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Full Length Article

Effect of polyoxymethylene dimethyl ethers addition on spray and atomization characteristics using a common rail diesel injection system

Donghua Li, Yuxin Gao, Shenghua Liu *, Zhijie Ma, Yanju Wei

School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

HIGHLIGHTS

- The effect of PODE addition on the spray characteristics is observed.
- Nozzles with different diameters were employed in this work.
- The experimental results on spray tip penetration were compared with empirical equations.
- The macroscopic and microscopic spray characteristics were investigated.

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ABSTRACT

PODE is named for the mixture of polyoxymethylene dimethyl ethers. Recently, it is used as diesel oxygen additive to reduce diesel engine smoke. In this study, the effect of PODE addition on the spray and atomization of diesel spray was investigated by using a high pressure common rail system. The spray tip penetration (STP), the spray cone angle and the spray projected area were extracted at the injection pressure of 60, 90 and 120 MPa and the ambient pressure of 4 MPa through a high speed photographic device. The results show that as PODE is added into diesel, the STP is slightly decreased and the average spray cone angle and projected area are slightly increased. In addition, the microscopic spray characteristics such as statistical droplets size distribution and characteristic diameters and relative size range were obtained by a particle/droplet image analysis (PDIA) technique. The results shows that as PODE is added into diesel, the droplets number tends to be uniformly distributed around 12–20 μm range and smaller characteristic diameters are observed and the relative size range keeps constant. All of such characteristics of the spray indicate that PODE addition can better the atomization of diesel spray.

1. Introduction

PM mass and number control on diesel engine becomes a serious problem now. To meet stringent regulations, DOC and DPF are widely used in exhaust aftertreatment system. However, there exists regeneration and fuel economy punishment [1,2]. Increasingly stringent emissions regulations provide chances for the development of new alternative fuel. Oxygenated alternative fuel study proves that fuel bond oxygen can reduce PM and PN remarkably, which may lead to an easy way to emission control and the use of oxygenated alternative fuel on diesel engines [3–7].

One typical concept is to achieve clean combustion performance with oxygenated fuels (molecules that contain oxygen in the structure) [8]. It has been validated by a lot of experimental results that the soot emission shrinks with the increase of the oxygen content of fuel itself. Meanwhile, the NOx emission decreases simultaneously or increases lightly. It can be explained with the aspect of bond energy. C—O (353 kJ/mol) is cleaved more easily than O—O (498 kJ/mol) [9]. Thus, C—O of oxygenated compound plays an important role in inhibiting the soot formation [10].

DME, as a kind of oxygenated fuels of diesel engine, has been researched by the worldwide engine researchers for many years. DME, the simplest ether, can be synthesized more easily than other ethers and this leads to low cost of DME production. DME has a cetane number of 55–60, which is higher than diesel. DME exists in gaseous state at room temperature and pressure conditions [11–13]. When DME is added into diesel fuel, the vapor pressure of blended fuel increases and the viscosity decreases. And thus the engine's fuel supply and injection system have to be modified accordingly. These disadvantages impede the application and promotion of DME on diesel engine.

* Corresponding author at: School of Energy and Power Engineering, Xi'an Jiaotong University, Xianning West Road 28#, Xi'an 710049, China.
E-mail address: shenghua@mail.xjtu.edu.cn (S. Liu).

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Polyoxymethylene dimethyl ethers (PODE) which stands for the mixture of ethers with general structure $CH_3O(CH_2O)nCH_3$, is regarded as new ideal alternative fuel compared with DME [14–16]. DME can be treated as PODE with n = 0, and DMM (Dimethoxymethane) is another case of PODE with n = 1. So PODE is also written as DMMn, where n is usually between 3 and 5 for the use of diesel fuel additive. The properties of diesel, DME and DMMn are listed in Table 1. Some disadvantages of DME are overcome by DMM, but its cetane number constrains its application. Moreover, Zhu et al. [17] found that vapor lock happened frequently in DMM/diesel blended fuel supply system. In recent years, a few researches have been conducted on DMMn with n = 3–5. Comparing with DME and DMM, $PODE_{3-5}$ has higher cetane number and lower vapor pressure. $PODE_2$ is not applied on engine for its boiling point of 42 °C, while $PODE_6$ is excepted for its too high melting point of 58 °C, which may result in vapor lock at engine operating conditions or precipitate at lower temperature conditions. Therefore, only PODEn with n = 3–5 are suitable for engine applications. Pellegrini et al. [18,19] investigated the combustion process of neat $PODE_{3-5}$ and $PODE_{3-5}$/diesel blends at the ratio of 12.5% and 50% on a single-cylinder optical research engine. The emission characteristics research of these fuels were also conducted on a light-duty multi-cylinder diesel engine, and the experimental data demonstrates that the presence of intermolecular oxygen promotes soot oxidation. The results also prove that neat and 50% blends are possible to optimize NOx and PM emission performance simultaneously, while addition with ratio of 12.5% can be used on non-modified engines and PM emission can be reduced by 40%.

Wang et al. [20] investigated the characteristics of PODE homogenous charge compression ignition (HCCI) combustion for the first time. The results show that ultra-low NO_x emissions and soot-free combustion were achieved for PODE HCCI combustion under lean mixture conditions. While PODE lean HCCI combustion produced high levels of CO and HC emissions. Liu et al. [21] studied combustion and emission characteristics of PODE/diesel blends in both light-duty and heavy-duty diesel engines. The study shows that diesel engines are able to work normally fueled by $PODE_{3-4}$/diesel blends with lower than 30% $PODE_{3-4}$. By adding $PODE_{3-4}$ in diesel fuel, soot emissions decrease significantly. CO and HC emissions decrease with increasing $PODE_{3-4}$ blending ratio. Liu et al. [22] also investigated the improvement of emission characteristics and thermal efficiency in diesel engines by fueling gasoline/diesel/$PODE_n$ blends. The research found that blending $PODE_{3-4}$ in gasoline/diesel blends reduces HC and CO emissions and engine efficiency was improved by blending $PODE_{3-4}$ in gasoline/diesel blends. From the above analysis, it is obvious that $PODE_n$ show great potential as an alternative fuel for diesel engine.

Fuel spray and atomization characteristics have significant effect on mixture formation and combustion process. Such characteristic plays an important role in improving engine combustion performance and reducing emission. The evaporation of spray is significantly influenced by droplets size. With the use of microscopic facilities, microscopic characteristic, namely the droplets size, is measured and employed to quantitatively present the atomization quality. Combined with the study of macroscopic characteristics, a comprehensive view of the spray is observed from both macroscopic and microscopic angle.

So far there has been no research on the spray characteristics of PODE. Therefore, it is necessary to conduct an investigation on the spray and atomization characteristics of PODE and PODE/diesel blends under various conditions in order to widely apply PODE on diesel engines.

Table 1
Properties of PODEn compared with diesel and DME at 25 °C.

Molecule	Density (g/cm^3)	Cetane number	Oxygen content (%)	Boiling point (°C)
Diesel	0.831	56	0	180–370
DME	0.67	55	34.8	−25
DMM	0.86	29	42.1	42
PODE2	0.96	63	45.3	105
PODE3	1.02	78	47.1	156
PODE4	1.06	90	48.2	202
PODE5	1.1	100	49	242
PODE6	1.13	104	49.6	280

2. Experimental setup and procedures

2.1. Chamber and fuel injection system

The schematic diagram of the spray visualization bench is shown in Fig. 1. A columnar, constant volume chamber was used in this study. Two sides of the chamber provided an optical access using two 100 mm diameter quartz windows. A single-hole injector was fixed centrally on the top side of the chamber. Nitrogen gas was charged from a manual intake valve into the chamber and exhausted from another manual exhaust valve. The ambient pressure was measured by a pressure sensor and was adjusted manually by the intake and exhaust valves.

A 2.2 kW 3-phase AC motor controlled by a 3-phase frequency inverter was used to drive the high pressure pump to produce varied injection pressure. An electronic control unit was developed purposely to control the injection pressure, and the injection pressure was monitored by the pressure transducer on the common rail. This electronic control unit also gives the trigger signal to provide variable time interval between injector and camera during the experiment.

A BOSCH second-generation common-rail injector was used in the present study and the injection pulse width of the injector was set to 1500 μs. Three injector nozzles with varied diameter of 0.12 mm, 0.15 mm and 0.18 mm were used respectively, which is shown in Fig. 2.

2.2. Tested fuels and test conditions

Four fuels were prepared and tested. They are P0, P20, P50 and P100, representing neat diesel, 20% by volume PODE in PODE-diesel blends, 50% by volume PODE and neat PODE, respectively. The tested PODE fuel here is $PODE_{3-5}$ and this fuel is simplified as PODE in the following paragraphs. The properties of these fuels are respectively listed in Table 2. The density, viscosity and surface tension were measured by devices named by Dahometer, NDJ-1 and SFZL-U3, respectively. All the measurements were conducted at 20 °C according to Chinese national standards.

The test conditions were listed in Table 3. All the experiments were conducted at the injection pressure of 60, 90 and 120 MPa and the ambient pressure of 4 MPa. On the diesel engine, 60, 90 and 120 MPa are the typical injection pressure in common running condition. At the case of nature inspiration diesel engine, the typical internal pressure of the combustion chamber at the start of injection is around 4 MPa. So the test conditions have a high similarity with the real conditions on the diesel engine.

The lower heat value of PODE is less than one half of diesel. For fuel with high blending ratio, cyclic injection quantity should be increased. One way is to increase injection pressure, the other is to enlarge the hole. So the nozzle diameter of 0.12, 0.15 and 0.18 mm were set. In addition, the injection duration was set to a low value of 1500 μs with consideration of the limited optical quartz window size.