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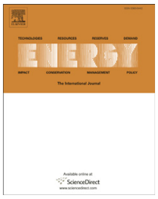

Combustion and emission performance of a split injection diesel engine in a double swirl combustion system

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ABSTRACT

The authors developed and tested a split injection strategy in a double swirl combustion system (DSCS). Different split injection strategies with different ratios of pilot injection fuel to total fuel mass (herein defined as “pilot injection/fuel mass ratios”) and dwell times were compared with an optimized single injection strategy in terms of the break specific fuel consumption (BSFC). The in-cylinder pressure, heat release rate and in-cylinder temperature were analyzed to explore the in-cylinder combustion process. The NOx emission was also measured. With the total fuel mass being 100 mg/cycle and excess air coefficient being 2 at 2100 r/min at a 5% pilot injection/fuel mass ratio and a 10 deg dwell time, the BSFC decreased by 2.7% compared with the single injection strategy. The NOx emission increased from 940 ppm to 1140 ppm. An ‘acceleration effect’ helped the DSCS when dwell time was short. A spray visualization experiment and numerical simulations were carried out to explain these phenomena. It is concluded that the split injection condition with a smaller pilot injection/fuel mass ratio and a shorter dwell time performed better than the single injection condition in terms of the thermo-atmosphere utilization, space utilization and acceleration effect.

1. Introduction

Diesel engines have become one of the most widely used power sources due to their fuel conversion efficiency and high power output [1–3]. However, with increasingly stringent emission regulations [4–10], many methods, such as exhaust gas recirculation [11,12], premixed charge compression ignition [13,14], ultra-high injection pressure [15] and split/multiple injection [16,17], have all been rigorously studied to improve combustion performance and reduce harmful exhaust emissions. A strategy that improves the air-fuel mixture, combustion process and soot emissions but not the NOx emissions could still be widely accepted, because NOx emissions can be reduced by after-treatment [18]. Therefore, this study focused on improving combustion performance outside of NOx emissions, which were simply monitored for observational purposes and for providing data for after-treatment.

Different combustion chamber designs have been proposed and studied to improve the air-fuel mixture [19–21]. A double swirl combustion system (DSCS) was developed to improve the in-cylinder combustion process, in which the main component is comprised of an inner chamber and an outer chamber [21–25]; there exists a convex, called the circular ridge, between the inner chamber and outer chamber, as shown in Fig. 1. In this system, two swirls form—one in the inner chamber and one in the outer chamber—after the fuel spray impinges the circular ridge. There are two advantages of the DSCS: 1) the double-swirl effect causes the fuel spray to surround the air at the center of the swirl and increase the entrainment gas into the fuel spray; and 2) after impinging the circular ridge, the fuel spray is directed to the oxygen-enriched region by the bowl of the DSCS and is distributed more uniformly [21]. Therefore, the air-fuel mixture is effectively improved in the combustion chamber. At present, the DSCS is a mature system that has been studied and applied in mass-produced diesel engines with 132 mm and 150 mm cylinder diameters [22–25]. It has been reported that the brake specific fuel consumption (BSFC) and soot emissions could be improved in the DSCS with further research [25].

Another effective method for improving the air-fuel mixture is split injection [26]. Split injection, with its flexible injection strategy, reduces noise, emissions and the BSFC [16]. In this paper, the split injection strategy focused on the air-fuel mixture. Yoshihiro Hotta [27] found that the premixed combustion in a pilot injection reduced smoke due to an enhanced mixing of air in the cylinder. Sylvain Mendez [26] found that it was possible to improve fuel

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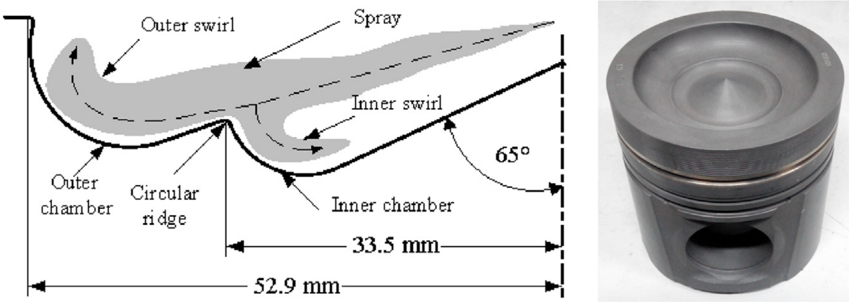

(a) The structure of the test DSCS chamber (b) The test DSCS piston

Fig. 1. The DSCS.

economy with a double injection while retaining similar noise and soot levels. S. d'Ambrosio [17] found that the premixed combustion of the pilot injection increased the in-cylinder temperature and provided a thermo-atmosphere for the main injection that was of great significance for fuel to atomize, mix and evaporate. Jeongwoo Lee [28] found that a pilot injection that was sufficiently close in proximity to the main injection had the potential to improve combustion efficiency and the BSFC.

Split injection strategies have been previously studied, but mainly in traditional omega combustion systems (OMECS) [16,17,26–28], and there was only one single injection strategy previously studied in the DSCS [21–25]. However, it is necessary to also study split injection strategies applied in a DSCS to further improve combustion performance. In response, this paper addresses two yet unresolved issues: 1) the problem of using the flow field of the split injection to enhance the double swirl effect in the DSCS and 2) the problem of matching fuel distribution, thermo-atmosphere distribution and double swirl regions with DSCS improvements. These issues have not been fully resolved in the current literature. Therefore, this study aims to fill that void. In this work, a DSCS combined with different split injection strategies was applied in a single cylinder diesel engine experiment. The effects of the split injection strategies and the DSCS were comprehensively explored through a spray visualization experiment and numerical simulations.

2. Experimental setups

2.1. Single cylinder engine

The performance and NOx emission tests were carried out on a single cylinder diesel engine. The basic parameters are listed in Table 1. The structure and size of the test DSCS is shown in Fig. 1(a), and a photograph of the test piston is shown in Fig. 1(b).

An eddy current dynamometer (provided by Maikai) and a frequency convertor (provided by Siemens) were the main devices in the dynamometer system. The pressure charging system included a VHN-16/8 air compressor, a buffer tank and several pipes. In the temperature control system, an AEH100 air heater was applied to keep the intake air temperature constant, while the cool water temperature and lubricating oil temperature was modified by a specialized heating and control device (produced by Xiangyi). For the data acquisition and analysis system, the BSFC was captured by a CMF series dynamical fuel mass flow meter with an accuracy of 0.12% FS (produced by Shanghai ToCeil). A Kistler 6052B piezoelectric pressure sensor and a Kistler 4067B oil pressure sensor were used to measure in-cylinder pressure and oil pressure, respectively. A combustion analyzer Kibox was also provided by Kistler. A HORIBA MEXA-720 NOx analyzer was used to measure the NOx concentration with an accuracy within ±1 ppm.

Table 1
Basic parameters of the test engine.

Bore × stoke/mm	132 × 145
Connecting rod length/mm	262
Rail pressure/MPa	140
Compression ratio	13.5
Nozzle diameter/mm	0.195
Number of holes	7
Spray angle/°	153

2.2. Constant volume vessel

The constant volume vessel was provided by Beijing BITEC Co., Ltd. A common rail injection system provided 160 ± 4 MPa oil pressure, and the nozzle diameter of the adopted single-hole injector was 0.22 mm. The accuracy of the in-vessel temperature was ±5 K, while the accuracy of the in-vessel pressure was ±0.2 bar. The vessel could hold an 800 K temperature and a 6 MPa pressure. Ref. [29] may be consulted for additional details about the constant volume vessel.

A Phantom V7.3 high-speed camera (produced by Vision Research) was used to capture the liquid jet and vapor jet images through direct imaging and schlieren imaging, respectively. The camera had a video resolution of 504 by 256 pixels at a 20 kHz rate. Two dysprosium lamps were installed on both sides of the vessel to allow the camera to capture the direct imaging in front of the vessel with an exposure time of 0.030 ms and an aperture of f/5.6. A z-type schlieren system, including two parabolic mirrors of a diameter of 200 mm, a knife-edge, a 0.3 mm slit and a halogen lamp, was applied to capture the schlieren imaging. In the schlieren system, the camera operated with an exposure time of 0.048 ms and an aperture of f/3.5.

3. Methodology and process

3.1. Single cylinder diesel engine experiment

In the single cylinder diesel engine experiment, the fuel quantity/cycle was set at 100 mg with an accuracy within ±2 mg. The engine speed was 2100 r/min and the excess air coefficient was 2. The intake air temperature was 333 K. In order to ensure the validity of the experiment data, all of the tests were repeated three times in each operating condition.

Firstly, the highest power and the lowest BSFC was obtained when the injection advance angle was −16 deg ATDC, as shown in