 MPa, 0.38 MPa, 0.55 MPa and 0.70 MPa, respectively, in comparison with Euro V diesel fuel. The higher oxygen content of biodiesel leads to better combustion,

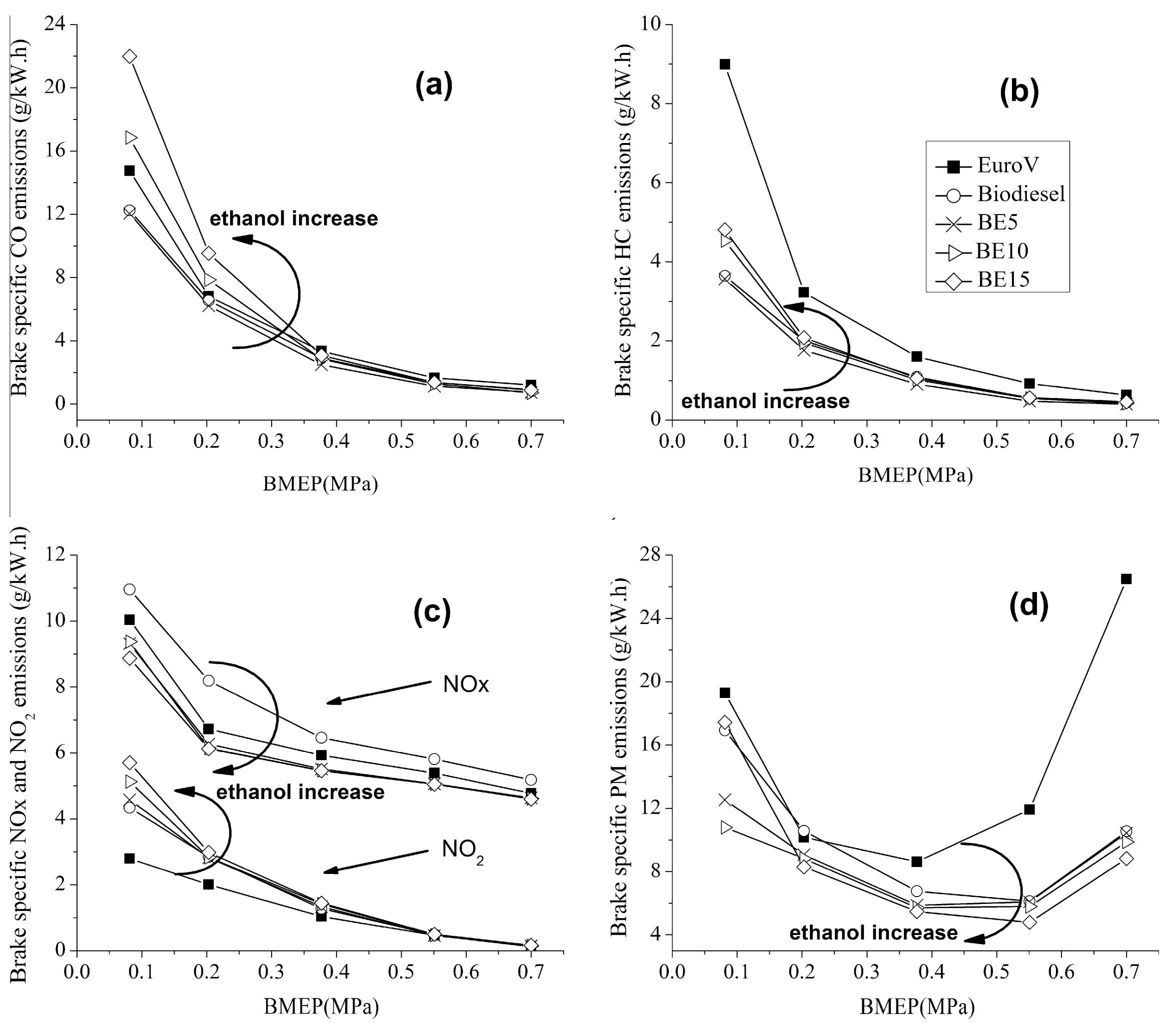

Fig. 7. Brake specific emissions.

resulting in lower BSHC. Moreover, Di et al. [31] suggested that the lower volatility of biodiesel compared with the diesel fuel might be the major factor for the large difference of HC emissions especially at low engine loads. It is because that some unburned biodiesel or its hydrocarbons could condense in the tailpipe due to the lower exhaust gas temperature at low engine loads.

Compared with biodiesel, the BSHC emissions of BE5 are lower. However, the BSHC emissions of BE10 and BE15 are higher than that of biodiesel at low engine loads, but at similar level at middle and high engine loads. Shudo et al. [28] obtained similar results of BSHC emission with ethanol-palm oil methyl ester blends. For BE5, the small amount of ethanol could increase the oxygen content and reduce the viscosity and density of the blended fuel, leading to improved spray and atomization, better combustion and hence lower CO and HC emissions. While for BE10 and BE15, the cooling effect of ethanol could reduce the in-cylinder gas temperature, leading to poorer oxidation reaction rate and hence increase in BSCO and BSHC emissions at low engine loads. At high engine loads, as more fuel is combusted, the in-cylinder gas temperature is much higher. This counteracts the cooling effect of the ethanol and hence the difference in BSCO and BSHC emissions between biodiesel and the blended fuels are much less significant than those observed at light engine loads. In fact the difference in BSCO and BSHC emissions among the different fuels decreases with engine load.

The brake specific NO_x ($BSNO_x$) emissions are shown in Fig. 7c. The $BSNO_x$ emissions decrease with increase in the engine load. Compared with the diesel fuel, for biodiesel, the $BSNO_x$ emissions increased by 11%, averaged over the engine loads. In addition, with increase of ethanol in the BE blends, the $BSNO_x$ emissions decrease at low engine loads of 0.08 MPa and 0.20 MPa, while at medium and high engine loads, there is no significant difference among the BE blends. The $BSNO_x$ emissions of the BE blends are even lower than that of the diesel fuel.

Fernando et al. [1] concluded that the thermal mechanism dominates the formation of NO_x in biodiesel combustion. Thus the major factors affecting NO_x formation are combustion temperature, local oxygen concentration and residence time in the high temperature zone. Obviously, with biodiesel, the combustion temperature as well as the oxygen contents could be higher, leading to the higher NO_x emissions. For the BE blends, the cooling effect of ethanol associated with its lower calorific value and higher latent heat of evaporation could reduce the combustion temperature and hence reduce the NO_x emissions. However, ethanol could reduce the cetane number of the blended fuel, which means longer ignition delay period and a larger amount of fuel burned in the premixed mode, and hence higher NO_x emission. The higher oxygen contents of ethanol could also enhance NO_x emission. These factors act against each other. For the BE fuels, the cooling effect of ethanol seems to be the dominating effect leading to the overall reduction of NO_x emission.

NO_x contains NO and NO_2, thus it is important to investigate the influence of the BE blends on NO_2 emissions. The results are also shown in Fig. 7c. Similar to the $BSNO_x$ emissions, the $BSNO_2$ emissions decrease with engine load. Compared with the diesel fuel, the $BSNO_2$ emissions of biodiesel and the blended fuels are much higher, especially at light and medium engine loads. The $BSNO_2$ emissions of the BE blends are higher than those of biodiesel. From biodiesel to BE15, the $BSNO_2$ emissions increased by 11% at light loads. However, at high engine loads, the difference in $BSNO_2$ emissions is not significant. NO_2 is primarily formed in hot gases by the reaction of NO with the HO_2 radicals [32]. The efficiency of NO oxidation depends on the production of the peroxyl radicals, HO_2. Taylor et al. [33] studied the influence of NO on the oxidation of methanol and ethanol. Their result shows that ethanol could produce peroxyl radicals through the thermal degradation behavior of ethanol with NO. Lyon et al. [34] also concluded that HO_2 is readily formed during the oxidation of oxygenated fuel, which could function as a source of HO_2 and thus enhance the oxidation of NO to NO_2. Thus, with the increase of ethanol in the blended fuel, NO_2 emission increases correspondingly, especially at low and medium engine loads.

The brake specific PM emissions are shown in Fig. 7d. With the engine loads increasing from 0.08 MPa to 0.38 MPa, the BSPM decreased in general while from 38 MPa to 0.7 MPa it increased. Compared with Euro V diesel fuel, biodiesel gives lower BSPM emissions in most test modes. The reduction in BSPM emissions when using biodiesel is due to the oxygen content of biodiesel which leads to more complete oxidation. Tsolakis [35] reported that compared with diesel fuel, biodiesel led to a reduction in particulate mass emissions due to advanced combustion, which coincides with heat release characteristics of this study. Moreover, biodiesel contains less aromatic than that of diesel fuel. The reduction of smoke may be due to the dilution of aromatics, which are soot precursors.

When the diesel engine is fueled with the BE blends, the BSPM emissions decreased obviously, compared with Euro V diesel fuel and biodiesel. Cheng et al. [36] concluded that ethanol could reduce the soot precursors (and therefore soot and PM), due to the production of OH radicals by the ethanol. Moreover, for ethanol, the source of OH was due to the following reactions:

$$C_2H_5OH \rightarrow C_2H_4 + H_2O \quad (1)$$

$$H_2O + H \rightarrow OH + H_2 \quad (2)$$

The above reactions involve the conversion of a reactive hydrogen atom to molecular hydrogen, leading to a slowdown in the formation of soot [37]. Shudo et al. [28] reported that the retarded ignition timing associated with the ethanol–biodiesel blended fuel increases the rate of heat release during the premixed combustion, and concluded that the reduction of smoke could be attributed to the improved premixed combustion rate. Moreover, the addition of ethanol reduces the initial radicals for the formation of aromatic rings, which are considered as the soot precursors, mainly through reducing the amount of carbon that is available to form precursor species [37]. While for BE15, at the light engine load of 0.2 MPa, the BSPM emission is higher than that of biodiesel, due to the cooling effect of ethanol at this engine load [36].

5. Conclusion

The objective of this study is to investigate the combustion, engine performance and emissions of a diesel engine operating on ethanol–biodiesel blends and to compare these results with those operating on neat biodiesel and Euro V diesel fuel. Based on the experimental results, the conclusions can be summarized as follows:

Compared with Euro V diesel fuel, for biodiesel, the maximum pressure is higher at high engine loads; the maximum heat release rate of premixed combustion phase is lower in all test modes, and occurs earlier; combustion starts earlier and the combustion duration is shorter. Compared with biodiesel, the maximum pressure and the heat release rate of the BE blends increase with the increase of ethanol fraction in the blended fuel and occurs further away from the TDC; the start of combustion is retarded and the combustion duration is shortened. The brake thermal efficiency increases slightly with BE5, while there is no significant difference with BE10 and BE15.

Biodiesel produces lower BSCO, BSHC and BSPM emissions, while higher BSNOx and $BSNO_2$ emissions, in comparison with Euro V diesel fuel. Compared with biodiesel, BE5 gives slightly lower BSCO and BSHC emissions in all test modes while BE10 and BE15 have higher BSCO and BSHC emissions at light and medium engine loads but similar level of emissions at medium and high engine loads. In generally, the BE blends have lower $BSNO_x$ and higher $BSNO_2$ emissions, compared with biodiesel. With the increase of ethanol in the blended fuel, the $BSNO_x$ emissions decrease and the $BSNO_2$ emissions increase at low engine loads, while there is no significant difference among the BE blends at medium and high engine loads. The BSPM emissions of the BE blends decrease obviously, compared with Euro V diesel fuel and biodiesel.

Compared with the diesel fuel, biodiesel gives lower particulate emission but higher NO_x emissions. However, the BE blends gives lower particulate emission as well as lower NO_x emission.

Acknowledgment

The authors would like to thank The Hong Kong Polytechnic University (GU482, GU706), the National Natural Science Fund of China (No. 50676056), Key Project of Chinese Ministry of Education (No. 307011) and Shanghai Jiaotong University for financial support to this study.

References

[1] Fernando S, Hall C, Jha S. NO_x reduction from biodiesel fuels. Energy Fuels 2006;20:376–82.
[2] Ramadhas AS, Jayaraj S, Muraleedharan C. Use of vegetable oils as I.C. engine fuels – a review. Renew Energy 2004;29:727–42.
[3] Graboski MS, McCormick RL. Combustion of fat and vegetable oil derived fuels in diesel engines. Prog Energy Combust Sci 1998;24:125–64.
[4] Zheng M, Mulenga MC, Reader GT, Wang M, Ting DSK, Tjong J. Biodiesel engine performance and emissions in low temperature combustion. Fuel 2008;87:714–22.
[5] Environmental Protection Agency of USA. A comprehensive analysis of biodiesel impacts on exhaust emissions, Draft tech. report.; 2002. EPA420-P-02-001.
[6] Lapuerta M, Armas O, Rodríguez-Fernández J. Effect of biodiesel fuels on diesel engine emissions. Prog Energy Combust Sci 2008;34:198–223.
[7] Rakopoulos CD, Antonopoulos KA, Rakopoulos DC, Hountalas DT, Giakoumis EG. Comparative performance and emissions study of a direct injection diesel engine using blends of Diesel fuel with vegetable oils or bio-diesels of various origins. Energy Convers Manage 2006;47:3272–87.
[8] Lapuerta M, Armas O, Herreros José M. Emissions from a diesel–bioethanol blend in an automotive diesel engine. Fuel 2008;1:25–31.
[9] Ahmed I. Oxygenated diesel: emissions and performance characteristics of ethanol–diesel blends in CI engines. SAE Tec Pap Ser; 2001. No. 2001-01-2475.
[10] Kwanchareon P, Luengnaruemitchai A, Jai-In S. Solubility of a diesel–biodiesel–ethanol blend, its fuel properties, and its emission characteristics from diesel engine. Fuel 2007;86:1053–61.
[11] Chen H, Shi-Jin S, Jian-Xin W. Study on combustion characteristics and PM emission of diesel engines using ester–ethanol–diesel blended fuels. Proc Combust Inst 2007;31:2981–9.
[12] Ren Y, Huang ZH, Jiang DM, Li W, Liu B, Wang XB. Effect of the addition of ethanol and cetane number improver on the combustion and emission characteristics of a compression ignition engine. Proc Inst Mech Eng Part D – J Automob Eng 2008;222:1077–87.
[13] Hansen AC, Gratton MR, Yuan W. Diesel engine performance and NO*x* emissions from oxygenated biofuels and blends with diesel fuel. Trans Am Soc Agric Biol Eng 2006;49:589–95.
[14] Kumar MS, Kerihuel A, Bellettre J, Tazerout M. Ethanol animal fat emulsions as a diesel engine fuel – Part 2: engine test analysis. Fuel 2006;85:2646–52.
[15] Lebedevas S, Lebedeva G, Makareviciene V, Janulis P, Sendzikiene E. Usage of fuel mixtures containing ethanol and rapeseed oil methyl esters in a diesel engine. Energy Fuels 2009;23:217–23.
[16] Bhale PV, Deshpande NV, Thombre SB. Improving the low temperature properties of biodiesel fuel. Renew Energy 2009;34:794–800.
[17] Bayraktar H. An experimental study on the performance parameters of an experimental CI engine fueled with diesel–methanol–dodecanol blends. Fuel 2008;87:158–64.
[18] Utlu Z. Evaluation of biodiesel fuel obtained from waste cooking oil. Energy Sources, Part A: Recov Util Environ Effects 2007;29:1295–304.
[19] Sgroi M, Bollito G, Saracco G, Specchia S. BIOFEAT: biodiesel fuel processor for a vehicle fuel cell auxiliary power unit-study of the feed system. J Power Source 2005;149:8–14.
[20] Kline SJ, McClintock FA. Describing uncertainties in single sample experiments. Mech Eng 1953;75:3–8.
[21] Ames WF, Cain G, Steele WG. Mathematics for mechanical engineers. Boca Raton (FL): CRC Press; 2000.
[22] Lu XC, Yang JG, Zhang WG, Huang Z. Effect of cetane number improver on heat release rate and emissions of high speed diesel engine fueled with ethanol–diesel blend fuel. Fuel 2004;83:2013–20.
[23] Yu CW, Bari S, Ameen A. A comparison of combustion characteristics of waste cooking oil with diesel as fuel in a direct injection diesel engine. Proc Inst Mech Eng Part D: J Automob Eng 2002;216:237–43.
[24] Ozsezen AN, Canakci M, Turkcan A, Sayin C. Performance and combustion characteristics of a DI diesel engine fueled with waste palm oil and canola oil methyl esters. Fuel 2009;88:629–36.
[25] Boehman AL, Morris D, Szybist J, Esen E. The impact of the bulk modulus of diesel fuel on fuel injection timing. Energy Fuels 2004;18:1877–82.
[26] Tat ME, Van Gerpen J, Soylu S, Canakci M, Monyem A, Wormley S. The speed of sound and isentropic bulk modulus of biodiesel at 21 °C from atmospheric pressure to 35 MPa. J Am Chem Soc 2000;77:285–9.
[27] Tsolakis A, Megaritis A, Wyszynski ML, Theinnoi K. Engine performance and emissions of a diesel engine operating on diesel-RME (rapeseed methyl ester) blends with EGR (exhaust gas recirculation). Energy 2007;32:2072–80.
[28] Shudo T, Hiraga K, Ogawa H. Mechanisms in reducing smoke and NO*x* from BDF combustion by ethanol blending and EGR. SAE Tec Pap Ser 2007; No. 2007-01-0622.
[29] Hansen AC, Zhang Q, Lyne PWL. Ethanol–diesel fuel blends –– a review. Biosour Technol 2005;96:277–85.
[30] Donahue R, Foster DE. Effects of oxygen enhancement on the emissions from a DI diesel via. Manipulation of fuels and combustion chamber gas composition. SAE Tec Pap Ser 2000; No. 2000-01-0512.
[31] Di Yage, Cheung CS, Huang ZH. Experimental investigation on regulated and unregulated emissions of a diesel engine fueled with ultra-low sulfur diesel fuel blended with biodiesel from waste cooking oil. Sci Total Environ 2009;407:835–46.
[32] Jimenez JL, Mcrae GJ, Nelson DD, Zahniser MS, Kolb CE. Remote sensing of NO and NO_2 emissions from heavy-duty diesel trucks using tunable diode lasers. Environ Sci Technol 2000;34:2380–7.
[33] Taylor PH, Cheng L, Dellinger B. The influence of nitric oxide on the oxidation of methanol and ethanol. Combust Flame 1998;115:561–7.
[34] Lyon RK, Cole JA, Kramlich JC, Chen SL. The selective reduction of SO_3 to SO_2 and the oxidation of NO to NO_2 by methanol. Combust Flame 1990;81:30–9.
[35] Tsolakis A. Effects on particle size distribution from the diesel engine operating on RME-biodiesel with EGR. Energy Fuels 2006;20:1418–24.
[36] Cheng AS, Dibble RW, Buchholz BA. The effect of oxygenates on diesel engine particulate matter. SAE Tec Pap Ser 2002; No. 2002-01-1705.
[37] Wu JT, Litzinger T, Lee SY, Santoro R, Linevsky M, Colket M, et al. Reduction of PAH and soot in premixed ethylene–air flames by addition of ethanol. Combust Flame 2006;144:675–87.