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Combustion and emission characteristics of a lateral swirl combustion system for DI diesel engines under low excess air ratio conditions

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ABSTRACT

In order to improve the utilization of air in the cylinder, decrease the thermal load and improve the emission performance of diesel engines, a new lateral swirl combustion system (LSCS) has been proposed in this study. An experimental investigation of the LSCS at various excess air ratios was conducted using a 132 mm single-cylinder direct injection (DI) engine. The experimental results indicate that, compared to a double swirl combustion system (DSCS), the LSCS achieves better fuel consumption and lower soot emissions. The fuel consumption was decreased by 4–5 g/(kW h) at each excess air ratio, corresponding to a reduction of about 1.13–2.8%. The decreasing trend of soot formation was also clear, with a significant reduction in the range of 63.4–70.8%. The LSCS also showed excellent performance under an excess air ratio of 1.3–1.6. At an excess air ratio of 1.3, the brake-specific fuel consumption (BSFC) of the LSCS was 228 g/(kW h), the soot emission level was 1.1 Filter Smoke Number (FSN) and the exhaust temperature was about 560 °C. Related numerical research on the impact of in-cylinder fuel/air equivalence ratio, in-cylinder temperature and in-cylinder velocity of the DSCS and the LSCS was performed, and the results show that a large proportion of the fuel/air diffusion was at the bottom of the chamber in the LSCS (away from the cylinder head). The lower concentration of the fuel/air mixture near the cylinder head in the LSCS had a positive effect and reduced the thermal load so that less engine heat was taken away by the cooling water in the water jacket of the cylinder head. Due to the lower thermal load and higher efficiency, the exhaust temperature of the LSCS was higher than that of the DSCS. The higher exhaust temperature had a positive influence on soot oxidation, which caused the soot decrease in the LSCS. It is suggested that the LSCS, with its excellent fuel consumption and low soot emission, has better application prospects in diesel engines, than the DSCS under a low excess air ratio.

1. Introduction

Direct injection (DI) diesel engines are used in the field of transportation and engineering machinery due to their excellent thermal efficiency and practical economic value [1–3]. However, due to the diffusion combustion of fuel, the requirement of air in diesel engines is higher than that in gasoline engines (excess air ratio is about 2.0 and 1.0, respectively) [4,5]; more air must be supplied by the turbocharger system and the intake/exhaust systems in order to improve the fuel/air mixture for diesel engines. However, the turbocharger system is limited by its inefficiency, and the intake/exhaust systems are limited by its resistance and volumetric inefficiency [6–9]. Therefore, when using those systems, it is difficult to increase the power density of diesel engines, specifically under the conditions of thin air in a plateau. If the excess air ratio is too high, the peak in-cylinder pressure is also relatively high, which has a negative influence on the reliability of the engine. When the excess air ratio is low, soot emissions and thermal load are increased [10–13].

The combustion performance and emission characteristics of diesel engines are affected by the fuel/air mixture formation [14–16]. Therefore, a homogeneous fuel/air mixture in the combustion chamber and an increase of the fuel/air mixture area can significantly improve the utilization of air and restrict the soot formation in diesel engines.

At present, the excess air ratio of diesel engines is about 1.8–2.2 and the excess air ratio of heavy duty diesel engines is about 1.6–1.8. Thus, it is valuable and necessary to propose a new combustion system to reduce the burden on the turbocharger system and intake/exhaust systems and show excellent performance under low excess air ratio. In this study, the authors propose a

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Nomenclature

LSCS	a lateral swirl combustion system
DSCS	a double swirl combustion system
BSFC	the brake-specific fuel consumption
FSN	Filter Smoke Number
DI engine	direct injection engine
LS chamber	lateral swirl chamber
DS chamber	double swirl chamber
TDC	top dead center
HRR	heat release rate
OMECS	omega combustion system
TH1	the temperature of the first test position of cylinder head
TH2	the temperature of the second test position of cylinder head

new diesel engine combustion system, which has an excellent practical economic value and emission performance at an excess air ratio of 1.3. The burden of the turbocharger system and the intake/exhaust systems is reduced. The power density and thermal efficiency is improved, and fuel consumption is decreased. In addition, the new combustion system shows excellent emission performance under the condition of thin air in a plateau.

The lateral swirl combustion system (LSCS) was proposed in another study [17,18] and the lateral swirl (LS) combustion chamber is shown in Fig. 1, where it can be observed that when the spray hit the convex edge, two lateral swirl vortices was formed on both sides of the convex edge, accelerating the fuel/air mixture formation and enhancing the utilization of the air in the chamber. The fuel/air mixture of the traditional diesel engine combustion system, as shown in Fig. 2, was mainly concentrated in the α and A zone. The air in the β and B zone was not fully utilized until an intake swirl was introduced. However, flow loss increased and the air inflow decreased in this case.

To verify the combustion performance and emission characteristics, the LSCS at various excess air ratios were experimentally studied in a single-cylinder engine. Furthermore, numerical research on the impact of the in-cylinder fuel/air equivalence ratio, in-cylinder temperature and in-cylinder velocity was conducted to reveal the mechanism of the excellent practical economic value and emission characteristics of the LSCS. This study will be of sound reference for power density improvement and emission reduction research of direct injection diesel engines, specifically under the condition of thin air.

2. Analytical methodology

2.1. Experimental setup

The test was conducted using a 132 mm single-cylinder direct injection engine. The connecting rod length and stroke length were 262 mm and 145 mm, respectively. The nozzle diameter and nozzle number of the injector was 0.27 mm × 8.

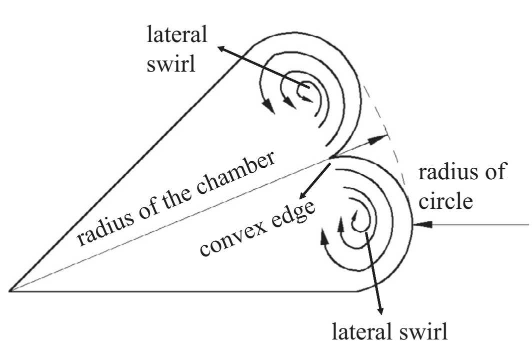

Fig. 1. Lateral swirl combustion system (LSCS).

A unit pump provided by Bosch was used to supply fuel to the engine. A VHN-16/8 air compressor was used to provide a supercharged environment. In order to heat the intake air and establish a constant temperature environment, the engine was coupled with an AEH100. The fuel consumption meter was provided by Shanghai ToCeil, whose response time was less than 0.1 s, and the accuracy was 0.12% FS. The pressure and temperature sensors were provided by Kistler. The engine was coupled with the combustion analyzer-KiBox to collect and analyze the test dates. An AVL 415S smoke meter was used to measure the soot level in the exhaust gas, with an accuracy of 0.001 Filter Smoke Number (FSN). A MEXA-720 NOx analyzer provided by HORIBA was used to measure the NOx concentration with an accuracy within ±1 ppm, and the sample volume for each measurement was 1 L. The soot and NOx emissions were measured three times for each test point in order to verify the correctness of the emission results. The engine was first warmed up, based on the temperature of the engine coolant and lubricating oil. All measurements and readings were recorded when the engine was at a steady state condition. The system diagram is shown in Fig. 3.

The geometric parameters of the double swirl combustion system (DSCS) and the LSCS chambers are shown in Fig. 4(a) and (b). A photo of the two test pistons are shown in Fig. 4(c) and (d). The compression ratio of the two combustors was maintained at 13.5.

2.2. Numerical study

The in-cylinder fuel/air equivalence ratio, in-cylinder temperature and in-cylinder velocity of the DSCS and the LSCS were analyzed and evaluated using AVL-FIRE 2010 [19,20]. Because the chamber and the injector were symmetrical, just one eighth of the chamber was modeled. In consideration of reducing the simulation time and ensuring the accuracy of results, Hexahedron meshes were applied for the models of the LS and the DS chamber [21]. The influence of the mesh size on the simulation results had been previously studied, and the results show that the proper mesh size is 1 mm [22,23] (as reported in previous research). The number of meshes and nodes at top dead center (TDC) for the models of the LS and the DS chamber were about 11,580 and 13,509 respectively. The mesh specification of the LS and the DS chamber at TDC are shown in Fig. 5.

The boundary and initial conditions of the simulation models were based on a single-cylinder engine. The k-ε Turbulence model, Wave model, Duckowicz model and Extended Coherent Flamelet Model – 3 Zone were selected for simulation [24–28].

To show the correctness of the computational model, computational results compared with experimental results of the in-cylinder pressure and heat release rate (HRR) are illustrated in Fig. 6. It can be seen that the computational results were in good agreement with the experimental results. Thus, a conclusion can be drawn that the computational models and boundary conditions of the numerical simulation were credible.