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Full Length Article

Experimental investigation of particulate matter structures under partially premixed combustion in a compression ignition engine

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ABSTRACT

A study on particulate matter (PM) of a compression ignition engine under partial premixed combustion has been performed. Particularly, the microscopic analyses (SEM and TEM) of several samples at the exhaust were carried out to describe the morphology and ordering degree of particles produced by the combustion of diesel and 15% diesel blended with 85% light hydrocarbon (named DLH). Characterization parameters such as fractal dimension, fringe separation distance, fringe length and fringe tortuosity were analyzed to further study the particle structure. Besides, the particle size distributions at medium and high load were compared. The results demonstrated that the particle size distribution presents as quasi-monodisperse and the average diameter of DLH is smaller than that of diesel. The diesel particles move to a larger size range at higher load, while DLH particles show an obvious shift to smaller particles at higher load, which is related to the competition between surface growth and oxidation rates.

1. Introduction

Due to high thermal efficiency, reliability and economy, diesel engines are widely used in vehicles, agricultural machineries and engineering equipment. However, diesel engine emissions are one of the main sources of environmental pollution [1]. Particulate matter (PM) emissions have caused haze formation to a great extent and is also harmful to human health [2]. Therefore, the formation mechanism and control of PM have become an increasingly important issue in recent years.

Under the background of global energy shortage and increasingly stringent emission regulations of internal combustion engines, various alternative fuels were explored. And the combustion and emission performance of engines were comprehensively studied in real engines by changing the proportion of fuel components. Koder et al. [3] investigated the injection, ignition and combustion of jatropha oil, soybean oil and diesel oil in a 2.2L common-rail diesel engine with a two-stage turbocharging concept and high pressure EGR. The size distribution for all test fuels at a low- and mid-load engine-operating point (EOP) were examined by applying different EGR rates. For oxygenated additives application, diesel engines adapted dual fuel mode more and more, and soot emissions decreased significantly with the increase of oxygenated alternative fuels, such as alcohols, natural gas, biodiesel and dimethyl ether (DME) [4]. Chen et al. [5] investigated the combustion and emission performance of a common rail diesel engine fueled with diesel and ethylene glycol. It was found that ethylene glycol reduce ultrafine particles (UFPs) and decrease the average diameter of UFPs particularly. In addition, some studies have been carried out on the emissions of hydrocarbon fuel surrogate components blended with diesel. Qian et al. [6,7] studied the effect of *iso*-alkanes structure and aromatics blended with diesel on combustion characteristics and regular emissions respectively, and demonstrated that the addition of *iso*-alkanes reduced HC, NO_x and soot emissions [6]. However, blending aromatics caused peak value of particle number/size distribution curve moving towards to the small-size sides, and the single-ring aromatics showed higher particle emissions than multi-ring aromatics [7]. Li et al. [8] chose n-dodecane, *iso*-dodecane, tetralin and decalin to mix with diesel in 10% and 20% volume fraction. The effect of fuel components on unregulated emissions such as formaldehyde, acetaldehyde, ethylene, propylene, methane, and particle number and particle size were analyzed in detail.

In order to meet the requirements of fuel economy and emission characteristics, the new combustion modes have also been deeply studied. Homogeneous charge compression ignition (HCCI) combustion model is a typical representative. However, the high pressure rise rate, load extension and combustion phasing control need to be overcome in

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the actual implementation of HCCI strategy [9]. Partial premixed compression ignition (PPCI) in diesel engine cylinder is a combustion mode between direct injection compression ignition (DICI) and HCCI. Literature [10–12] investigated the gasoline PPCI concept by using gasoline-like fuels in common-rail compression ignition engines. Won et al. [13], Yu et al. [14] and Valentino et al. [15] conducted an experimental study of gasoline/diesel blended fuel in PPCI mode on a high-pressure common-rail direct injection compression combustion engine. It can be seen that PPCI mode has been applied in practice and has the potential to improve both NO_x and soot emissions and thermal efficiency. Jaasim et al. [16] simulated soot particle formation and emissions from low octane gasoline-like naphtha fuel under PPCI condition. The results showed that PPCI presents typical stratified combustion characteristics, and under its operating conditions, most of the main soot conditions throughout the entire combustion are avoided. The most direct way to determine whether alternative fuels and new combustion modes can be applied in practice is to study and compare their economy and emission characteristics. Diameters distribution, composition and concentration, SEM-TEM analyses are the most commonly used methods to understand PM morphology [17,18]. Liu et al. [19] carried out SEM analysis on soot particles generated from catalytic diesel combustion. The result showed that the average particle size of catalytic diesel decreases apparently compared with diesel fuel. Potenza et al. [20] studied the PM compound morphology based on SEM-TEM by changing the injection parameters that could affect soot production on a turbocharged engine. The results demonstrated high influence of injection strategies on soot morphology-composition and on catalyst efficiency. However, previous researches [20,21] focused on the impact of injection strategy variation (fuel injection timing, injection pressure, pilot injection) on engine particulate emissions. What's more, several studies [22,23] focused on pure diesel combustion, revealing the evolution of particle size and number under different conditions (operation parameters, EGR rate, injection parameters, combustion type). So far, little research has been done on the microscopic characteristics of light hydrocarbon particles under PPCI combustion mode.

In this study, the particle emission of diesel and DLH was studied by changing the engine operating condition in PPCI mode. Comparing with pure diesel fuel, the microstructure and particle size distribution of DLH were analyzed in detail based on electronic microscopic images. In addition, the effects of light hydrocarbon blending and operating conditions on the particulate emission characteristics of dual fuel engines were revealed, which provides a theoretical basis for finding ways to reduce particulate emission in the future.

2. Experimental setup and method

The test engine is Z6170ZLCZ-1 diesel engine produced by Zibo Diesel Company in China. Table 1 lists the main technical parameters of the test diesel engine. The whole test system mainly includes engine, dynamometer, fuel supply system, intake and exhaust system, electronic control system and sampling device. The engine speed and output torque were controlled automatically using an electrical dynamometer (AVL504/4.6 SL). Using a piezoelectric pressure sensor (Kistler 6052C) coupled with a combustion analyzer (Dewetron M0391E) to measure the combustion pressure in the cylinder. Fig. 1 shows the schematic diagram of the test engine. In the ideal condition of PPCI mode, the end point of fuel injection and the start point of combustion are separated, which makes the fuel and air have a better premixed state at the beginning of combustion. This not only avoids the formation of soot caused by the local mixture over-concentration, but also facilitates the expansion of operating load in both high and low directions. In this study, light hydrocarbons are premixed with air through port fuel injection (PFI), and then mixed with a small amount of diesel directly injected (DI) into cylinder to form the mixture for combustion. The agglomerated aluminum foil is plugged in the soot sampling port of the exhaust pipe, so that the soot particles can accumulate on the surface of it for sampling.

Table 1
Specifications of test engine.

Parameters	Details
Combustion system	4-Valve PPCI
Number of cylinders	6
Displacement/bore/stroke	27 L/170 mm/200 mm
Compression ratio	14.5
Rated speed/rated power	1000 r/min/330 kW
Brake specific fuel consumption	200 g/kW.h
Injection/injection pressure	Direct injection/up to 35 MPa PFI injection/0.45 MPa
Intake valve opening/closing	50°CA BTDC/40°CA ABDC
Exhaust valve opening/closing	65°CA BBDC/50°CA ATDC

Diesel and light hydrocarbon are used in the experiment to form the mixture fuel according to the mass ratio. Light hydrocarbon is a mixture with C_5 and C_6 as the main components and has a higher low heating value than diesel. High blending ratio of light hydrocarbon will make it difficult for diesel engine to start and work normally. Therefore, 85% light hydrocarbon mixed with 15% diesel and pure diesel fuel are used in the test scheme. The physical parameters of diesel and light hydrocarbon are shown in Table 2.

Fig. 2 shows the in-cylinder pressure, heat release rate and pressure rise rate curves of the two test fuels at 100% engine load of 1000 r/min. As shown in the pressure curve, it can be observed that the maximum cylinder pressure of DLH is lower than that of diesel, and its appearance is also delayed 2°CA. Lower temperature and pressure lead to a delay in ignition time, which can be seen from the heat release rate curve. But the maximum heat release rate of DLH is higher than that of diesel. The full mixing of fuel-air improves the fuel burning rate and complete combustion. As can be observed from Fig. 2, the pressure rise rate curve and the heat release rate curve have almost the same trend, and the corresponding phase moves backwards.

Soluble organic fractions (SOF) on the particle surfaces have viscosities that promote the easy sticking of particles together. Therefore, particles should be pretreated to avoid affecting the shooting effect. Aluminum foil is placed in ethanol and oscillated by ultrasonic. We have done a lot of experiments to determine the reasonable ultrasonic time and frequency according to the properties of the sample and the reference provided by the ultrasonic instrument. The ultrasonic time was finally determined to be 30 min and then centrifuged for 5 min. This process filters out some of the SOF components, reduces the particle adhesion and disperses the agglomerated particles. It is conducive for SEM analysis.

SEM (JSM-7500F) with 1.0 nm resolution and 15 kV accelerating voltage is used. It mainly uses the high-energy electrons to bombard the surface of particle samples, and utilizes the secondary electron emission effect produced by the sample to obtain the high-resolution sample surface structure information. TEM (JEM-1400Plus) with 0.38 nm resolution is used to observe and analyze the micromorphology and structure of the particles characterized by the fractal dimension of diesel particulate matter. TEM with higher resolution (Talos F200S) with 0.25 nm resolution is used to observe the nanostructure of primary carbon particles, whose geometric structure irregularity and density can be characterized by fringe separation distance, fringe length and fringe tortuosity. ImageJ software is used to measure the particle size and 100 particles are randomly selected for measurement under typical running condition.

In the test, the engine speed is set to 1000r/min, and two loads, 75% and 100%, are selected. PPCI is achieved by PFI of 85% light hydrocarbon and DI of 15% diesel. For each experimental condition, several analyses have been realized, according to the summary in Table 3. The combustion particle morphological characteristics of pure diesel and DLH under the same conditions are compared. Finally, by changing the