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Impacts of nozzle geometry on spray combustion of high pressure common rail injectors in a constant volume combustion chamber

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ABSTRACT

Diesel engine performance and emissions are closely related to fuel atomization and spray processes, which in turn are strongly influenced by nozzle geometry. In this study, five kinds of single-hole cylindrical injectors which have different orifice diameters (0.13–0.23 mm) and lengths (0.7–1.0 mm) were employed to research the effects of the nozzle geometry on spray droplet size distribution and corresponding combustion characteristics. The spray droplet size spatial distribution was measured with the Phase Doppler Particle Analyzer (PDPA). The results show that the Sauter Mean Diameter (SMD) reduces with the increase of the distance from injector tip and the SMD of the central axis is bigger than that of the periphery. With the increase of the injection pressure (40–120 MPa), the spray SMD decreases significantly. In addition, as the orifice diameter goes smaller, the SMD decreases and the effect of the orifice diameter on the spray SMD becomes weak. Meanwhile, as the orifice length goes longer, the SMD decreases when the orifice diameter is 0.13 mm. And then, the combustion characteristics were experimentally investigated in a constant volume chamber with optical access. Time-resolved images of the natural luminosities (indicator of soot) from the combustion process were captured by high speed camera and combustion pressure was also acquired. It is found that there is a good corresponding relationship between spray SMD, combustion heat release rate and flame luminosity. That is to say, the way to decrease SMD reduces greatly the natural luminosities and improves combustion heat release rate. This article presents the effects of nozzle geometry on droplet size distribution and combustion, and provides important references for injector manufacture.

1. Introduction

It is widely known that the injector nozzle configuration affects the spray atomization and fuel/air mixing process, which directly influence the combustion and the exhaust emissions. Nowadays, besides employing alternative fuel [1–3] and installing complex after-treatment system [4], diesel nozzle geometry is considered a major issue in order to fulfil new stringent emissions regulations while maintaining or improving the efficiency of the engine.

It is a tendency that the nozzle hole diameter will become smaller and smaller and the injector pressure higher and higher. So it is necessary to know about the spray and combustion characteristics of different nozzle geometries. In order to better explore the spray atomization and the breakup mechanism, high speed camera coupled with Phase Doppler Particle Analyzer (PDPA) was always adopted to analyze the spray penetration, cone angle, droplet size distribution and velocity distribution in the gasoline nozzle under various conditions [5–7]. But many previous studies mainly focused on spray penetration and cone angle for high common rail diesel nozzle, which used spray penetration and cone angle to illuminate the diesel spray atomization [8–13]. Lee et al. [14,15] investigated the diesel droplet size distribution under low-pressure common rail, using the high speed camera coupled with PDPA. Previous results found that the difference of drop size between locations at the center and periphery of the spray was very large and the drop sizes increased with increasing radial distance from the spray centerline. Air entrained by the spray pulls the smaller drops toward the centerline, while the larger drops maintained their momentum and were detected along the periphery of the spray. In addition, the spray penetration and the SMD were studied on diesel fuel under different injection pressures. The combustion and exhaust emissions were also discussed in the optical engine. Previous studies mainly focused on the spray penetration and cone angle under high injection pressure or the spray droplet size

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distribution and velocity distribution under low injection pressure for multi-hole nozzle on an inline injection pump or unit injection pump. Few studies were investigated to research the spray droplet size distribution or velocity distribution under high common rail pressure for single-hole nozzle.

The main purpose of exploration spray is to understand how the fuel spray affects the characteristics of combustion and emissions. The combustion characteristics of different nozzle geometries, such as nozzle hole diameter, roundness of nozzle inlet and K-factor ($K = (D_{inlet} - D_{outlet})/10$, in μm) were investigated in previous studies. Five kinds of nozzle shapes were conducted to investigate the effects of orifice shape on fuel consumption and emissions in a real diesel engine by Bergstrand [16]. The results indicated that a divergent conical orifice shape (negative conicalness) generally has lower soot emissions, lower nitrogen oxide emissions and a lower fuel consumption than the cylindrical orifice shape that the reference nozzle has, and a small orifice diameter emits less soot than a larger orifice diameter. Karra and Kong [17] investigated the effects of injection pressure and nozzle diameter on engine performance and emissions in a multi-cylinder diesel engine. It was found that the small nozzle size in the ten-hole injector appeared to have better air utilization and resulted in significant reductions in NO_x and soot emissions over a wide range of operating conditions. Payri et al. [12,18] investigated the effects of nozzle geometry on direct injection diesel engine spray and combustion process, and put forward the correlations including effective diameter and K-factor terms with ignition delay. Siebers et al. [19] studied the effects of fuel composition, temperature and nozzle diameter on ignition and flame lift-off length in a constant volume chamber. It was found that flame lift-off length decreases with increasing ambient gas temperature or density, and increases with increasing injection pressure or orifice diameter. Zhou et al. [20] studied the nature flame evolution process of different fuel component and temperature using natural luminosity method. All previous studies suggests a strong relation between improvement emissions and nozzle geometry, however at least to the author's knowledge, the whole natural flame evolution and quantitative analysis to instantaneous emissions has not conducted yet for different nozzle geometries.

The goal of this work is to study the effect of nozzle geometry on spray and combustion characteristics under high injection pressure with a common rail fuel injection system. To avoid the interference among multi-hole oil sprays, a series of single-hole nozzles were adopted. The droplet size distribution, the combustion characteristics, and the soot formation were studied with PDPA coupled with high speed imaging technology in a constant volume combustion chamber. Results show that different orifice diameters and lengths greatly affect the spray atomization, and then change the combustion and emissions characteristics.

2. Experimental apparatus and setup

2.1. Nozzle

All tested nozzles are cylindrical injector and a series of single-hole nozzle which has different orifice diameters and lengths were provided by Wuxi Fuel Injection Equipment Research Institute. Using a conventional single-hole nozzle whose diameter and length are 0.18 mm and 0.7 mm respectively as a reference, the spray and combustion characteristics of different nozzle geometries were investigated. The specific parameters are shown in Table 1.

Table 1
The specific parameters of nozzle geometry.

Nozzle	Diameter (mm)	Length (mm)	L/D
N1	0.23	0.7	3.04
N2	0.18	0.7	3.89
N3	0.13	0.7	5.38
N4	0.13	0.9	6.92
N5	0.13	1.0	7.69

2.2. Phase Doppler Particle Analyzer (PDPA) system

To investigate spray development behavior and analyze spray atomization characteristics, experiments were performed using PDPA under different high injection pressures. The schematic diagram of Phase Doppler Particle Analyzer system is shown in Fig. 1. Experimental bench consists of Dantec's 3-D fiber phase Doppler system and high pressure common rail system. The PDPA system is made up of a water-cooled Ar-Ion laser with a maximum power output of 6 W, a multi-color beam separator, a 3-D Fiber Flow transmitter, a HiDense PDA receiver with a maximum data rate of 300,000 samples/sec equipped with a 500 mm focal length lens, a photoelectric converter and a Doppler signal processor (BSA P80) with a maximum frequency of 180 MHz. The high pressure common rail system contains asynchronous motor, high pressure oil pump (Bosch CPN2.2), common rail and ECU. All tests were carried out under ambient conditions for the free spray condition (atmospheric pressure and room temperature), and the injection pressure was varied from 40 MPa to 120 MPa every 40 MPa, and the injection duration was set to 3 ms. The PDPA system was triggered as soon as the injection sign was delivered to injector. Then the droplet size was recorded in the computer.

2.3. Constant volume combustion chamber system

The schematic diagram of constant volume combustion chamber system used in the study is shown in Fig. 2. The system can simulate inside conditions of engine cylinder, such as high pressure and temperature, which consists of constant volume combustion chamber system, high pressure common rail system and high speed photograph system. The inside structure of constant volume chamber is a bore of 80 mm in diameter and 268 mm in depth, which can be heated to desired temperature by high temperature resistance wire. The resistance wire is surrounded inside and controlled by a temperature control unit. The constant volume chamber can bear a maximum operating pressure of 10 MPa. The injector is mounted at the top of the chamber. The pressure transducer (Kistler6125C) and the temperature sensor were installed at a side of the chamber. The high speed photograph synchronization system contains high speed camera (Photron SA 1.1) equipped with a 100 mm focal length lens (Tokina) and NI DAQ (NI USB-6251 BNC). The camera photographic speed can reach up to 675,000 fps and the maximum of the shutter speed is 2 μs. DAQ sampling frequency can reach up to 70 kHz.

In this study, the air was charged into the chamber by high pressure vessel. The initial pressure was equal to 1 MPa. when the inside air temperature was heated from room temperature to 900 K, which is similar to the temperature of the engine injection timing, the pressure of the chamber was filled up to 3 MPa. Spray injection was triggered when the temperature reached to 900 K again and the pressure was 3 MPa. At the same time, a series of images were synchronously obtained by high speed camera. The tested condition is shown in Table 2.

2.4. Experimental methodology

According to the spray image captured by a high-speed camera, the measurement points were determined to obtain a higher PDPA data rate under different injection pressures. And the droplet size