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Experimental and numerical study on the influence of intake swirl on fuel spray and in-cylinder combustion characteristics on large bore diesel engine

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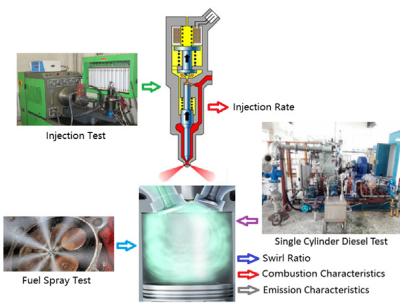
GRAPHICAL ABSTRACT



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ABSTRACT

In the present study, the numerical simulation of the performance of fuel injection and spray atomization on diesel engine combustion was conducted, which was validated against fuel injection test, spray test and single cylinder diesel engine test. Thus, the effect of the intake swirl on the fuel spray and diesel engine combustion performance was explored. Quantitative analysis of the characteristics of fuel-air mixing and combustion characteristics under different swirl ratio was given. It was found that the spray atomization and fuel-air mixing begins from the front of fuel beam which has deflection due to the presence of the intake swirl. The function of swirl is to accelerate the mixing and diffusion speed of fuel, thus promoting the combustion process in cylinder. Meanwhile, the NO and Soot emissions were quite sensitive to the swirl ratio, which leads higher NO but lower Soot as the swirl ratio is increased. In addition, the performance of varied swirl ratio on spray penetration and spray angle was well captured by numerical studies in the paper. Consequently, this study reveals the influence of different swirl ratio on the fuel spray performance, output power and fuel consumption, thus exploring the influence of inlet swirl of the controllable swirl diesel engine on the fuel atomization behavior as well as dynamic performance, and verifying the accuracy of the simulation results.

1. Introduction

The intake swirl of diesel engine is an effective means and plays important role on improvement of the fuel-air mixing and the combustion in the cylinder, especially for the cases with lower fuel injection pressure and insufficient fuel-air mixing at lower engine loads. The controllable intake swirl applicant on diesel engine proposed in this study can automatically control the intake swirl according to the magnitude of the intake pressure. It adjusts the air intake of the direct current air passage and the swirl air passage by changing the opening

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Nomenclature

EP	effective power [kW]
BSFC	brake specific fuel consumption [g/kW·h]
BMEP	brake mean effective pressure [bar]
MCP	maximum combustion pressure [MPa]
CA	crank angle [deg]
TDC	top dead center
BTDC	before top dead center
ATDC	after top dead center
SR	swirl ratio
MCT	maximum combustion temperature [K]

angle of the baffle in the direct-intake air inlet, thereby achieving the flexible control of the intake swirl with intake pressure tuning. As shown in the Fig. 1, the intake swirl has a two-stage characteristic. That is a high swirl ratio at low loads and a relatively small swirl at high loads to ensure improved fuel-air mixing at low engine loads and sufficient intake air requirements at high loads.

However, the influence of swirl by a controlled intake swirl diesel engine on the spray process and the combustion characteristics still need further exploration. Regardless of today's high supercharged diesel engine or high pressure common rail injection diesel engine, swirl plays an irreplaceable role in diesel engine fuel-air mixing and combustion. In recent years, related research work had been carried out on the combustion and emission performance, along with fuel-air mixing of the intake swirl diesel engine. For example, Met al. [1] found that the swirl can shorten ignition delay at certain injection timings, and enhance the heat release rate in all studied experimental conditions. David Rathnaraj et al. [2] concluded that the increase in the swirl generating capacity of the port due to variable swirl plate ensuredbetter combustion even with less amount of oxygen. This methodology is promising for optimum design of the variable swirl plate. Gupta et al. [3] revealed that the direction of swirl used to stabilize a flame from annular jets provides a great influence on flame symmetry. Benajes et al. [4] concluded that swirl has a significant influence on the combustion process and exhaust emissions. When swirl ratio was increased up to a certain level, a more intense premixed combustion phase was observed, and the diffusion controlled combustion phase was also improved. The above studies provide a theoretical and practical basis for studying the mechanism of the influence of swirl on the combustion characteristics of diesel engines. In terms of intake swirl diesel engine emissions and fuel-air mixing, many studies were also conducted in recent years. For example, XiangRong Li et al. [5] proposed a new lateral swirl combustion system, which can improve the utilization of air in the cylinder, decrease the thermal load and improve the emission performance of diesel engines. SuLiwang et al. [6] found that the fuel-air mixing and engine performance could be promoted in forced swirl combustion system owing to the introduction of swirling combustion. YuhYih et al. [7] indicated that lean-limit was extended to maximum air-fuel ratio 26.28 at swirl ratio 3.5 while brake specific fuel consumption and coefficient of cycle variation were very low. In addition, analysis on engine exhausted gas showed the decreased CO and HC emissions. Moreover, Wei Shengli et al. [8] developed a new swirl chamber combustion system for direct injection diesel engines. The mixture formation and combustion progress in the cylinder were simulated and investigated at several different swirl ratios by using the AVL-FIRE code. The results showed that in view of the fuel-air equivalence ratio distribution, the uniformity of mixture with swirl ratio of 0.2 is better. As mentioned above, the emissions and fuel air mixing are sensitive to swirl, therefore how to determine the swirl ratio reasonably, and meanwhile keeping high efficiency and lower emissions from diesel engine is the key issue to the study of swirl characteristics.

In terms of the swirl characteristics of diesel engines and the influence of geometry structure on swirl, a series of research work had been done. For example, Sharma et al. [9] obtained optimized swirl by optimizing the geometry of the intake manifold. Net al. [10] proposed four strategies to control the swirl intensity of intake air, and concluded the variation of the intake valve lift induces different swirling and tumbling intensities. Wang et al. [11] presented an investigation into in-cylinder swirl and tumble flow characteristics with reduced maximum valve lifts. Results of ensemble-averaged flow field showed that reduced maximum valve lifts could produce strong swirl flow velocity, and then resulted in very regular swirl motion in the late stage of the intake process.

The above research provides technical support and method guidance for the study of the influence mechanism of swirl on combustion, fuel injection and emission characteristics of high power, large bore controllable intake swirl diesel engine. The multi-system coupled with intake swirl, fuel injection and combustion is the focus of this study. It is the key issue to study its interaction rules, especially the influence of swirl on spray and combustion, and then on the power and emissions of diesel engine [12]. The perfect combustion process depends on the matching of the fuel system, the intake system and the organized combustion of diesel engine, and there is a certain coupling relationship between the three systems [13]. Comprehensively analyzing the internal relations and matching rules among different systems is the main objective in this study. As shown in Fig. 2, this study is conducted based on a controllable intake swirl diesel engine, where in the synergy organization of fuel system, intake system and combustion in the cylinder was investigated, in order to explore the roles of swirl on diesel engine performance.

2. Results and discussion

Firstly, according to the actual structure of the controllable intake swirl diesel fuel injection system, a one-dimensional simulation model is established. The diesel engine is equipped with mechanical pump, constant pressure valve, high-pressure fuel pipe and injector (as shown in Fig. 3). The injection behavior is performed by one dimension numerical study. Then the intake swirl is coupled into the three dimensional CFD model for prediction of fuel injection and combustion process in the diesel engine cylinder. So the influence of intake swirl on diesel engine performance can be further explored.

2.1. Analysis of fuel injection system

The simulation model of fuel injection system of diesel engine is established by using AVL-Hydsim software. The calculation model consists of three parts: high pressure pump, equal pressure delivery valve and injector. The high pressure pump module includes cam, plunger matching part, plunger chamber, inlet and outlet oil hole, pressure boundary and plunger leakage module, etc. The equal pressure delivery valve module mainly includes delivery valve, return valve and

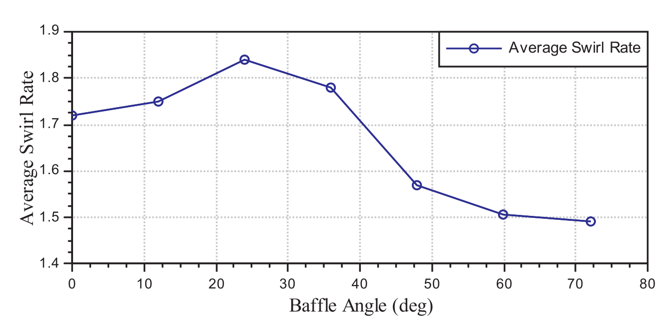

Fig. 1. The change law curve of average swirl ratio with baffle angle.