18 Combustion and Emission Characteristics of a Compression Ignition Engine Fuelled with Diesel-Dimethoxy Methane Blends

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The combustion and emission characteristics of a compression ignition engine fuelled with diesel-dimethoxy methane (DMM) blends were conducted. The results showed that the initial combustion duration gave a slight variation with the increase of DMM fraction in the fuel blends, while the rapid combustion duration and the total combustion duration decreased with the increase of DMM fraction in fuel blends, and the crank angle of the centre of heat release curve moved closer to the top-dead-center, this would be due to the increase in the amount of combustible mixture for the initial premixed combustion phase as the fast evaporation of DMM and the promotion of the subsequent diffusive combustion phase as the oxygen enrichment. The maximum cylinder pressure gives a slight increase with the increase of DMM addition, the enrichment of oxygen by injecting the oxygenate fuel is responsible for the combustion improvement. The maximum rate of pressure rise and the maximum rate of heat release will increase with the increase of DMM fraction in fuel blend, and this would also be due to the increase in the amount of combustible mixture for the premixed combustion phase fuelled with the diesel-DMM blends. Remarkable reduction in the exhaust CO and smoke can be achieved when operating on the diesel-DMM blend. Flat NOx-Smoke curves are presented when operating on the diesel-DMM fuel blends, or and a simultaneous reduction in both NOx and smoke can be realised at large DMM addition. Thermal efficiency and NOx give the highest value at 2% oxygen mass fraction (or 5% DMM volume fraction) for the combustion of diesel-DMM blends.

***Keywords*: Combustion, Emissions, Diesel-dimethoxy methane blends, Compression ignition engine**

1. INTRODUCTION

Reduction of engine emissions is a major research aspect in engine development with the increasing concern on environmental protection and the stringent exhaust gas regulation. It is difficult to simultaneously reduce NOx and smoke in normal diesel engines due to the trade-off curve between NOx 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 *et al* [2] and Sorenson *et al* [3] have studied the dimethyl ether (DME) in the modified diesel engine, and their results showed that the engine could achieve ultra-low emission prospects without fundamental change in combustion systems. Huang et al [4] investigated the combustion and emission characteristics in a compression ignition engine with DME and found that the DME engine has high thermal efficiency, short premixed combustion and fast diffusion combustion, and their work was to realize low noise, smoke-free combustion. Kajitani et al [5] studied the DME engine with delaying of the injection time to reduce both smoke and NOx.

Practically, adding some oxygenated compounds to fuels to reduce engine emissions without engine modification seems a more attractive proposition. Huang *et al* tested the gasoline-oxygenate blends in a spark ignited engine and got a satisfactory result on emission reduction [6] and also investigated the combustion and emission characteristics of diesel/dimethyl carbonate (DMC) in a compression ignition engine [7]. Murayama et al [8] studied the emissions and combustion with EGR and dimethyl carbonate (DMC). Ajav et al [9] studied the diesel/ethanol blends for emission reduction and Huang et al investigated the engine performance and emissions of diesel engine fuelled with diesel/methanol blends [10]. Miyamoto et al [11] and Akasaka et al [12] also conducted research on diesel combustion improvement and emission reduction by the use of various types of the oxygenated fuel blends.

Dimethoxy methane (DMM) has high oxygen fraction and relative high cetane number, and this makes it a better oxygenate additive for diesel/oxygenate blended fuel. Some preliminary studies revealed that the reduction of particulate emissions [13] and toxic gas pollutants could be achieved fuelled with the diesel/DMM blends [14], however, those previous work just reported the emission results for a specific DMM addition and did not give the results on combustion characteristics and/or heat release analysis under various DMM addition. However, the combustion behaviors are directly linking to the engine performances and the mechanism of emission reduction operating on various fractions of diesel-DMM blends. In order to acquire the comprehensive evaluation for diesel-DMM blends, many aspects still worth of investigating, especially in a quantitative level, these quantitative parameters are expected to supply more information on engine combustion operating on oxygenated fuels and provide more practical measures for the improvement of combustion and reduction of emissions.

Based on the authors' previous study, the objectives of this study will investigate combustion characteristics based on the heat release analysis for different fractions of DMM addition in diesel fuel and expect to increase the understanding of the combustion parameters versus the DMM fraction and/or the oxygen fraction in fuel blends of compression ignition engine operated on the diesel-DMM blends.

2. TEST ENGINE AND FUEL PROPERTIES

The specifications of the test engine are listed in table 1. In the study, diesel fuel is the base fuel while DMM is used as the oxygenated additive. Four fractions of the diesel-DMM blends were designated for the study, and the volume fraction of DMM in the fuel blends are 5%, 10%, 15% and 20% respectively. Fuel properties and the fraction of four blends are given in table 2, table 3, and the mass fraction of oxygen in the fuel blends ranges from 2.16% to 8.62% as shown table 3. The fuel properties show that DMM has high oxygen content while the heat value and cetane number are low compared to those of pure diesel fuel. In the experiment, the above four fuel blends with different DMM fractions were tested on the engine. Meanwhile, the engine exhaust emissions were analyzed under the same brake mean effective pressure (*bmep*), the resolution for NOx measurement is 1 ppm, the resolution for CO is 0.01% and the resolution for smoke measurement is 0.1 Bosch unit. Furthermore, these parameters were made a comparison with those of pure diesel combustion in order to clarify the effect of oxygenate additives on combustion. A Horiba exhaust gas analyzer was used to measure the combustion products.

Table 1 Engine specifications.

Bore / *mm*	100
Stroke / *mm*	115
Displacement / cm^3	903
Compression ratio	18
Shape of combustion chamber	ω shape in the bottom of bowl-in-piston
Rated power/speed	11 kW / 2300 rpm
Nozzle hole diameter / *mm*	0.3
Number of nozzle holes	4

Table 2 Fuel properties of diesel and dimethoxy methane and blended fuel constitutions.

	Base fuel	Blended fuel
Type of fuels	Diesel	DMM
Mole weight / *g*	148.3	32
Density/ g/cm^3	0.86	0.865
Lower heating value / *MJ/kg*	42.5	22.4
Heat of evaporation / *kJ/kg*	260	318.6
Self-ignition temperature / ^0C	200-220	430
Cetane number	45	30
C wt.%	86	47.4
H wt.%	14	10.5
O wt.%	0	42.1
Fuel blend #1 *vol.%*	95	5
Fuel blend #2 *vol.%*	90	10
Fuel blend #3 *vol.%*	85	15
Fuel blend #4 *vol.%*	80	20
Fuel blend #1 *wt.%*	94.86	5.14
Fuel blend #2 *wt.%*	89.73	10.27
Fuel blend #3 *wt.%*	84.62	15.38
Fuel blend #4 *wt.%*	79.53	20.47

Table 3 Fuel properties of the diesel/DMM blended fuels.

	fuel #1	fuel #2	fuel #3	fuel #4
Lower heating value/*MJ/kg*	41.47	40.44	39.41	38.38
Heat of evaporation/ *kJ/kg*	303.7	347.3	390.7	434
Cetane number	44.23	43.46	42.69	41.93
C *wt.%*	84.02	82.04	80.06	78.1
H *wt.%*	13.82	13.64	13.46	13.28
O *wt.%*	2.16	4.32	6.48	8.62

4. RESULTS AND DISCUSSIONS

Figure 1 gives the combustion duration of the diesel-DMM blends versus the DMM volume fraction in fuel blends under various engine loads (*bmep*). Determination of combustion durations are calculated using the method in reference 7. In the case of initial combustion duration $\Delta\varphi_{tc}$, slight variation of $\Delta\varphi_{tc}$ versus the fraction of DMM addition is observed for the specific *bmep* at both high engine speed (1600 rpm) and low engine speed (1200 rpm). However, a different behavior of $\Delta\varphi_{tc}$ versus the engine load is shown at high and low engine speeds, that is, a slight difference is presented at low engine speed (1200 rpm) while the initial combustion duration shows an increase with the increase of engine load. The following interpretation can be explained for this behavior, with the increase of engine speed, the amount of fuel for 10% accumulated heat release will increase, and this will subsequently increase the duration to burn this fraction of fuel. On the other hand, high load will increase the cylinder gas temperature and this will supply the environment for increasing the combustion speed. The comprehensive of these two factors would make the increasing of the initial combustion duration with the increase of engine load. For a given duration of time (ms), the duration in crank angle will increase with the increase of engine speed, and relative large difference in the initial combustion duration under different engine loads is presented at the high engine speed. The results indicated that, under the same *bmep* condition, the addition of DMM in diesel fuel did little influence on the initial combustion duration.

In the case of the rapid combustion duration $\Delta\varphi_{rc}$, a slight decrease of $\Delta\varphi_{rc}$ is observed with the increase of DMM in the fuel blends at both high (1800 rpm) and low (1200 rpm) engine speeds, while $\Delta\varphi_{rc}$ shows an increase with the increase of engine load. Increasing DMM fraction in fuel blend will increase the oxygen fraction in fuel blend, and this will contribute to the improvement of combustion, especially for the improvement of the diffusive combustion phase where the enrichment of oxygen will promote the combustion process, indicating a better advantage by oxygenate fuels in diesel fuel. The long duration of $\Delta\varphi_{tc}$ at high engine load would be due to the increase in fuel amount and increase of the duration for reaching 90% of the accumulated heat release.

The total combustion duration $\Delta\varphi_{tc}$ versus DMM fraction in fuel blend exhibits a similar behavior to that of the rapid combustion duration, the shortening of the rapid combustion duration is considered to contribute to the decrease of the total combustion duration. Thus, the results indicate that adding the oxygenate fuel in diesel fuel can shorten the combustion duration due to the oxygen enrichment and is beneficial to the increase of engine thermal efficiency.

Figure 2 illustrates the crank angle of the centre of heat release curve φ_c for diesel-DMM fuel blends. The figure also shows the decrease of φ_c with the increase of DMM addition. As be explained above, the decrease in combustion duration and the improvement of the diffusive combustion phase will make the heat release process closer to the top-dead-centre.

The maximum cylinder pressure (p_{max}) versus DMM fraction in fuel blend is plotted in Fig. 3. For a given engine load (*bmep*), the maximum cylinder pressure and the maximum mean gas temperature show a slight increase with the increase of DMM addition, the amount of blend will increase with the increase of DMM fraction in fuel blend in order to get the same *bmep*, thus more combustible mixture will be available for the premixed combustion phase due to low boiling point of DMM. Moreover, the enrichment of oxygen by injecting the oxygenate fuel will also promote the combustion. The results suggested that diesel-DMM blend would be helpful for the reduction of engine exhaust CO and smoke since it could bring the increase in cylinder gas temperature and oxygen enrichment.

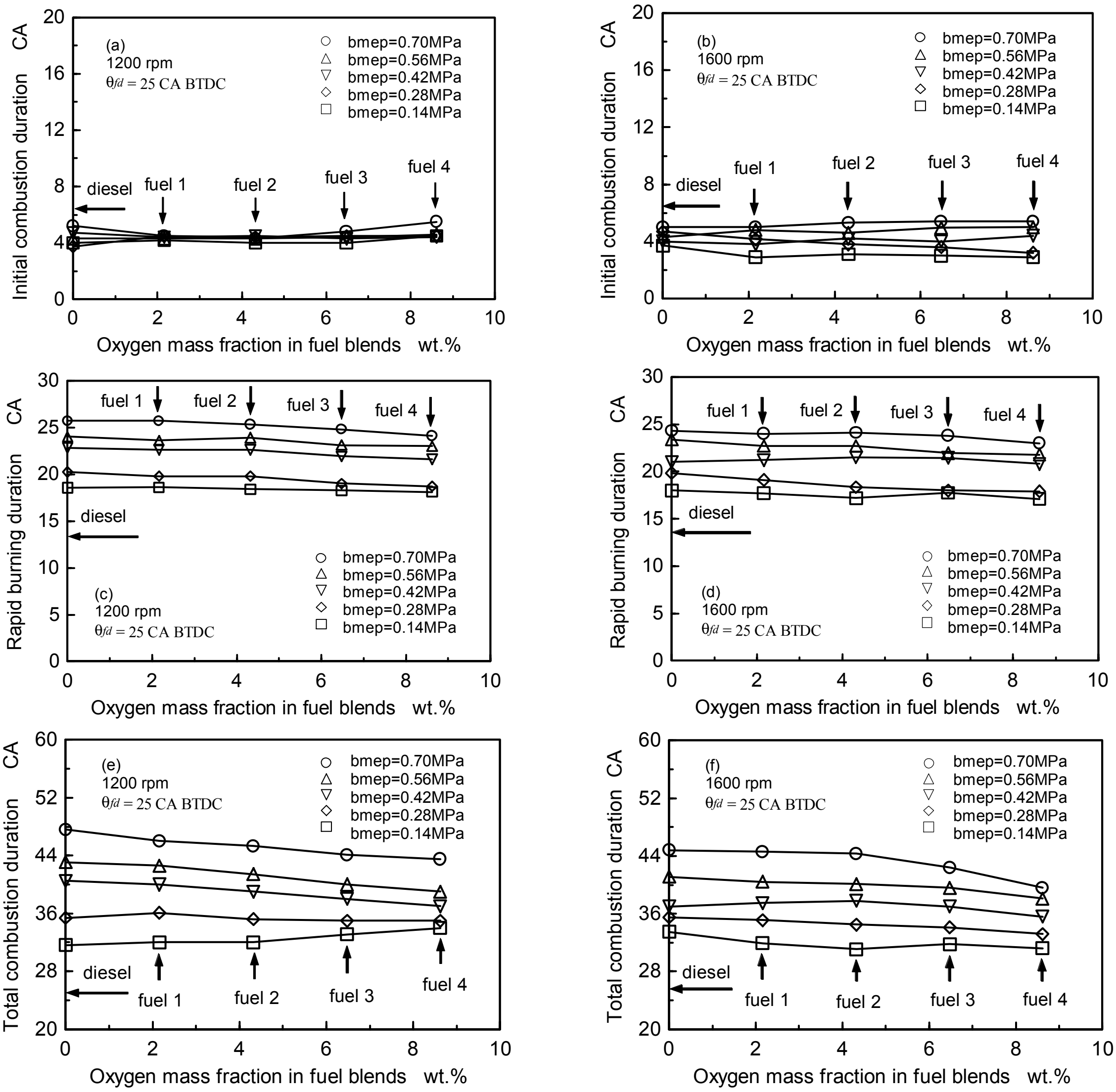

Fig. 1 Combustion durations of the diesel-DMM fuel blends.

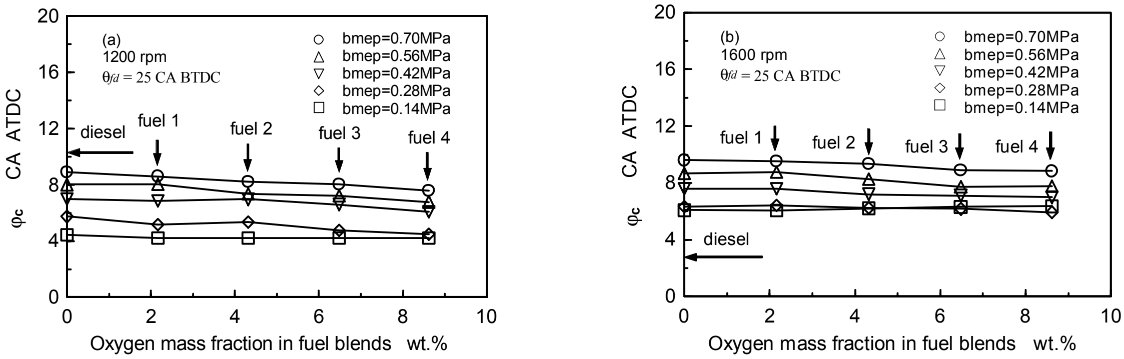

Fig. 2 Crank angle of the centre of heat release curve.

The NOx concentration of diesel/DMM blends under various brake mean effective pressure (*bmep*) is shown in Fig.4. The behavior of NOx versus the oxygen mass fraction gives a similar trend under all engine loads and engine speeds while NOx reaches its highest value at 2% oxygen mass fraction (or 5% DMM volume fraction), indicating the improvement of combustion at this fraction of DMM addition. NOx slightly decreases with the increase of DMM in diesel fuel, and the decrease in heating value and the increase in fuel injection duration of blends is contributed to the lowering of NOx concentration. Generally speaking, for a given *bmep*, NOx shows little variation with the addition of DMM in diesel fuel and this is consistent to the results obtained by Yeh et al[16], their work showed that little or no change in NOx emissions were observed with the oxygenated fuels.

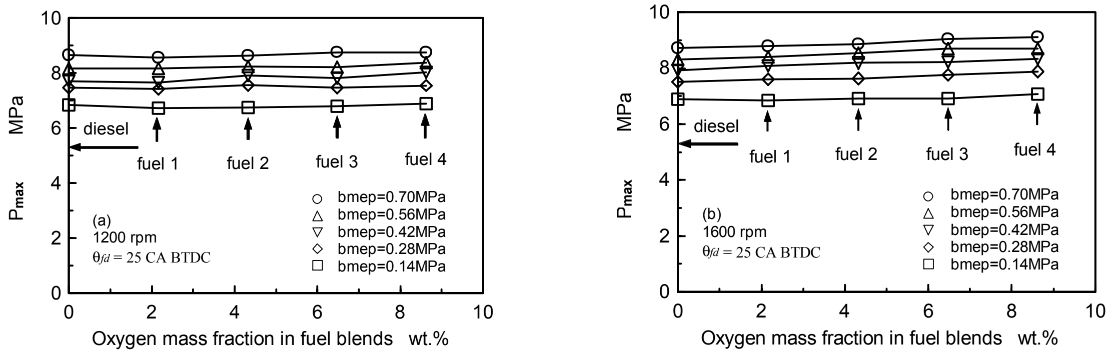

Fig. 3 $p_{\max}$ of the diesel-DMM fuel blends.

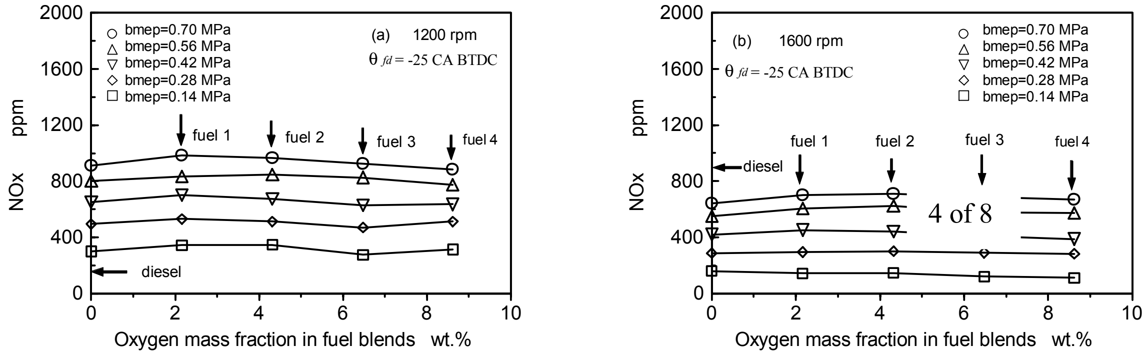

Fig. 4 Exhaust NOx concentration of the fuel blends.

Fig. 5 shows the exhaust CO concentration of diesel/DMM blends and its reduction rate versus the oxygen mass fraction at various *bmep*. At all engine loads (*bmep*) and engine speeds, CO concentration shows an decrease with the increase of oxygen mass fraction of the diesel/DMM fuel blends, and a remarkable decrease in CO with an increase in oxygen mass fraction is presented at the high engine load, while a slight decrease is observed at the middle and low loads. This suggested that oxygen-contained fuel blends could effectively decrease the locally rich spray regions where CO is mainly formed, especially at the high engine load where more fraction of the locally rich spray region will exist. Moreover, the oxygen enrichment can also improve the post-flame oxidation of CO in the late engine expansion and exhaust processes, and high load results in high cylinder temperature and consequently high degree of CO oxidation. The results also revealed that 40% reduction of CO in average could be achieved when 10% of oxygen was available in the diesel-DMM blends for both high engine speed (1600 rpm) and low engine speed (1200 rpm), and the average CO reduction rate gives a linear reduction with the increase of the oxygen mass fraction in the blends.

The smoke and its reduction rate for diesel-DMM blends at various *bmep* are illustrated in Fig. 6. The purpose of using the oxygen-contained fuel blend is expected to decrease the engine smoke by supplying more oxygen to make it burn completely. The results clearly showed that the engine smoke could be decreased remarkably with the addition of dimethoxy methane in diesel fuel at all engine speeds and engine loads, and this is reasonable since the oxygen-contained fuel blends can reduce the rich spray region and increase the post-flame oxidation of the formed soot. The results also showed 50~60% reduction in smoke could be achieved when the oxygen mass fraction in the blends reached 10% by adding DMM in diesel fuel, and this is consistent to the results obtained by Spreen et al[17], their study showed that smoke could be reduced by about 5% for each 1% increase in oxygenate addition . The reduction rate of smoke is more obvious at low engine speed, the combustion under the low swirl intensity depends largely on the air-fuel ratio in cylinder during combustion and the oxygen enrichment will be beneficial to the decrease of rich mixture region and decrease the smoke formation in cylinder. Furthermore, long residence time during engine expansion and exhaust processes at low engine speed will promote the post-flame oxidation of the combustion formed smoke and decrease the exhaust smoke level.

Figure 7 gives the exhaust smoke versus engine speed under high and middle loads. The results showed that the behavior of smoke versus engine speed for the diesel/DMM blends showed a similar trend to that of diesel combustion, that is, exhaust smoke increases with the increase in engine speed. The short time for fuel evaporation and mixing at high engine speed causes more rich mixture zones in combustion chamber and increase smoke formation during combustion, meanwhile, the short time of expansion and exhaust processes at high engine speed restricts the oxidation of smoke in the post-flame process and gives a high level of smoke.

The relationship between NOx and smoke of diesel/DMM fuel blends at various *bmep* is plotted in Fig. 8. A flat NOx/Smoke trade-off curve is presented when operating on the diesel/DMM fuel blends. Even a reduction in NOx and smoke together is observed with large addition of DMM in diesel fuel, and this means a simultaneous reduction in both smoke and NOx can be realised when operating on the diesel/DMM blends. Since the blends are oxygen-contained fuels and have a high tolerance for exhaust gas recirculation, the combination of diesel/DMM blends with the exhaust gas recirculation can make a further decrease of NOx without increasing the smoke emission.

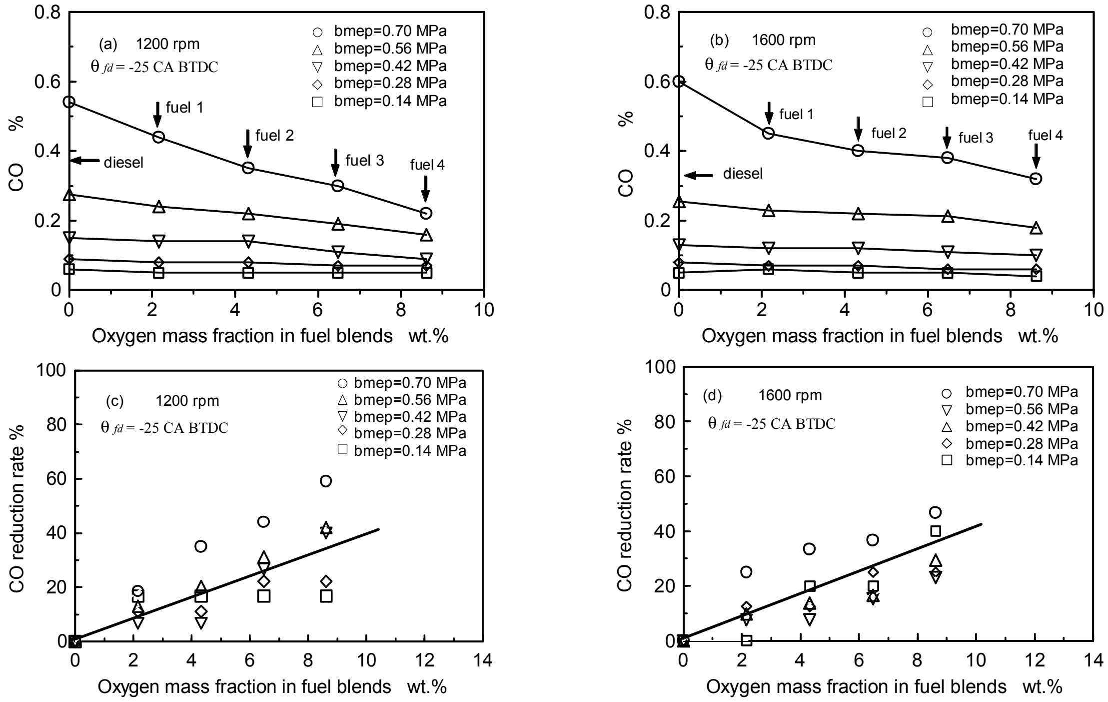

Fig. 5 Exhaust CO concentration and its reduction rate of the fuel blends.

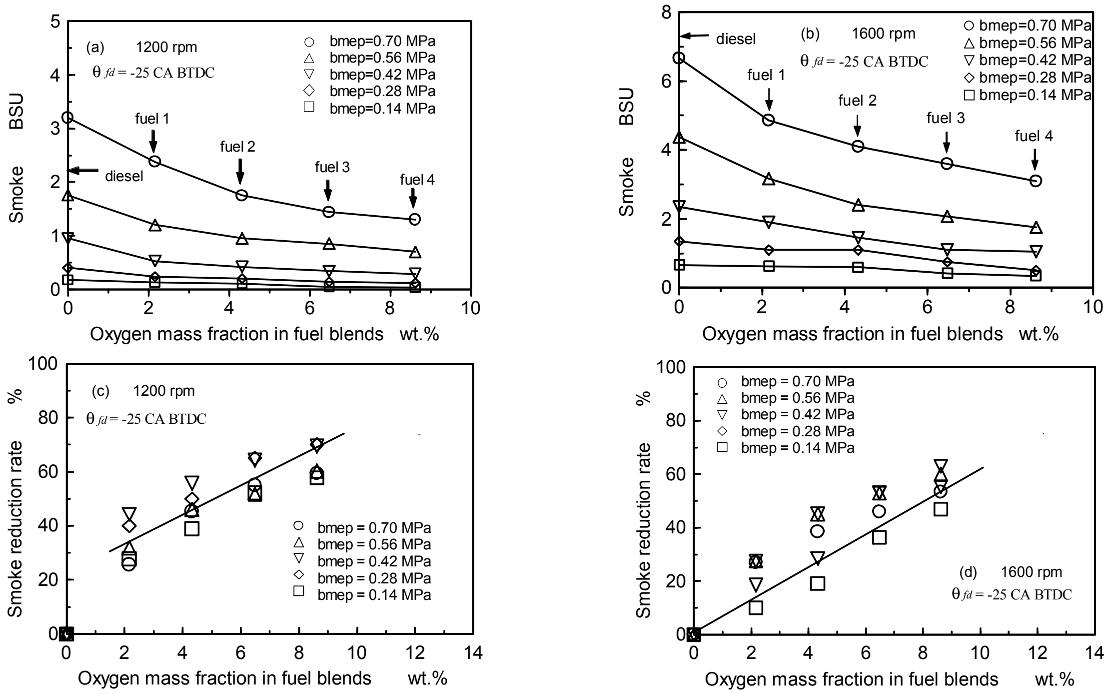

Fig. 6 Engine exhaust smoke and its reduction rate of the fuel blends.

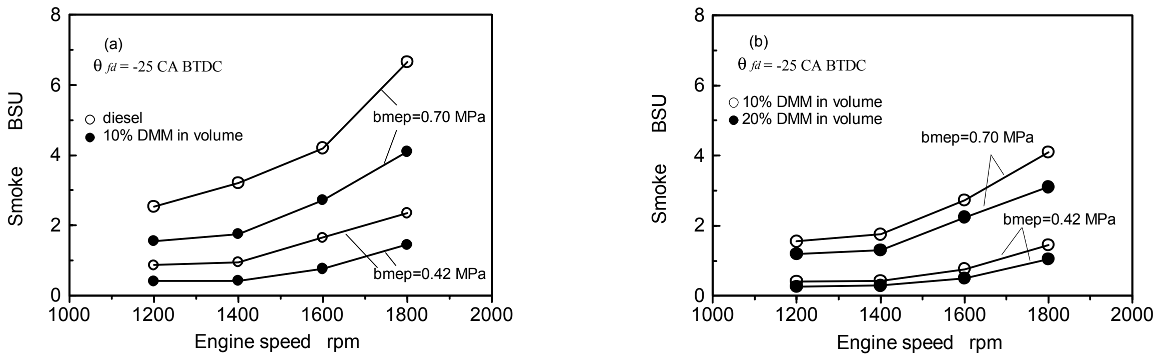

Fig. 7 Exhaust smoke versus engine speed for the fuel blends.

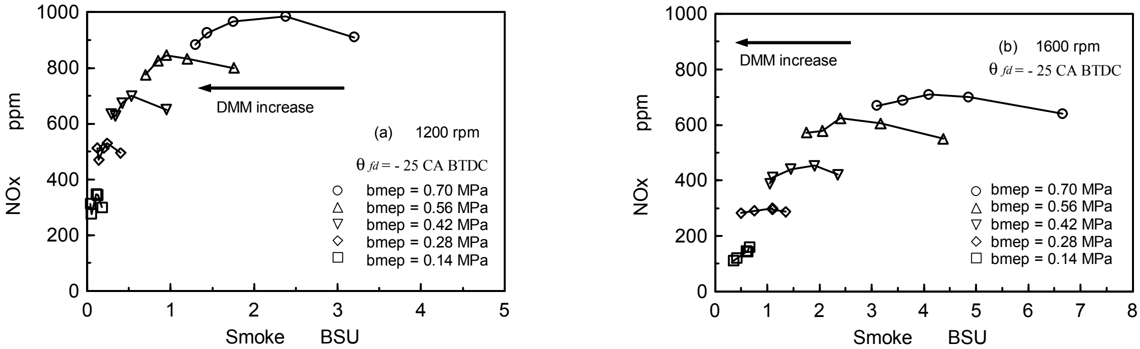

Fig. 8 Relationship between NOx and smoke of the fuel blends.

5. CONCLUSIONS

1. The initial combustion duration shows a slight variation with the increase of DMM fraction in fuel blend, while the rapid combustion duration, the total combustion duration and the crank angle of the centre of heat release curve decrease with the increase of DMM fraction in fuel blend due to the improvement of the diffusive combustion phase.
2. The maximum cylinder pressure gives a slight increase with the increase of DMM addition, the enrichment of oxygen by injecting the oxygenate fuel is responsible for the combustion improvement.
3. Remarkable reduction in the exhaust CO and smoke is realised when operating on the diesel/DMM blends. Flat NOx/Smoke and thermal efficiency/smoke curves are presented when operating on the diesel/DMM fuel blends and even a simultaneous reduction in both NOx and smoke can be realised at large DMM addition.

6. ACKNOWLEDGEMENTS

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