# Performance and Emission Characteristics of Diesel Engines Fueled with Diesel#Dimethoxymethane (DMM) Blends

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# Performance and Emission Characteristics of Diesel Engines Fueled with Diesel−Dimethoxymethane (DMM) Blends

Ruijun Zhu, Xibin Wang,* Haiyan Miao, Zuohua Huang, Jing Gao, and Deming Jiang

*State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049 People's Republic of China*

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Combustion, performance, and emission were studied for a direct-injection (DI) diesel engine fueled with dimethoxymethane (DMM)/diesel blends, with DMM content from 0 to 50%. Results showed that, without changing the fuel supply system and the combustion system of a diesel engine, when using blended fuel with increased DMM percentage, break-specific fuel consumption (BSFC) is higher for a smaller lower heating value of DMM, while thermal efficiency increases a little. For exhaust emission, smoke and CO emission decrease and $NO_x$ remains almost unchanged, while hydrocarbons (HCs) increase. For combustion characteristics, peak pressure and pressure rise become slightly higher, ignition delay is longer, which means more and faster premixed combustion, and the diffusion combustion is faster because of oxygenated fuel. The diesel engine fueled with 30% DMM blending fuel can obtain satisfactory fuel efficiency and emission level.

## 1. Introduction

The diesel engine is widely used for its high fuel efficiency, low emission of $CO_2$, and unburned hydrocarbons (HCs) and CO. However, one problem of the diesel engine is that it has a high emission of $NO_x$ and particulate matter (PM), and it is difficult to reduce both emissions simultaneously because of the tradeoff between $NO_x$ and PM emissions. Although application of high-pressure injection and common rail system can reduce both $NO_x$ and PM emissions, the expense is also very high and unaffordable for many engine producers and consumers, especially for diesel engines widely applied for agricultural machinery, most of which are single-cylinder and of low price. In recent years, research showed that one solution, rather cheap and effective, was found, which is the application of oxygenated fuels or adding oxygenated fuels in diesel fuel.

Recent studies illustrated the improvements in diesel combustion and emissions by the use of oxygenated organic compounds for fuels or as fuel additives.[1−15] Dimethyl ether (DME) is a promising oxygenated fuel easily made from methanol, natural gas, and coal. Huang et al.[1] 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

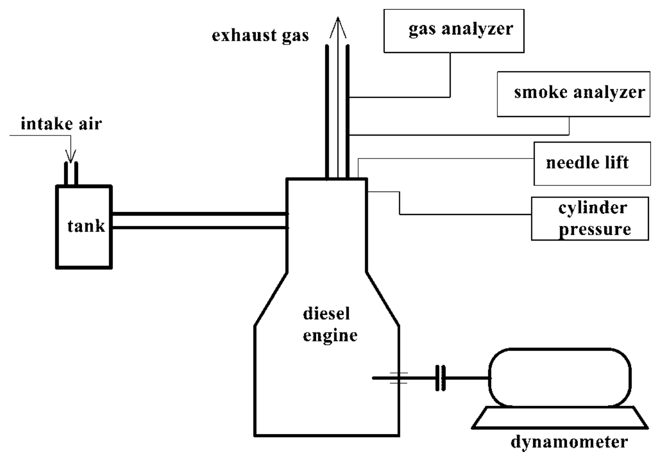


**Figure 1.** Schematic diagram of the experimental setup.

**Table 1. Specifications of the Test Engine**

| items | value |
|---|---|
| engine type | single-cylinder DI diesel engine |
| combustion chamber | $\omega$ type |
| bore (mm) | 100 |
| stroke (mm) | 115 |
| displacement ($cm^3$) | 903 |
| compression ratio | 18 |
| rated power (kW)/speed (r/min) | 11/2300 |
| nozzle hole diameter (mm) × number | 0.3 × 4 |
| fuel delivery angle | 26°CA BTDC |

* To whom correspondence should be addressed: School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China. E-mail: xbwang@mail.xjtu.edu.cn.

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**Table 2. Fuel Properties of Diesel and DMM**

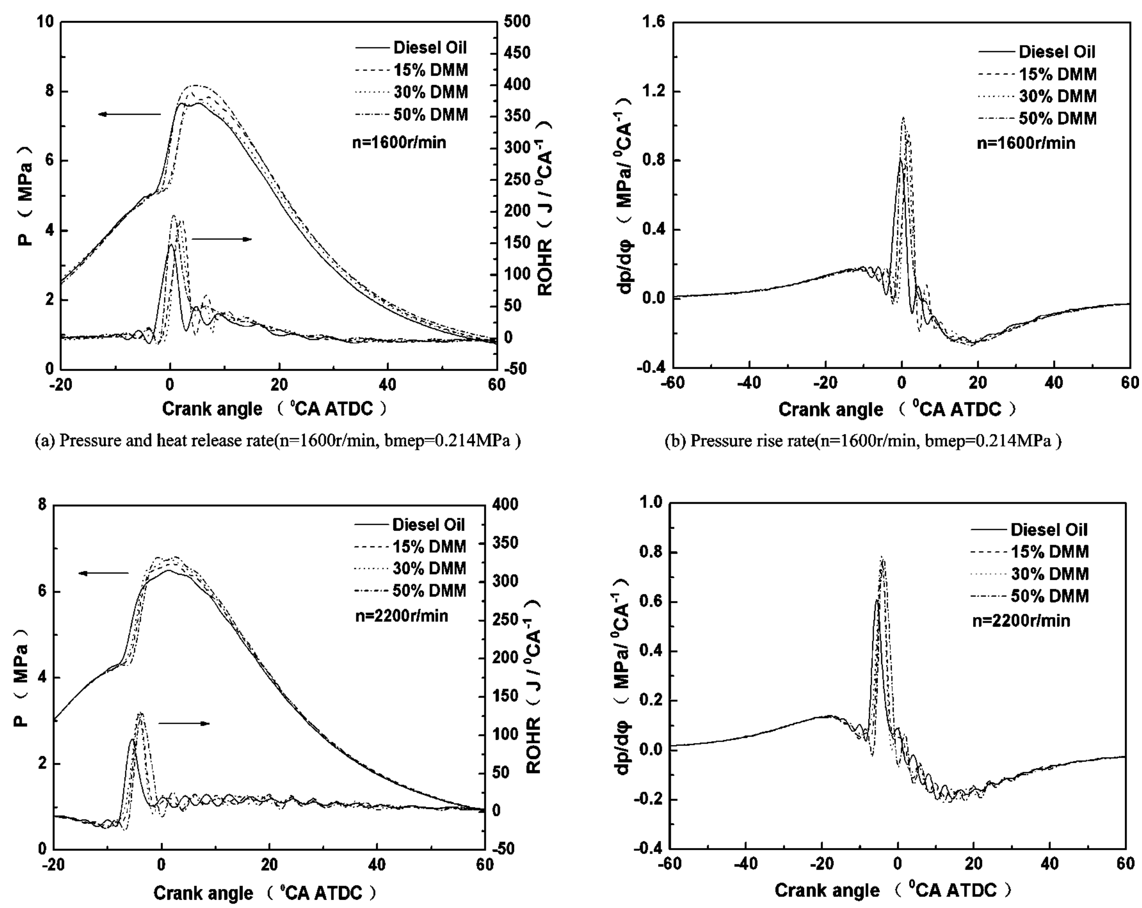
| items | diesel | DMM |
|---|---|---|
| chemical formula | $C_{10.8}H_{18.7}$ | $C_3H_8O_2$ |
| mole weight (g) | 148.3 | 76.1 |
| density (g/cm$^3$) | 0.86 | 0.865 |
| lower heating value (MJ/kg) | 42.5 | 22.4 |
| heat of evaporation (kJ/kg) | 260 | 318.6 |
| self-ignition temperature (°C) | 200−220 | 237 |
| cetane number | 45 | 30 |
| C (wt %) | 86 | 47.4 |
| H (wt %) | 14 | 10.5 |
| O (wt %) | 0 | 42.1 |

**Table 3. Fuel Properties of the Diesel/DMM Blended Fuels**

| | blend fuel 1 | blend fuel 2 | blend fuel 3 |
|---|---|---|---|
| volume fraction (%) | 15 | 30 | 50 |
| DMM mass fraction (%) | 15.38 | 30.62 | 50.73 |
| lower heating value (MJ/kg) | 39.41 | 36.35 | 32.3 |
| heat of evaporation (kJ/kg) | 268.79 | 277.58 | 289.3 |
| cetane number | 42.69 | 40.5 | 37.39 |
| C (wt %) | 80.06 | 74.18 | 66.42 |
| H (wt %) | 13.46 | 12.93 | 12.22 |
| O (wt %) | 6.47 | 12.89 | 21.36 |

combustion. Fleisch et al.,[2] Kapus and Ofner,[3] and Sorenson and Mikkelsen[4] have studied DME in a modified diesel engine, and their results showed that the engine could meet ultra-low emission levels without a fundamental change in the combustion systems. Some researchers investigated several kinds of oxygenated compounds to reduce emissions without much modification to the engine. Huang et al. tested gasoline−oxygenate blends in a spark-ignition engine and obtained satisfactory results on emission reduction.[5] They also investigated the combustion and emission characteristics of diesel/dimethyl carbonate (DMC) in a compression ignition engine.[6] Carbonates, ethers, and acetates mixed with diesel fuel were also investigated. The results indicated that smoke and PM are reduced without sacrificing other emission characteristics or thermal efficiency and that the reduction only depends upon the oxygen content of the fuels.[7] Ajav et al.[8] studied the diesel/ethanol blends for emission reduction, while Huang et al. investigated the engine performance and emissions of the diesel engine fueled with diesel/methanol blends.[9] Miyamoto et al.[10] and Akasaka et al.[11] conducted research on diesel combustion improvement and emission reduction by the use of various types of oxygenated fuel blends.

In recent years, dimethoxymethane (DMM) has been attracting more and more concentration as a promising alternative diesel fuel. DMM has a high oxygen fraction and high cetane number, and because it exists in a liquid state in normal conditions, it is convenient for storage and transportation. Such advantages make DMM a good candidate to be used in diesel engines. Previous research showed that the reduction of PM[12] and $NO_x$ could be achieved by fueling with diesel/DMM blends.[13] However, these studies were performed only for a specific DMM percentage and did not give the results on engine performance and emissions under various DMM percentages. Ren et al.[14] reported engine performance, emission, and combustion characteristics under DMM volume fraction from 0 to 20%.[15] To obtain a deeper understanding of a diesel engine fueled with diesel/DMM blends, it is necessary to study the engine performance, emission, and combustion characteristics over a wider range of DMM fractions. Such work is beneficial to the future research of exhaust gas recirculation (EGR) and post-procession.



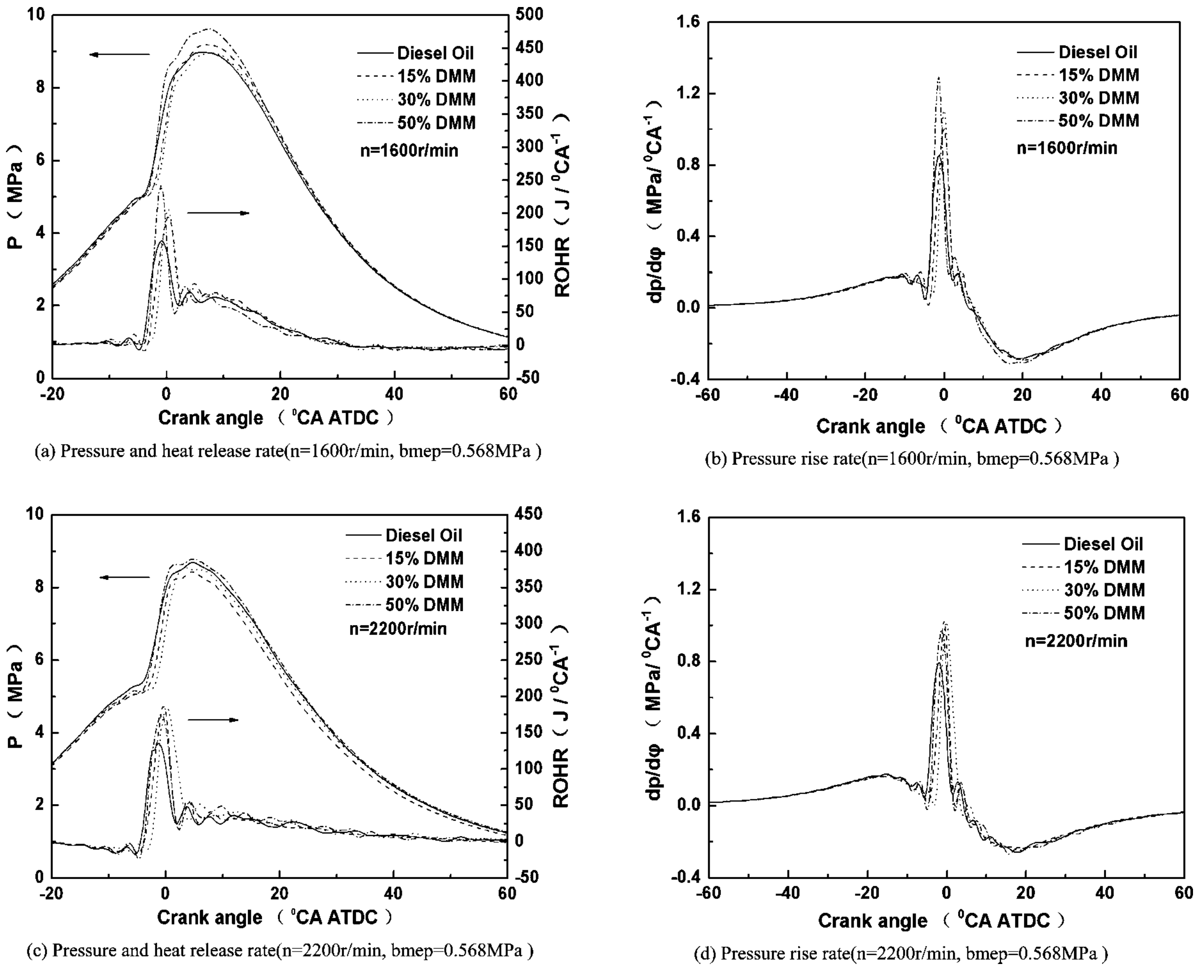

(a) Pressure and heat release rate(n=1600r/min, bmep=0.214MPa )

(b) Pressure rise rate(n=1600r/min, bmep=0.214MPa )

(c) Pressure and heat release rate(n=2200r/min, , bmep=0.214MPa )

(d) Pressure rise rate(n=2200r/min, bmep=0.214MPa )

**Figure 2.** Comparison of the cylinder pressure, pressure rise rate, and heat release rate versus the DMM volume fraction (bmep = 0.214 MPa).




(a) Pressure and heat release rate(n=1600r/min, bmep=0.568MPa )

(b) Pressure rise rate(n=1600r/min, bmep=0.568MPa )

(c) Pressure and heat release rate(n=2200r/min, bmep=0.568MPa )

(d) Pressure rise rate(n=2200r/min, bmep=0.568MPa )

**Figure 3.** Comparison of the cylinder pressure, pressure rise rate, and heat release rate versus the DMM volume fraction (bmep = 0.568 MPa).

In this paper, experiment was performed for a diesel engine fueled with diesel/DMM blends for DMM volume fractions (0−50%) and the influence of the DMM and oxygen fractions on engine performance, emission and combustion parameters was analyzed over a wide range of DMM fractions.

## 2. Experimental Apparatus and Fuel Properties

The experimental research was performed on a single-cylinder diesel engine. The experimental setup can be seen in Figure 1, and the specifications of the test engine are listed in Table 1.

As shown in Figure 1, in this experiment, an AVL DiGas 4000 exhaust gas analyzer was used to measure the exhaust gas emission and an AVL DiSmoke 4000 opacity smoke meter was used to measure the smoke level. The cylinder pressure was recorded by a Kistler piezoelectric transducer. The crankshaft angle was obtained from a crank angle encoder made by Kistler, mounted on the front end of the crankshaft. The signal of the cylinder pressure was acquired for every 0.2°CA; the acquisition duration covered 50 cycles; and the pressure data were studied to obtain the combustion parameters. In the experiment, measurement was repeated 3 times, and the average data were used for analysis. If the deviation of the measurement data is beyond the predefined limit (3%), the measurement should be conducted again to avoid measurement errors.

Three kinds of diesel/DMM blends were prepared for the DMM volume fraction at 15, 30, and 50%, respectively. Fuel properties of the three blends are given in Tables 2 and 3. As shown in Table 3, with the increase of the DMM content, the fuel blends have increased oxygen content, ranging from 6.47 to 21.36%, while the heat value becomes lower, meaning that cyclic fuel injection should be increased to maintain the power output. Table 3 also shows that, with the increase of the DMM fraction, the cetane number decreases and the heat value of evaporation increases, possibly leading to the increase of ignition delay for a diesel/DMM fuel blend with increased DMM addition. Because no experimental results can be obtained for the cetane number of the blended fuels, the cetane number was estimated by the linear interpolation method based on the cetane number of diesel fuel and pure DMM.

In the experiment, the three fuel blends with different DMM fractions were tested, emission and combustion characteristics were analyzed under different load (bmep) and engine speed. Furthermore, these parameters were made in comparison to those of pure diesel combustion to clarify the effect of oxygenate additives on combustion and emission.

## 3. Results

**Combustion Characteristics and Fuel Efficiency.** The combustion parameters are calculated by applying the first thermodynamic law in this paper. The model neglects the leakage through the piston rings, and the cylinder charge is considered as an ideal gas. Therefore, the heat release rate ($\mathrm{d}Q_B/\mathrm{d}\varphi$) is expressed as follows:

$$\frac{\mathrm{d}Q_B}{\mathrm{d}\varphi} = p\frac{C_p}{R}\frac{\mathrm{d}V}{\mathrm{d}\varphi} + \frac{C_v V}{R}\frac{\mathrm{d}P}{\mathrm{d}\varphi} + mT\frac{\mathrm{d}C_v}{\mathrm{d}\varphi} + \frac{\mathrm{d}Q_w}{\mathrm{d}\varphi}$$

where $C_p$ and $C_v$ are temperature-dependent parameters, $V$ is the cylinder volume, $m$ is the mass of cylinder gases, $T$ is the mean gas temperature, and $R$ is the gas constant. $\mathrm{d}Q_w/\mathrm{d}\varphi$ is the heat-transfer rate, given by

$$\frac{\mathrm{d}Q_w}{\mathrm{d}\varphi} = h_c A(T - T_w)$$

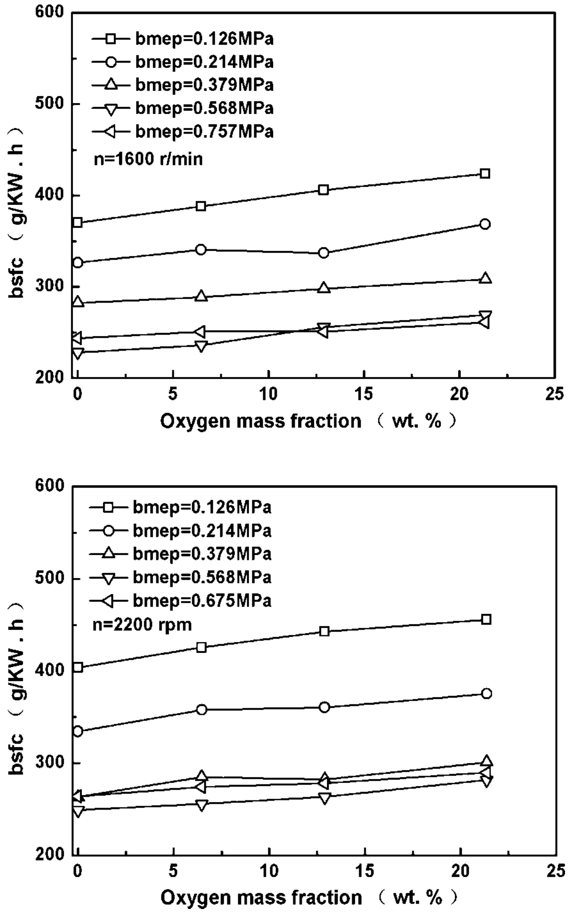



**Figure 4.** Comparison of BSFC versus oxygen mass fraction in fuel blends under different load and speed conditions.

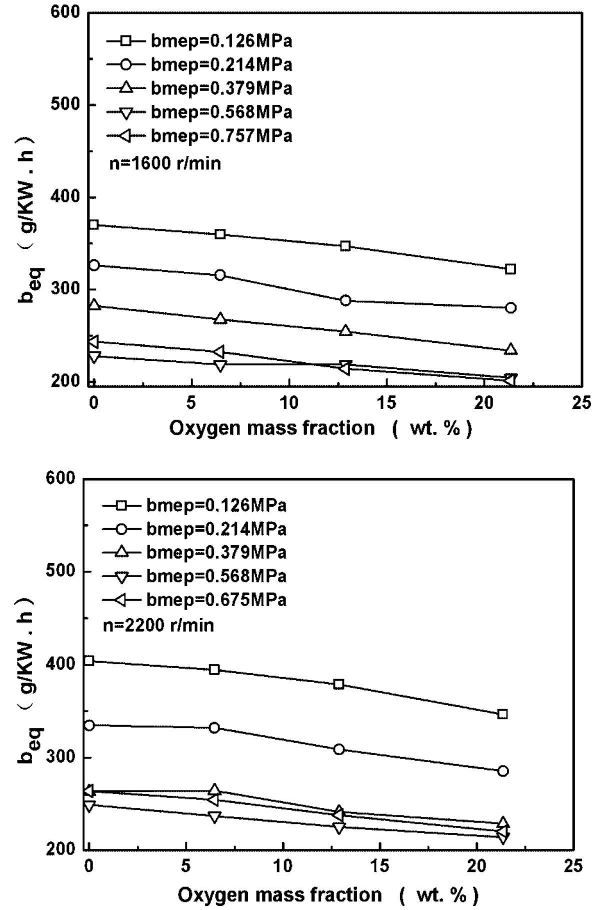



**Figure 5.** Comparison of diesel equivalent BSFC oxygen mass fraction in fuel blends under different load and speed conditions.

where $A$ is the wall area, $T_w$ is the wall temperature, and $h_c$ is the heat-transfer coefficient given by Woschni. The formulas of $C_p$, $C_v$, and $h_c$ are given in ref 16.

Using the above formulas and the data of cylinder pressure, the heat release rate and combustion characteristics, such as ignition point, premixed combustion, and diffusion combustion, can be calculated.

The comparison of cylinder pressure, heat release rate, and pressure rise rate at different operation conditions were given in Figures 2 and 3. The results showed that, for the same load and speed, the peak pressure is becoming larger and its crank angle is delayed with the increase of the DMM volume fraction. As for the heat release curve, the ignition point is the latest for fuel 2 (30% DMM), and the ignition point becomes earlier for smaller (diesel and fuel 1) and/or larger (fuel 3) DMM fractions; the duration of premixed combustion is becoming longer, the peak heat release rate is becoming larger, and the heat release of premixed combustion is becoming more as the DMM fraction is increased. The same trends exist at small loads, as shown in Figure 2.

As indicated above, the increase of the DMM volume fraction has three effects: the first is the increased heat of evaporation, because DMM has a rather low boiling temperature and can evaporate very easily, which means more evaporated DMM fuel, leading to lowered cylinder temperature, and therefore, the ignition has a trend to be delayed; the second is the increased oxygen fraction in the fuels, which as a previous study indicated that, in comparison to oxygen in the gas state, fuel oxygen in oxygenated fuels, such as DME, DMM, and alcohols, prompts the chemical reaction and combustion much more intensively[14] and such characteristics prompt premixed and diffusion combustion, leading to higher peak heat release rate, shorter combustion duration, and therefore, advanced ignition; and the third is the decrease of the cetane number of blending fuels, causing longer ignition delay.

For the DMM fraction from 0 to 30%, the influence of latent heat of evaporation plays a predominant role in ignition; therefore, ignition is retarded for increased DMM fractions. However, for the DMM fraction at 50%, the influence of oxygenated fuels predominate and the ignition is earlier than that of the 30% DMM fraction. Meanwhile, the promotion of oxygenated fuels to combustion is likewise for all fuel blends and working conditions; therefore, the peak heat release rate increases, and the diffusion combustion duration is shortened with increased DMM fractions, although a lowered cylinder temperature during ignition delay at higher DMM fractions debases such a trend to some extent. For the above reasons, the premixed fuel amount, the maximum burning rate, and maximum pressure rise rate increase with an increased DMM fraction, as seen in Figures 2 and 3

The DMM volume fraction also has an influence on fuel efficiency. A comparison of brake-specific fuel consumption (BSFC) for different fuel blends is shown in Figure 4. At both

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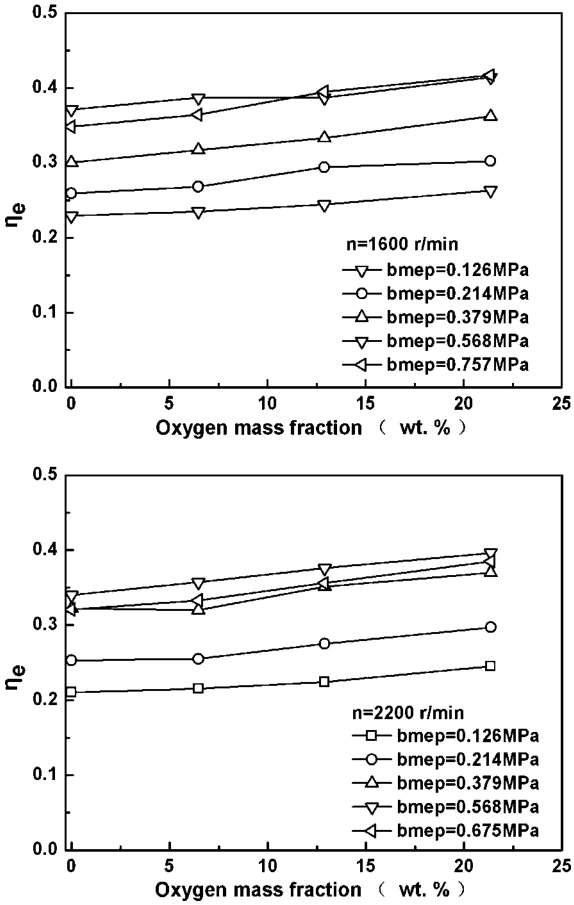


**Figure 6.** Comparison of thermal efficiency versus oxygen mass fraction in fuel blends under different load and speed conditions.

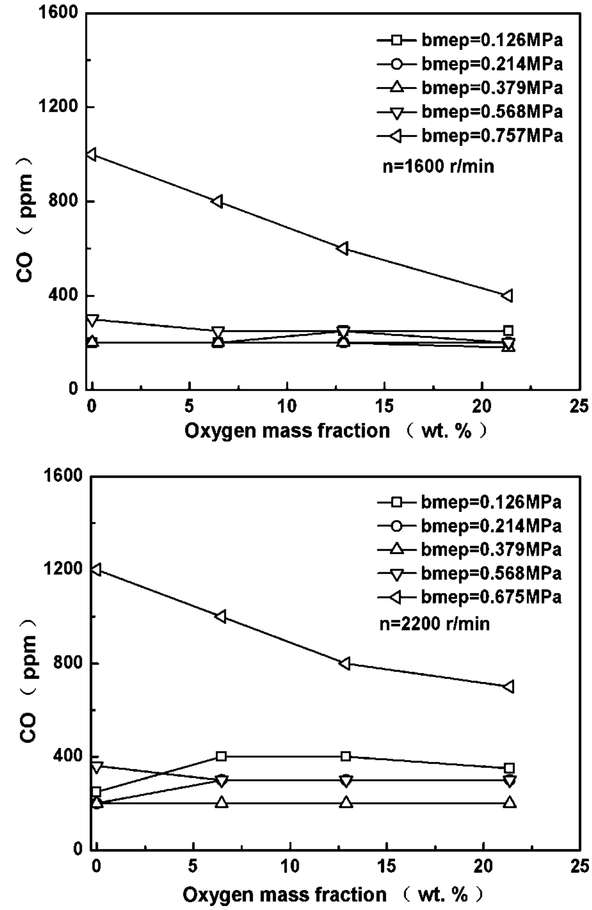


**Figure 7.** Comparison of CO emission versus the oxygen mass fraction in fuel blends under different load and speed conditions.

1600 and 2200 r/min, BSFC becomes higher with the increase of the DMM volume fraction and BSFC almost changes linearly with the DMM fraction. For small loads, BSFC increases almost linearly for the DMM volume fraction less than 30% but the slope of the curves becomes smaller for the DMM volume fraction over 30%.

As indicated above, the lower heating value of DMM is just half of that of diesel fuel. To maintain the power output, more fuel should be consumed; therefore, the BSFC increases for increased DMM volume fractions. On the other hand, as a kind of oxygenated fuel, DMM also prompts combustion, improves burning rate and combustion efficiency, makes peak heat release rate higher and combustion duration shorter, and reduces and even eliminates the phenomena of late burning. With the increase of the DMM volume fraction, such effects become more and more remarkable. For small loads, fuel injection is small, the DMM amount is small, the influence of latent heat can be ignored, and the promotion of DMM as an oxygenated fuel plays the dominant role.

According to the equivalent heat value of different fuels, diesel equivalent BSFC may be obtained. In comparison to diesel equivalent BSFC and thermal efficiency for various DMM volume fractions under different working conditions, as illustrated in Figures 5 and 6, the results are similar to the above characteristics. In comparison to 2200 r/min, less BSFC and higher thermal efficiency for the same BMEP can be obtained at 1600 r/min, because of the less friction loss at lower engine speed. At all engine loads and speeds, thermal efficiency increases and the diesel equivalent BSFC decreases with the increase of the DMM volume fraction, meaning that combustion is improved with an increased DMM fraction. Under rated load (11 kW, BMEP = 0.675 MPa) and speed (2200 r/min), diesel equivalent BSFC changes from 250 g $kWh^{-1}$ (pure diesel) to 235 g $kWh^{-1}$ (30% DMM) and 220 g $kWh^{-1}$ (50% DMM), the thermal efficiency changes from 34% (diesel) to 36.5% (30% DMM) and 38% (50% DMM). The effect of DMM addition on thermal efficiency is remarkable.

Apart from fuel efficiency, the emission level is an even more important point for the engine researchers. Therefore, the influence of DMM addition on exhaust emission was analyzed systematically in the following sections.

**CO and HC Emissions.** Figure 7 shows the influence of the DMM fraction on CO emission. It can be seen that CO emission versus the DMM fraction under full load or high load presents different behavior from part load conditions. For an engine fueled with pure diesel fuel, CO emission is very low under part load but much higher under full load conditions because of uncompleted combustion. Such characteristics are very common for common diesel engines. However, in this test, DMM fraction seems to have no significant influence on CO emission at part load, while at full load, DMM addition reduces CO emission to a large extent. This suggests that oxygenated DMM fuel could effectively decrease the locally rich spray regions, where CO is mainly formed, especially at high engine load, where a larger fraction of the locally rich spray region will exist. Moreover, the oxygen enrichment can also improve the postflame oxidation of CO in the late expansion stage, and high load results in high cylinder temperature and benefits CO oxidation. The reduction of CO emission at full load because of DMM addition is even more remarkable at low engine speed (1600 r/min) than at high engine speed (2200 r/min). This is because, at low engine speed, the reaction time is longer and

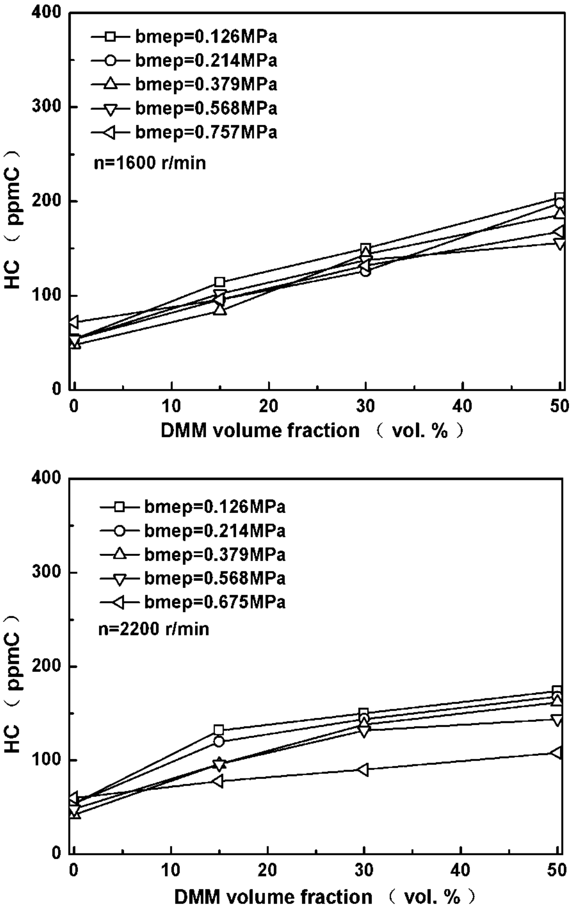


**Figure 8.** Comparison of HC emission versus the DMM volume fraction in fuel blends under different load and speed conditions.

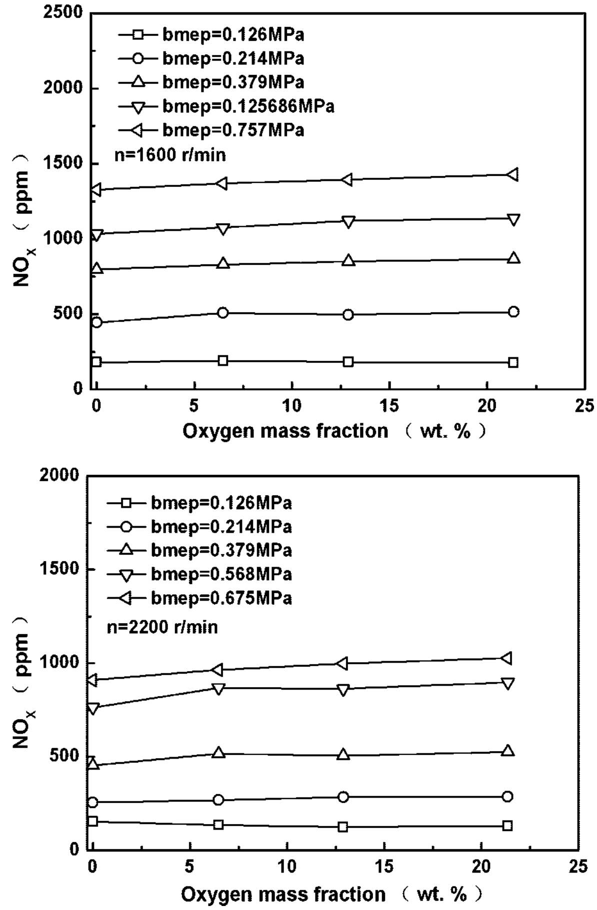


**Figure 9.** Comparison of $NO_x$ emission versus oxygen mass fraction in fuel blends under different load and speed conditions.

CO has enough time to be completely oxidized to $CO_2$. However, at small loads, CO oxidation in the late diffusion stage is weaker because of the lower cylinder temperature, and high evaporation enthopy of DMM makes cylinder temperature even lower. Such elements counteract the effect of combustion promotion of DMM addition; therefore, CO emission changes little with the DMM addition at small-load conditions.

Such a trend is different from Ren's results,[14] in which CO emission is reduced by DMM addition at all engine loads and speeds. The difference might be due to the usage of a different engine. In fact, the CO emission of the diesel engine in this paper is much smaller, about $^1/_4$ of Ren's result for full load conditions and even lower at part load. In other words, the engine performance here is better, and the overall CO emission is much lower; therefore, the different results are reasonable.

A comparison of HC emission versus the DMM volume fraction for different blended fuels is shown in Figure 8. HC emission is very low for pure diesel fuel under all engine conditions. With the increase of the DMM fraction, HC emission increases; under high load conditions, HC emission increases slowly with DMM addition but increases more rapidly at low and middle load.

Because the boiling point of DMM is about 40 °C, far below that of diesel fuel. After the fuel blends are injected into the cylinder, DMM content evaporates rapidly and disperses around the cylinder. The increase of the DMM fraction leads to the increase of DMM vapor in the cylinder. The DMM vapor far away from the flame can only oxidize slowly. At small loads, the oxidization speed is very slow for low cylinder temperature. At high or full load, the cylinder temperature is higher; therefore, the oxidization speed is faster. Thus, HC emission increases with DMM addition and increases more rapidly at low and middle load conditions.

However, there is one thing to be noted: similar to all diesel engines, HC emission of this diesel engine is very low at all engine conditions, less than 200 ppm C at most, far below the requirement of the current emission standard. There is no reported results to compare to our HC results.

**$NO_x$ and Smoke Emissions.** The variation of $NO_x$ emission versus DMM fraction is shown in Figure 9. It can be seen that $NO_x$ emission slightly increases with the increase of the DMM fraction, and the curves give a similar trend under all engine loads and engine speeds. The variation is not evident at low load conditions because of the very small value of $NO_x$ emission. It is suggested that combustion could be improved with DMM addition as an oxygenated fuel, but the cylinder temperature is lowered also by DMM addition for its high latent heat. These effects of the two elements counteract with each other; therefore, $NO_x$ emission changes slightly with DMM addition. This means that $NO_x$ emission is not sensitive to DMM addition.

The smoke emission and its reduction rate for diesel/DMM blends versus the oxygen mass fraction were plotted in Figure 10. The smoke level was indicated by the opacity of the exhaust gas. The results clearly showed that the smoke level could be decreased evidently with DMM addition at all engine speeds and engine loads, and such a trend is much more remarkable for high load conditions and high DMM volume fractions (oxygen mass fraction). In comparison to pure diesel fuel, about 70−80% of smoke was reduced at full load for the 50% DMM volume fraction (or 20% oxygen mass fraction).

Because soot or smoke is mainly produced in the diffusive combustion phase, it is affected by the local air/fuel ratio

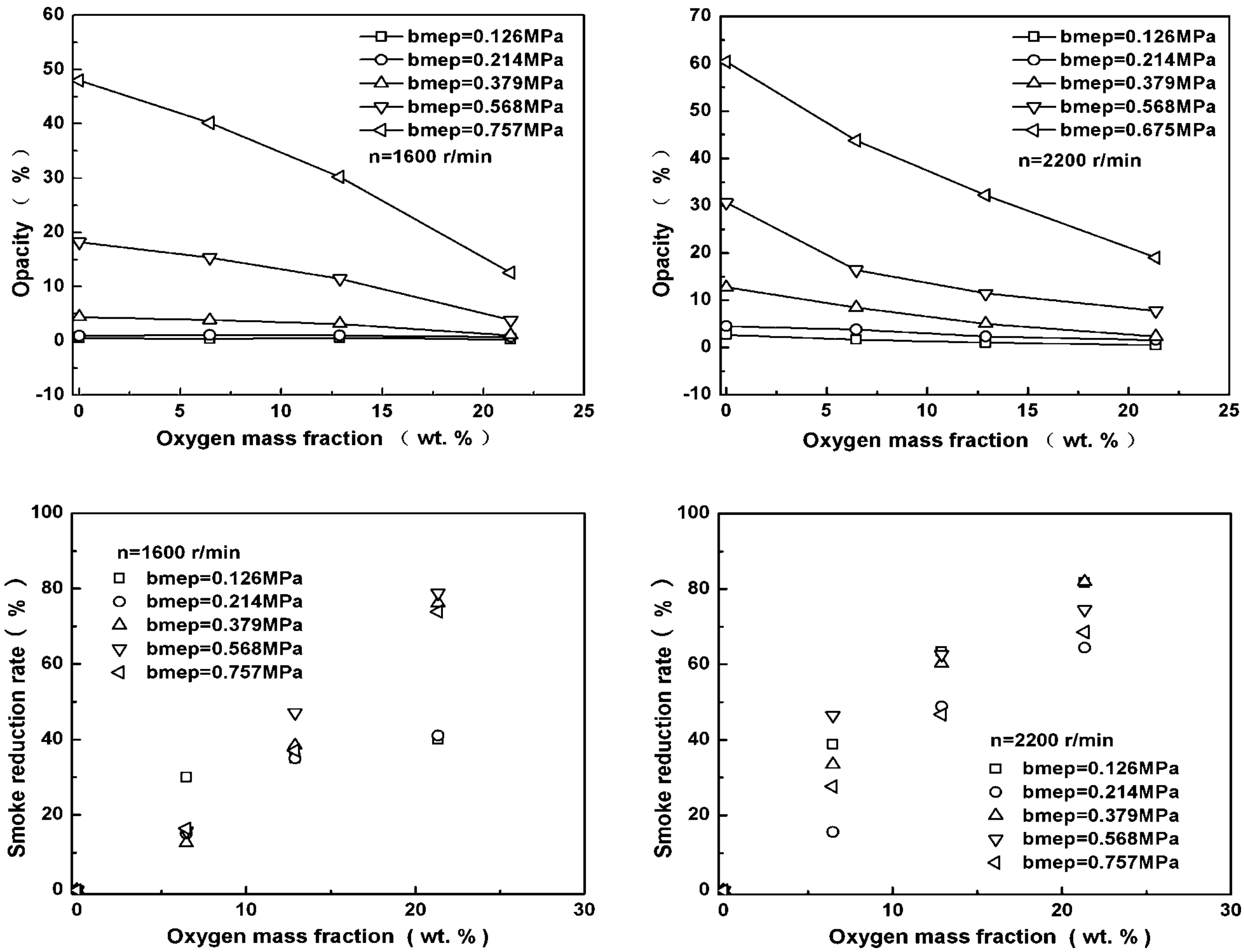


**Figure 10.** Comparison of smoke emission versus the oxygen fraction in fuel blends under different load and speed conditions.

distribution and local temperature. A high temperature and fuel-rich environment is essential for smoke production. DMM is a kind of fuel with a high oxygen mass fraction, and its addition will supply more oxygen and improve the air/fuel ratio, especially for those areas at the core of the fuel spray. Therefore, DMM addition reduces smoke formation; besides, it can also promote diffusive combustion and oxidize existing smoke.

**$NO_x$/Smoke Correlation.** The relationship between $NO_x$ and smoke of the diesel engine fueled with diesel/DMM fuel blends for the DMM volume fraction at 0−50% at various load conditions is plotted in Figure 11. It is well-known that the tradeoff relationship between $NO_x$ and smoke emissions exists for general diesel engines. On average, if one technical measurement causes the reduction of $NO_x$ emission, it will also cause smoke emission to increase simultaneously. Here, the tradeoff correlation between $NO_x$ and smoke emissions also exists, but the tradeoff curve is relatively flat. As indicated above, with the increase of the DMM fraction in fuel blends, $NO_x$ emission just increases slowly, while smoke is remarkably reduced. Take the full load condition for example, at an engine speed of 2200 r/min, when the DMM volume fraction changes from 0 to 50%, $NO_x$ emission changes from 910 to 1026 ppm (just increases only about 13%), while smoke opacity changes from 60 to 19% (significantly decreases). Similar results exist for other engine conditions. Such results agreed with Ren's work on DMM addition from 0 to 20%.[14] Because the blends are oxygen-containing fuels and have a high tolerance for exhaust gas recirculation, it means that the combination of diesel/DMM blends with EGR can make a further decrease of $NO_x$ emission without a significant increase of smoke emission, and thus, both $NO_x$ and smoke emissions can be reduced simultaneously to meet the strict emission legislation.

## 4. Discussions

From the experimental study in this paper, it can be learned that the HC and CO emissions of the diesel engine are rather low; $NO_x$ and smoke emissions are the main problem. BSFC together with cyclic fuel injection increases with the DMM volume fraction to keep the power output unchanged. Fuel 1 (15% DMM) makes smoke emission slightly reduced and cannot meet the requirement of the current emission standard, while fuel 2 (30% DMM) and fuel 3 (50% DMM) can remarkably reduce the smoke emission and realize the double purpose of $NO_x$ and smoke emission control simultaneously. However, the diesel engine fueled with fuel 3 (50% DMM) still has problems to solve, which are to enlarge the diameter of the pump plunger to supply more fuel to avoid power loss and to avoid the "gas lock effect" because of the evaporation of the DMM content in the high-pressure fuel pipe, which may cause the reduction of power output to a large extent. The latter one is very difficult to solve in a real diesel engine.

In other words, the diesel engine fueled with fuel 2 (30% DMM) can obtain satisfactory fuel efficiency and emission level. Because the diesel engine fueled with oxygenated fuel can tolerate a large percentage of EGR for further reduction of $NO_x$ emission, EGR research of the diesel engine fueled with DMM/diesel blending fuels should be performed in the future.

Another problem of the application of DMM/diesel fuel in the diesel engine is the larger pressure and pressure rise rate

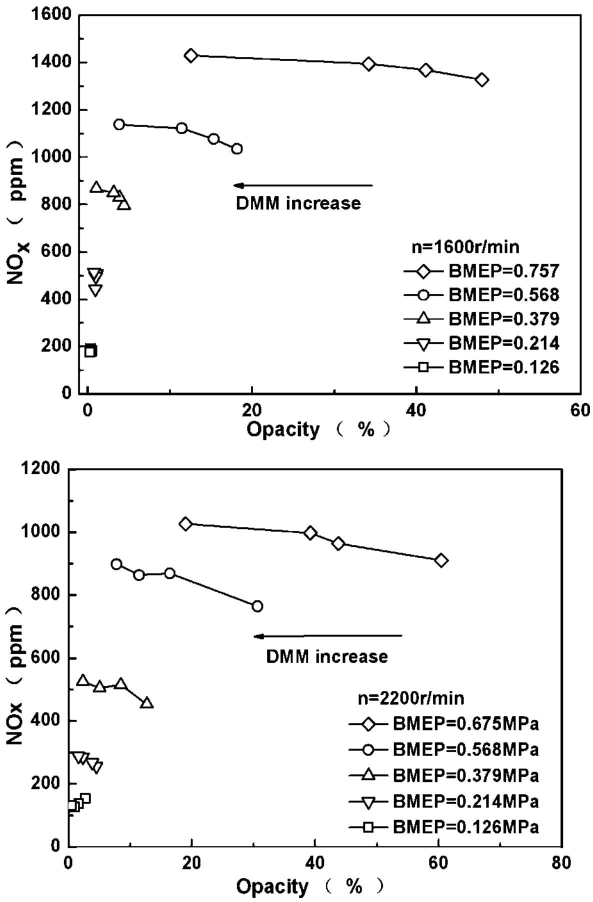


**Figure 11.** Relationship between $NO_x$ and smoke of the fuel blends under different load and speed conditions.

caused by the long ignition delay, which will increase the engine friction and reduce the engine life and reliability. However, because the DMM addition can promote diffusion combustion and combustion duration changes little under various conditions, injection timing can be delayed to avoid such problems and further reduce $NO_x$ emission. Research of injection timing on combustion and emission for the engine fueled with DMM−diesel blends should also be performed.

## 5. Conclusions

The combustion and emission characteristics of a compression ignition engine fueled with diesel/DMM blends with the DMM volume fraction from 0 to 50% were investigated, and the following conclusions can be reached: (1) Ignition delay is retarded; premixed combustion increases; and the duration of diffusive combustion is shortened with an increased DMM fraction. (2) The engine thermal efficiency increases and the diesel equivalent BSFC decreases with an increase in the oxygen mass fraction (DMM mass fraction) in blend fuels because of the promotion of oxygenated fuels to combustion. (3) Remarkable reduction in the smoke and CO emission is realized under middle and high loads for the diesel engine fueled with diesel/DMM blends. Flat $NO_x$/smoke correlation is presented for the diesel engine fueled with diesel/DMM fuel blends, and even a simultaneous reduction in both $NO_x$ and smoke can be realized at large DMM additions. (4) The diesel engine fueled with fuel 2 (30% DMM) can obtain satisfactory fuel efficiency and emission level.

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