Performance and Emissions of a Compression Ignition Engine Fueled with Diesel/Oxygenate Blends for Various Fuel Delivery Advance Angles

ARTICLE *in* ENERGY & FUELS · FEBRUARY 2005

Impact Factor: 2.79 · DOI: 10.1021/ef049855d

7 AUTHORS, INCLUDING:

Zuohua Huang
Xi'an Jiaotong University

Performance and Emissions of a Compression Ignition Engine Fueled with Diesel/Oxygenate Blends for Various Fuel Delivery Advance Angles

Zuohua Huang,* Hongbing Lu, Deming Jiang, Ke Zeng, Bing Liu, Junqiang Zhang, and Xibin Wang

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, People's Republic of China

Received June 17, 2004. Revised Manuscript Received December 18, 2004

Oxygenated blends were prepared by adding methanol and solvent to diesel fuel, and engine performance and emissions of the oxygenated blends under various fuel delivery advance angles were conducted in a compression ignition engine. The results showed that the engine thermal efficiency increased and the diesel-equivalent brake specific fuel consumption decreased as the fuel delivery advance angle for the oxygenated blends increased, and the behavior had a tendency to be more obvious at high engine speed. The NO_x concentration in the oxygenated blends increased as the fuel delivery advance angle increased. For a specific fuel delivery advance angle, the NO_x concentration increased as the oxygenate mass fraction in the fuel blends increased, whereas a large addition of oxygenates in the diesel fuel reduced the NO_x concentration. The addition of oxygenate in the diesel fuel had a strong influence on the NO_x concentration at high engine load, whereas it had little influence at low engine load. The CO content decreased as the fuel delivery advance angle at high engine load became retarded, whereas at middle and low loads, the CO concentration varied little with variation of the fuel delivery advance angle but presented a low value for the diesel/oxygenate blends. The fuel delivery advance angle had little influence on the exhaust hydrocarbon (HC) content for the diesel/oxygenate blends. The amount of smoke can be decreased remarkably by the addition of oxygenate in diesel fuel at the setting of various fuel delivery advance angles. The amount of smoke decreased as the fuel delivery advance angles for both diesel fuel and diesel/oxygenate blends increased; this phenomenon would be due to the increase in the fraction of fuel burned in the premixed burning phase and the decrease in the fraction of fuel burned in diffusive combustion phase, as well as the improvement of the diffusive combustion in the presence of oxygenated blends. The study also showed that a flat NO_x/smoke trade-off curve existed when the oxygenated blends were used.

1. Introduction

The reduction of engine emissions is a major research aspect in engine development, given the increasing concern about environmental protection and the stringent exhaust gas regulations. It is difficult to reduce NO_x and smoke emissions simultaneously in normal diesel engines, because of the trade-off curve between NO_x and smoke. One prospective method to solve this problem is to use oxygenated alternative fuels or to add the oxygenated fuels in diesel, to provide more oxygen during combustion. In the application of pure oxygenated fuels, Fleisch et al.,[1] Kapus and Ofner,[2] and Sorenson and Mikkelsen[3] have studied dimethyl ether (DME) in a modified diesel engine, and their results showed that the engine could achieve ultralow-emission prospects without a fundamental change in combustion systems. Huang et al.[4] investigated the combustion and emission characteristics in a compression ignition engine with DME and determined that the DME engine had high thermal efficiency, short premixed combustion, and fast diffusion combustion. Kajitani et al.[5] studied the DME engine with delaying of the injection time to reduce both smoke and NO_x. These works realized the purpose of low-noise, smoke-free combustion.

Practically, the addition of some oxygenated compounds to fuels to reduce engine emissions without engine modification seems to be a more attractive proposition. Huang et al.[6] tested the gasoline−oxygenate

* Author to whom correspondence should be addressed. E-mail: zhhuang@mail.xjtu.edu.cn.

(1) Fleisch, T.; McCarthy, C.; Basu, A. A New Clean Diesel Technology: Demonstration of ULEV Emissions on a Navistar Diesel Engine Fueled with Dimethyl Ether. *SAE Trans.* **1995**, *104* (4), 42−53.

(2) Kapus, P.; Ofner, H. Development of Fuel Injection Equipment and Combustion System for DI Diesels Operated on Dimethyl Ether. *SAE Trans.* **1995**, *104* (4), 54−69.

(3) Sorenson, S. C.; Mikkelsen, S. E. Performance and Emissions of a 0.273 L Direct Injection Diesel Engine Fueled with Neat Dimethyl Ether. *SAE Trans.* **1995**, *104* (4), 80−90.

(4) Huang, Z. H.; Wang, H. W.; Chen, H. Y. Study on Combustion Characteristics of a Compression Ignition Engine Fueled with Dimethyl Ether. *Proc. Inst. Mech. Eng., Part D, Automot. Eng.* **1999**, *213* (D6), 647−652.

(5) Kajitani, Z.; Chen, L.; Konno, M. Engine Performance and Exhaust Characteristics of Direct-Injection Diesel Engine Operated with DME. *SAE Trans.* **1997**, *106* (4), 1568−1577.

(6) Huang, Z.; Miao, H.; Zhou, L.; Jiang, D. Combustion Characteristics and Hydrocarbon Emissions of a Spark Ignition Engine Fuelled with Gasoline−Oxygenate Blends. *Proc. Inst. Mech. Eng., Part D, Automot. Eng.* **2000**, *214* (D3), 341−346.

10.1021/ef049855d CCC: $30.25
Published on Web 02/02/2005

blends in a spark-ignited engine and got a satisfactory results on emission reduction, and Huang et al.[7] also investigated the combustion and emission characteristics of the combination of diesel and dimethyl carbonate (DMC) in a compression ignition engine. Murayama et al.[8] studied the emissions and combustion with exhaust gas recirculation (EGR) and DMC. Ajav et al.[9] studied blends of diesel and ethanol for emission reduction. Bertoli et al.,[10] Miyamoto et al.,[11] Akasaka and Sakurai,[12] and McCormick et al.[13] also conducted research on diesel combustion improvement and emission reduction, using various types of the oxygenated fuel blends.

Methanol is regarded as one of the promising alternative fuels or oxygen additives for diesel engines, with its advantages of low price and high oxygen content. However, because of the difficulty in forming a stabilized diesel/methanol blend, few reports have been found on this topic. Although some previous work has revealed the characteristics of diesel/ethanol blends in a compression ignition engine (Satge de Caro et al.,[14] Ali et al.[15]), there, however, is still much work that needs to be done in regard to the application of diesel/methanol blends in compression ignition engines, especially in clarifying the basic combustion and emission. This study is expected to supply more information on engine combustion when the engine is operating on oxygenated fuels and provide more practical measures for the improvement of combustion and reduction of emissions.

The objectives of this study were to form the oxygenated blends by adding methanol and solvent in diesel fuel and then study the characteristics of performance and emissions in a compression ignition engine fueled with the oxygenated blends under various fuel delivery advance angles.

2. Fuel Blends: Test Engine and Fuel Properties

The specifications of the test engine are listed in Table 1. Three types of oxygenated blends with different fractions of methanol and solvent additions in diesel fuel were selected for the study. Because of the low solubility of the methanol in diesel fuel, a solvent that consisted of oleic and iso-butanol was added to the diesel/methanol blends, to develop a stabilized oxygenated blend. Fuel properties and the constitutions of three oxygenated blends are given in Table 2, Table 3, and Figure 1, and the oxygen fraction in the fuel blends ranged from 5.87 to 11.1, as shown in Table 3 and Figure 2. It can be seen that methanol addition supplies a large proportion of oxygen for fuel blends rather than the solvent, although the mass fraction of methanol and solvent has the same level, so methanol would have large influence on engine combustion and emissions than the solvent from the point of oxygen contribution. The fuel properties show that methanol has a high oxygen content, whereas the heat value and the cetane number are low, compared to those of diesel fuel. These three oxygenated blends with different methanol and solvent proportions were experimentally investigated in the engine, and the combustion characteristics and exhaust emissions were measured and analyzed under the condition of same brake mean effective pressure (bmep). Furthermore, these parameters were compared with those of pure diesel combustion, to clarify the influence of the oxygenated additive on combustion and emissions. Combustion products were measured using a Horiba exhaust gas analyzer.

Table 1. Engine Specifications

parameter	value
bore	100 mm
stroke	115 mm
displacement	903 cm^3
compression ratio	18
shape of combustion chamber	ω shape in the bottom of a bowl-in-piston configuration
rated power and speed	11 kW, 2300 rpm
nozzle hole diameter	0.3 mm
number of nozzle holes	4

3. Results and Discussions

The brake specific fuel consumption (bsfc) of the oxygenated blends versus the fuel delivery advance angle (θ_{fd}) is shown in Figure 3. For the case of an engine speed of 1500 rpm, the bsfc value decreased as the θ_{fd} value increased and increased as the mass fraction of the oxygenated additives in the fuel blends increased at all engine loads and θ_{fd} values. Increasing the θ_{fd} value would increase the amount of fuel burned in the premixed burning phase and make the heat-release curve closer to the top-dead-center, subsequently decreasing the bsfc value. With respect to the behavior of the bsfc value versus the oxygenate mass fraction, two aspects should be taken into account. One aspect is that an increase in methanol and solvent mass fraction will result in a decrease in the cetane number of the oxygenated blends, which, in turn, increases the ignition delay period and increases the amount of fuel burned in the premixed burning phase, causing a high cylinder pressure rise and reducing the bsfc value. In the other aspect, however, the increase in mass fraction of methanol and solvent will increase the amount of injected fuel necessary to maintain the same brake mean effective pressure (bmep). The comprehensive result gave the increase in bsfc value with the increase of oxygenate mass fraction. In the case of high engine speed (2000 rpm), the bsfc also showed a decrease with increasing θ_{fd}, except at high engine load, where the bsfc value of the diesel/oxygenate blends gave a lower value than that of diesel fuel. It was considered that high swirl

(7) Huang, Z. H.; Jiang, D. M.; Zeng, K.; Liu, B.; Yang, Z. L. Combustion Characteristics and Heat Release Analysis of a DI Compression Ignition Engine Fueled with Diesel−Dimethyl Carbonate Blends. *Proc. Inst. Mech. Eng., Part D, Automot. Eng.* **2003**, *217* (D7), 595−605.

(8) Murayama, T.; Zheng, M.; Chikahisa, T. Simultaneous Reduction of Smoke and NO_x from a DI Diesel Engine with EGR and Dimethyl Carbonate, SAE Paper No. 952518, 1995.

(9) Ajav, E. A.; Singh, B.; Bhattacharya, T. K. Experimental Study of Some Performance Parameters of a Constant Speed Stationary Diesel Engine Using Ethanol−Diesel Blend as Fuel. *Biomass Bioenergy* **1999**, *17*, 357−365.

(10) Bertoii, C.; Giacomo, N. D.; Beatrice, C. Diesel Combustion Improvements by the Use of Oxygenated Synthetic Fuels. *SAE Trans.* **1997**, *106* (4), 1557−1567.

(11) Miyamoto, N.; Ogawa, H.; Obata, K. Improvements of Diesel Combustion and Emissions by Addition of Oxygenated Agents to Diesel Fuels: Influence of Properties of Diesel Fuels and Kinds of Oxygenated Agents. *JSAE Rev.* **1998**, *19* (2), 154−156.

(12) Akasaka, Y.; Sakurai, Y. Effect of Oxygenated Fuel on Exhaust Emission from DI Diesel Engines. *Trans. JSME, Ser. B* **1996**, *63* (609), 1833−1839.

(13) McCormick, R. L.; Ross, J. D.; Graboski, M. S. Effect of Several Oxygenates on Regulated Emissions from Heavy-Duty Diesel Engines. *Environ. Sci. Technol.* **1997**, *31*, 1144−1150.

(14) Satge de Caro, P.; Mouloungui, E.; Vaitilingom, G.; Berge, J. C. Interest of Combining an Additive with Diesel−Ethanol Blends for Use in Diesel Engines. *Fuel* **2001**, *80*, 565−574.

(15) Ali, Y.; Hanna, M. A.; Borg, J. E. Optimization of Diesel, Methyl Tallowate and Ethanol Blend for Reducing Emissions from Diesel Engine. *Bioresour. Technol.* **1995**, *52*, 237−243.

Table 2. Fuel Properties of Diesel, Methanol, Solvents, and Oxygenated Blend Constitutions

	Base Fuel	Blended Fuel	Solvents	
	diesel	methanol	oleic	iso-butanol
chemical formula	$C_{10.8}H_{18.7}$	CH_3OH	$C_{18}H_{34}O_2$	$C_4H_{10}O$
molecular weight (g)	148.3	32	282	74
density (g/cm^3)	0.86	0.796	0.8905	0.802
lower heating value (MJ/kg)	44.40	19.68	38.65	33.14
heat of evaporation (kJ/kg)	260	1110	200	580
self-ignition temperature (°C)	200−220	470	335	385
cetane number	45	5	40	10
composition (wt %)				
C	86	37.5	76.6	64.8
H	14	12.5	12	13.5
O	0	50	11.4	21.7
blended fuel content (wt %)				
blended fuel 1	79.86	8.96	10.1	1.08
blended fuel 2	71.28	13.33	14.47	0.92
blended fuel 3	63.94	17.66	16.6	1.8

Table 3. Fuel Properties of the Diesel/Oxygenated Blends

	Value		
property	blended fuel 1	blended fuel 2	blended fuel 3
lower heating value (MJ/kg)	41.73	39.89	38.64
heat of evaporation (kJ/kg)	333.53	367.57	405.94
cetane number	40.41	38.4	36.21
composition (wt %)			
C	80.47	77.98	75.5
H	13.66	13.5	13.4
O (total)	5.87	8.52	11.1
O contribution from methanol	4.48	6.67	8.83
O contribution from solvents	1.39	1.85	2.27

intensity at high engine speed and high combustion temperature at high engine load would promote the mixing process of the injected fuel and improve the combustion in the diffusive burning phase for the oxygenated blends.

The thermal efficiency (η_e) and the diesel equivalent bsfc of the oxygenated blends versus fuel delivery advance angle θ_{fd} are illustrated in Figures 4 and 5, respectively. Because thermal efficiency is inversely proportional to the diesel equivalent bsfc (b_{eq}), as indicated in the relation

$$\eta_e = \frac{3.6 \times 10^6}{H_{u,diesel} b_{eq}}$$

they will reflect the same phenomenon in a different way. Thermal efficiency increased and the b_{eq} value decreased with the advancement of the fuel delivery advance angle for both diesel fuel and the oxygenated blends, and the behavior had a tendency to be more obvious at high engine speed. This behavior can be explained by the increase of ignition delay and the increase of the premixed burning phase, as mentioned previously. The thermal efficiency and the b_{eq} value decreased as the mass fraction of oxygenate under all conditions of engine loads (bmep), fuel delivery advance angles, and engine speeds. This suggested that the combustion could be improved with the addition of oxygenates in diesel fuel. Also, the decrease in cetane number of the oxygenated blends would result in a long ignition delay, bringing a high combustion rate in the premixed burning phase and a high cylinder pressure, because of the fast heat release. Moreover, the oxygen available in the oxygenated blends would improve the combustion rate of the diffusive burning phase. Thus, the addition of oxygenates in diesel fuel was beneficial to the improvement of the diffusive burning process, because oxygen has an important role in the diffusive combustion phase, and this suggested that a short diffusive burning duration could be achieved with oxygenated blends, and these results were consistent to the authors' previous study for diesel/DMC blends (Huang et al.[7]). The results also showed that a better

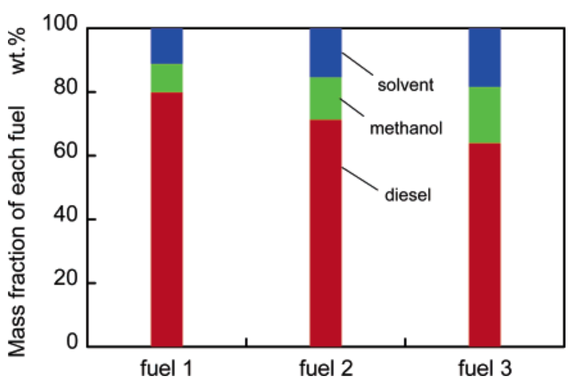

Figure 1. Mass fraction of fuel blends.

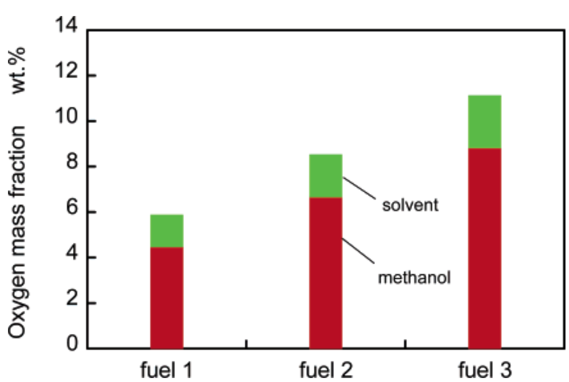

Figure 2. Oxygen mass fraction in fuel blends.

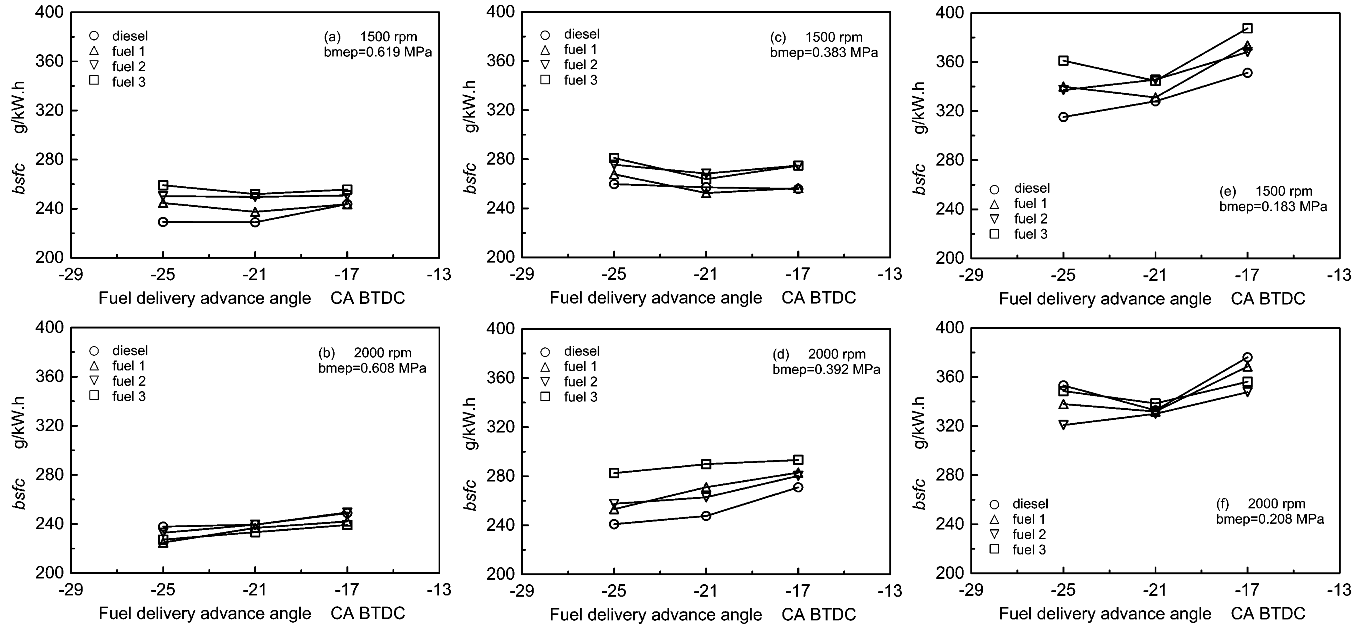

Figure 3. Brake specific fuel consumption (bsfc) of fuel blends versus fuel delivery advance angle (θ_{fd}): (a) 1500 rpm, brake mean effective pressure (bmep) = 0.619 MPa; (b) 2000 rpm, bmep = 0.608 MPa; (c) 1500 rpm, bmep = 0.383 MPa; (d) 2000 rpm, bmep = 0.392 MPa; (e) 1500 rpm, bmep = 0.183 MPa; and (f) 2000 rpm, bmep = 0.208 MPa.

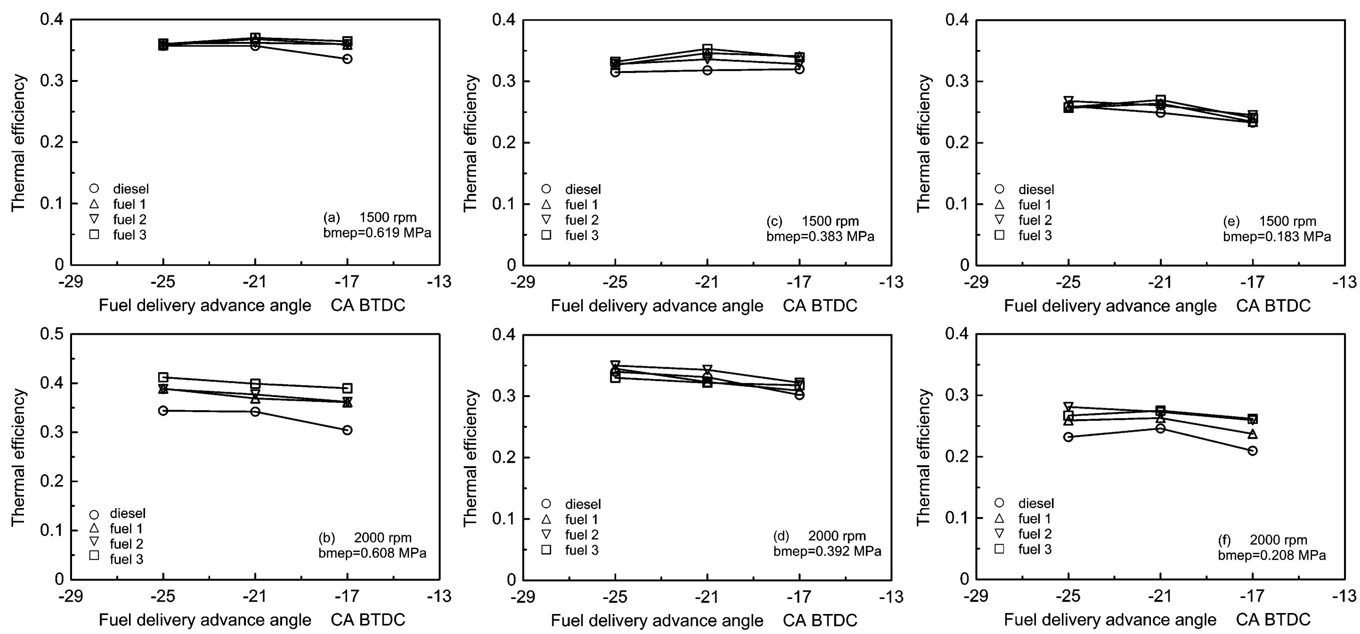

Figure 4. Thermal efficiency of fuel blends (η_e) versus θ_{fd}: (a) 1500 rpm, bmep = 0.619 MPa; (b) 2000 rpm, bmep = 0.608 MPa; (c) 1500 rpm, bmep = 0.383 MPa; (d) 2000 rpm, bmep = 0.392 MPa; (e) 1500 rpm, bmep = 0.183 MPa; and (f) 2000 rpm, bmep = 0.208 MPa.

improvement of thermal efficiency and b_{eq} were obtained at high engine speed (2000 rpm), and this would be due to the better mixing of the fuel spray with the surrounding air during the diffusive burning period in the presence of high swirl motion at high engine speed. It could be derived from the experimental results that the average improvement of thermal efficiency at 1500 rpm was 5%, and in the case of 2000 rpm, it would reach 10% when the oxygen mass fraction in the oxygenated blend reached up to 10%.

The NO_x concentration of the oxygenated blends versus fuel delivery advance angles is shown in Figure 6. Similar to the behavior of NO_x versus fuel delivery advance angle for engine operation with diesel fuel, the NO_x concentration of the oxygenated blends showed an increase with increasing θ_{fd}. This could be explained by the increase of ignition delay with increased θ_{fd}, because of low gas temperature in the case of early fuel injection, and this long ignition delay would increase the amount of fuel burned in the premixed burning phase, resulting in a high temperature and high cylinder gas pressure, finally increasing the NO_x concentration. The ignition delay increased as the methanol and solvent mass fraction increased, becuase of the decrease of the cetane number. For a specific θ_{fd} value, the NO_x concentration showed an increase with increased oxygenate mass fraction, and this would be due to the increase in the ignition delay and the increase in the amount of fuel burned in the premixed burning phase. Moreover, the presence of high combustion temperature and oxygen

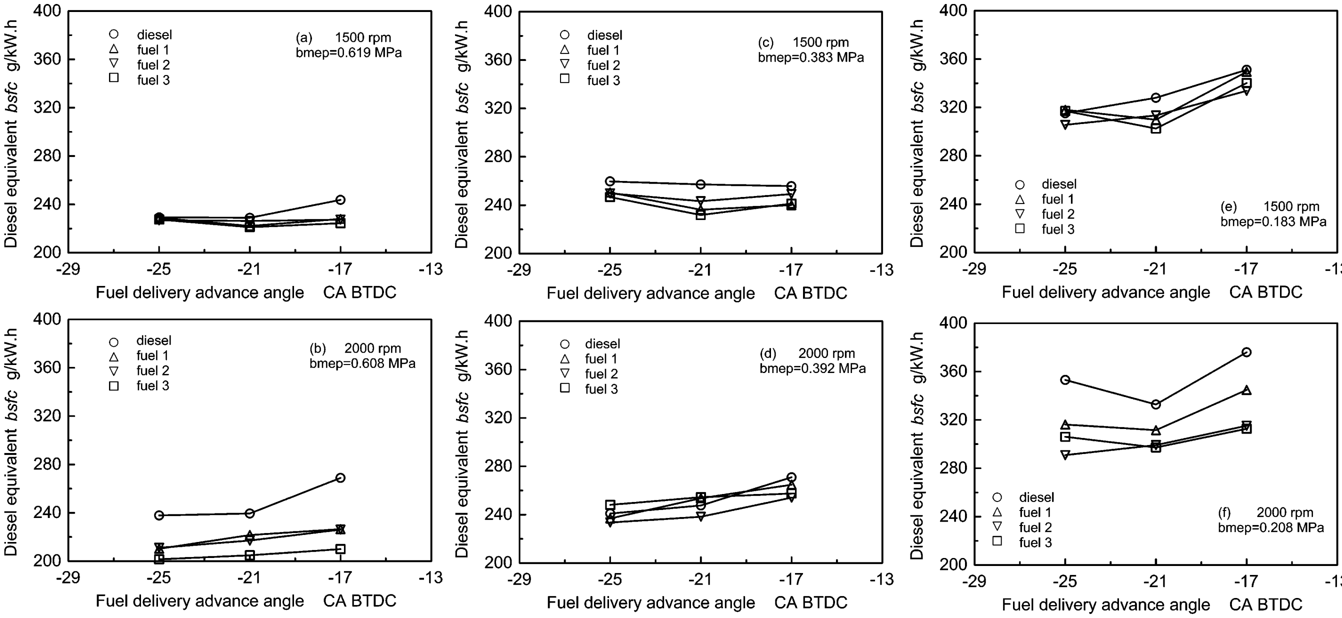

Figure 5. Diesel-equivalent bsfc (b_{eq}) versus θ_{fd}: (a) 1500 rpm, bmep = 0.619 MPa; (b) 2000 rpm, bmep = 0.608 MPa; (c) 1500 rpm, bmep = 0.383 MPa; (d) 2000 rpm, bmep = 0.392 MPa; (e) 1500 rpm, bmep = 0.183 MPa; and (f) 2000 rpm, bmep = 0.208 MPa.

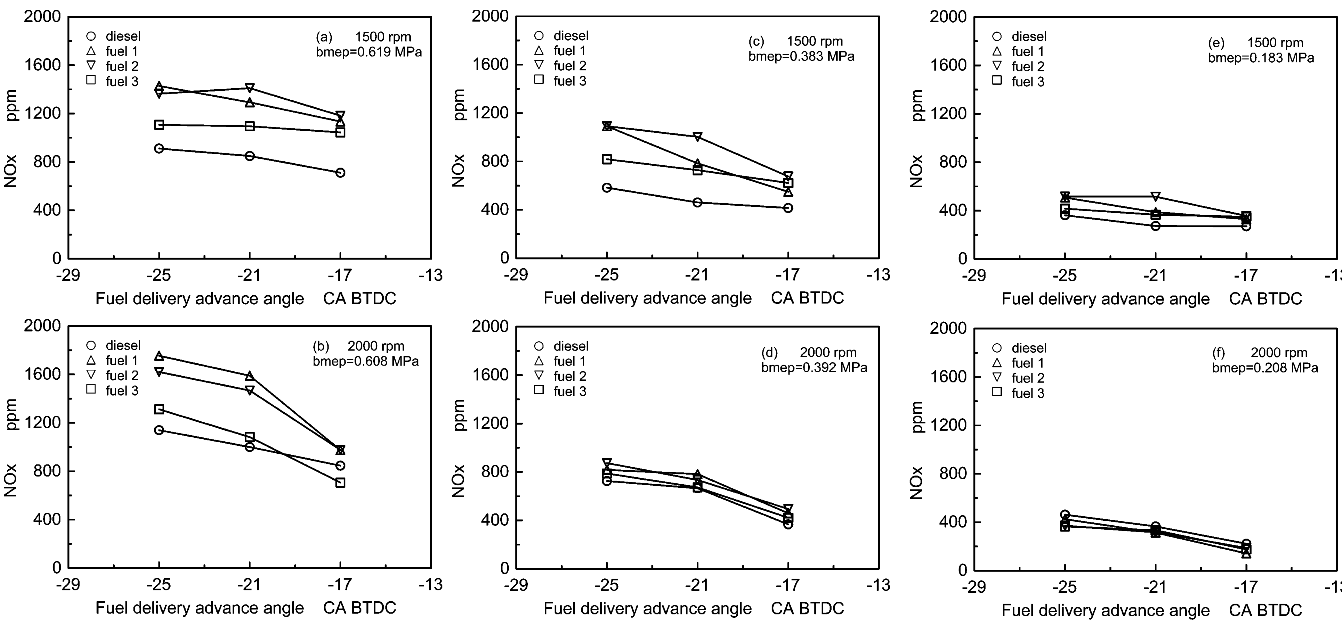

Figure 6. Exhaust NO_x concentration of fuel blends versus θ_{fd}: (a) 1500 rpm, bmep = 0.619 MPa; (b) 2000 rpm, bmep = 0.608 MPa; (c) 1500 rpm, bmep = 0.383 MPa; (d) 2000 rpm, bmep = 0.392 MPa; (e) 1500 rpm, bmep = 0.183 MPa; and (f) 2000 rpm, bmep = 0.208 MPa.

enrichment resulted in a high NO formation. However, further increases in the oxygenate mass fraction (as represented by blended fuel 3) would decrease the cylinder gas temperature, because of the increase in the heat of evaporation of the blends, and postpone the heat-release process; because of the long ignition delay, all these factors would contribute to the decrease in NO_x. The results suggested that oxygenate addition in diesel fuel had a strong influence on NO_x concentration at high engine load, whereas it had little influence at low engine load.

Figure 7 shows the CO concentration of the oxygenated blends versus θ_{fd}. With the addition of oxygenates in diesel fuel, the CO concentration could be decreased, because oxygen enrichment would ensure a completed combustion, and the behavior was more obvious at high engine load. At high engine load, it was found that CO would decrease with the retarding of θ_{fd}, whereas at middle and low loads, CO varied little with θ_{fd} but gave a low value for the oxygenated blends. It was suggested that, in the case of early injection, a more-lean mixture along the downstream of fuel spray would exist and increase the fraction of incomplete combustion product (CO). Furthermore, early injection would decrease the gas temperature in the expansion stroke and reduce the post-flame oxidation rate of CO. All these factors were considered to the cause of high CO concentration for the early fuel delivery advance angle. Thus, we could conclude that the oxygenated blends were beneficial to the reduction of CO, especially at the high engine load.

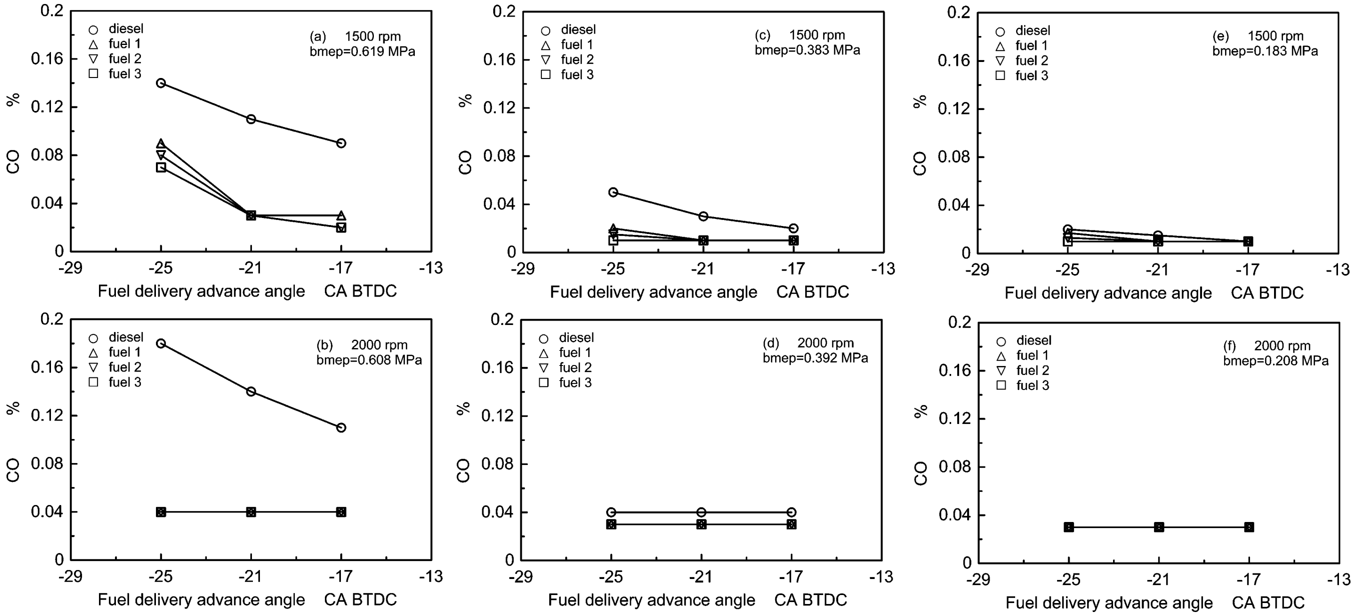

Figure 7. Exhaust CO concentration of fuel blends versus θ_{fd}: (a) 1500 rpm, bmep = 0.619 MPa; (b) 2000 rpm, bmep = 0.608 MPa; (c) 1500 rpm, bmep = 0.383 MPa; (d) 2000 rpm, bmep = 0.392 MPa; (e) 1500 rpm, bmep = 0.183 MPa; and (f) 2000 rpm, bmep = 0.208 MPa.

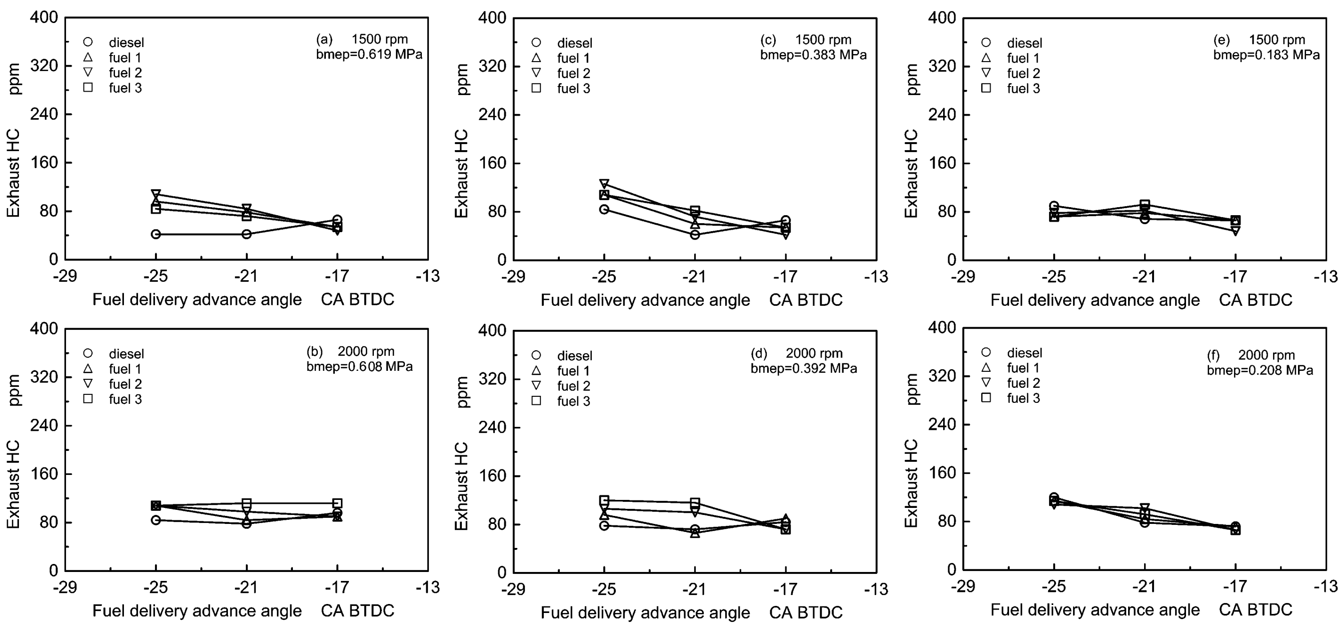

Figure 8. Exhaust HC concentration of fuel blends versus θ_{fd}: (a) 1500 rpm, bmep = 0.619 MPa; (b) 2000 rpm, bmep = 0.608 MPa; (c) 1500 rpm, bmep = 0.383 MPa; (d) 2000 rpm, bmep = 0.392 MPa; (e) 1500 rpm, bmep = 0.183 MPa; and (f) 2000 rpm, bmep = 0.208 MPa.

The results also revealed that an oxygen mass fraction of 6% in the oxygenated blends could remarkably reduce the engine-exhaust CO, whereas further increases in the oxygen mass fraction had a slight impact on the reduction of engine-exhaust CO.

Figure 8 illustrates the exhaust hydrocarbon (HC) concentration of the oxygenated blends versus θ_{fd}. Unlike the behavior of NO_x and CO versus θ_{fd}, the exhaust HC concentration gave little variation with oxygenate addition in diesel fuel. The HC concentration showed a slight increase with increasing θ_{fd}. Because the exhaust HC of a compression ignition engine comes from both the rich-spray region and the lean-spray region, it was suggested that an oxygenated blend would reduce the rich-spray region and increase the lean-spray region. Moreover, the increase in oxygenate mass fraction would be accompanied by an increase in the injected fuel per cycle and promotion of HC post-flame oxidation. Increasing the θ_{fd} value would increase the fraction of lean-spray region, because of long ignition delay. Consequently, the HC concentration increased slightly as the θ_{fd} increased, and the addition of oxygenates (methanol and solvent) in diesel fuel had little influence on the exhaust HC concentration.

The exhaust smoke of the oxygenated blends versus θ_{fd} is illustrated in Figure 9. The purpose of using oxygenated blend is to decrease the engine smoke by providing further oxygen for complete combustion. The results clearly showed that the engine smoke could be decreased remarkably with the addition of oxygenates

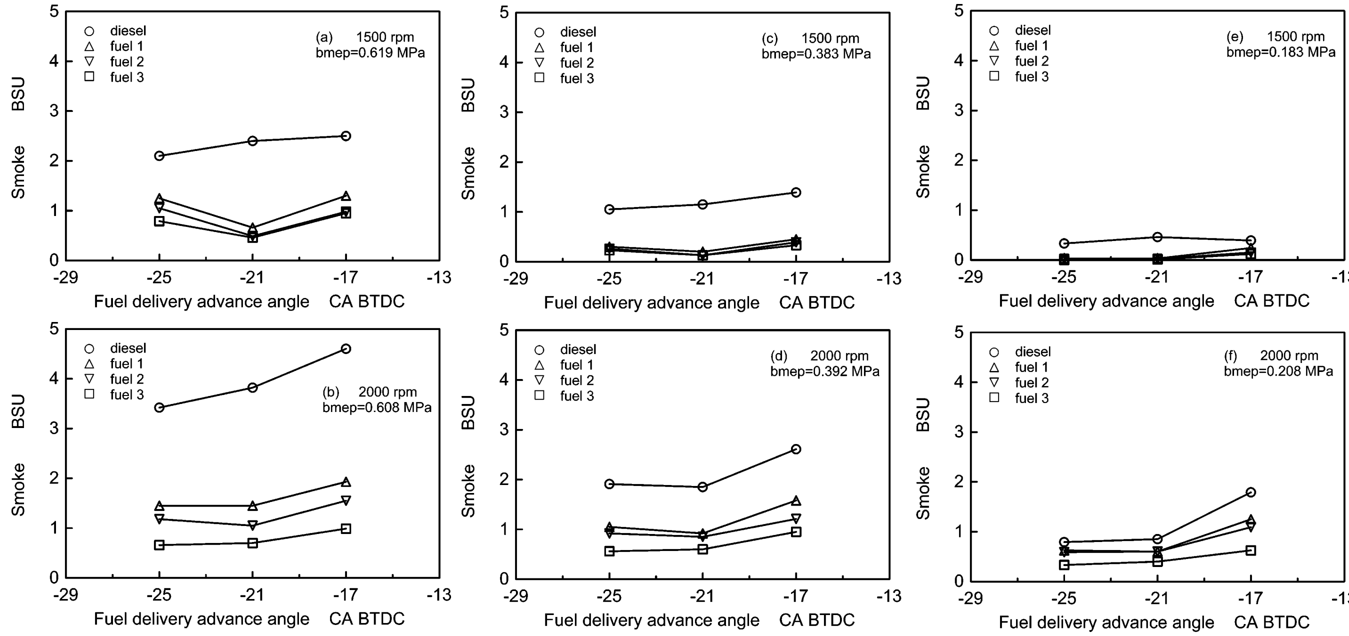

Figure 9. Smoke of fuel blends versus θ_{fd}: (a) 1500 rpm, bmep = 0.619 MPa; (b) 2000 rpm, bmep = 0.608 MPa; (c) 1500 rpm, bmep = 0.383 MPa; (d) 2000 rpm, bmep = 0.392 MPa; (e) 1500 rpm, bmep = 0.183 MPa; and (f) 2000 rpm, bmep = 0.208 MPa.

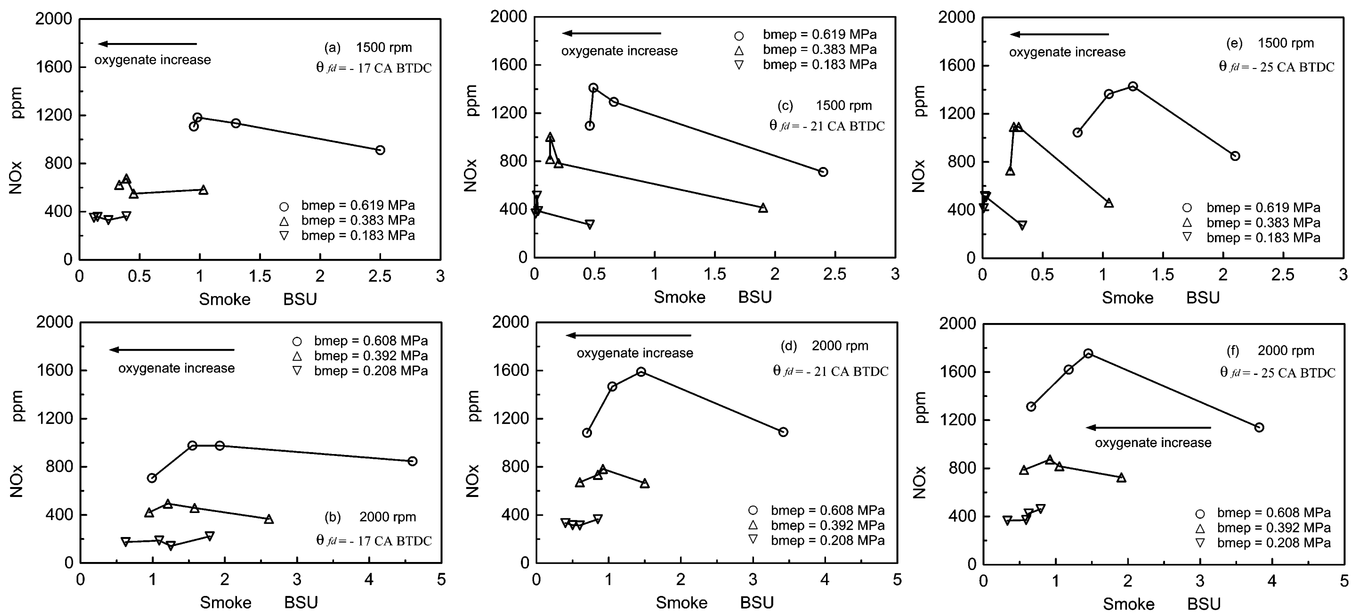

Figure 10. Relationship between NO_x and smoke of fuel blends: (a) 1500 rpm, $\theta_{fd} = -17$ CA BTDC; (b) 2000 rpm, $\theta_{fd} = -17$ CA BTDC; (c) 1500 rpm, $\theta_{fd} = -21$ CA BTDC; (d) 2000 rpm, $\theta_{fd} = -21$ CA BTDC; (e) 1500 rpm, $\theta_{fd} = -25$ CA BTDC; and (f) 2000 rpm, $\theta_{fd} = -25$ CA BTDC.

in diesel fuel under all conditions of various engine speeds, engine loads, and θ_{fd} values, and this was reasonable because the oxygenated blends could decrease the rich-spray region and increase the post-flame oxidation to the formed soot. The smoke content was determined to decrease as the θ_{fd} value increased for both the diesel fuel and the oxygenated blends, and this would be due to the increase in ignition delay, the increase of fuel fraction burned in the premixed burning phase, and the decrease of fuel fraction burned in the subsequently diffusive burning phase with the increase in θ_{fd}. Oxygen enrichment by the oxygenated blends would be helpful to the improvement of the diffusive burning phase and smoke reduction. All these factors would contribute to the reduction of smoke for the oxygenated blends. The reduction of smoke was determined to be more remarkable at high engine speed, and this was also reasonable, because high swirl intensity at high engine speed would improve the fuel−air mixing and reduce the excessive rich-spray region in the combustion chamber.

The relationship between NO_x and smoke of the oxygenated blends at three θ_{fd} settings is plotted in Figure 10. Unlike engine that was fueled with pure diesel fuel, a flat NO_x/smoke trade-off curve was presented for the oxygenated blends, and a more-flat curve was observed at low engine load. This was reasonable since the remarkable reduction in smoke was not accompanied by the increase in NO_x. A high addition of oxygenates could realize the simultaneous reduction in both smoke and NO_x. Further decreases of NO_x were suggested through EGR, because a high EGR ratio could be tolerated for the oxygenated blends.

4. Conclusions

The oxygenated blends were prepared by adding methanol and solvent into diesel fuel, and engine performance and emissions of the oxygenated blends versus fuel delivery advance angle (θ_{fd}) were conducted in a compression ignition engine. The main results were summarized as follows:

(1) Thermal efficiency increased and the diesel-equivalent brake specific fuel consumption (bsfc), denoted as b_{eq}, decreased as the θ_{fd} increased for the oxygenated blends, and the behavior had a tendency to be more obvious at high engine speed.

(2) NO_x concentration of the oxygenated blends increased as the θ_{fd} increased. For a specific fuel delivery advance angle, the NO_x concentration increased as the mass fraction oxygenates increased. The addition of oxygenates in the diesel fuel had a large influence on the exhaust NO_x concentration at high engine load, whereas, at low load, it had little influence.

(3) The CO concentration decreased with the retarding of θ_{fd} at high engine load, whereas at middle and low loads, the CO concentration varied little with the variation of θ_{fd}. The θ_{fd} value had little influence on exhaust HC emissions, which were fueled by the oxygenated blends.

(4) A remarkable decrease in smoke emission could be realized with the addition of oxygenates in diesel fuel for various θ_{fd}. Smoke emissions decreased with the increase in θ_{fd} for both diesel fuel and the oxygenated blends.

(5) A flat NO_x/smoke trade-off curve existed when the engine was operated using on the oxygenated blends.

Acknowledgment. This study was supported by the National Natural Science Foundation of China (under No. 50323001), the Ford−China Research and Development Fund (under No. 50122166), the National Basic Research Program (under Nos. 2001CB209207 and 2001CB209208), and the Key Project of the National Natural Science Fund (under No. 50136040). The authors acknowledge the students of Xi'an Jiaotong University for their help with the experiment. The authors also express their thanks to the colleagues of Xi'an Jiaotong University for their helpful comments and advice during the manuscript preparation.

EF049855D