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Mechanism study of scavenging process and its effect on combustion characteristics in a boosted GDI engine

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A B S T R A C T

The scavenging process is helpful to suppress super-knock in a 4-stroke turbocharged gasoline direct injection engine because it can reduce in-cylinder thermal load and clear the suspending residual particles from previous cycles. This paper investigated the effects of dual variable valve timing on scavenging and combustion process by simulation and experimental study. The simulation results showed that the scavenging process improved with the advance of intake valve timing and the retard of exhaust valve timing. When the valve overlap duration was the same, the early occurrence of valve overlap was helpful to the scavenging process. The longer the valve overlap duration was the better the scavenging process would be. When exhaust valve timing was fixed, spark timing retarded with the advance of intake valve timing, nevertheless, the mixture mass, basic specific fuel consumption rate, combustion duration, and exhaust temperature increased with the advance of intake valve timing. In two early intake valve timing conditions, when exhaust valve timing was retarded, the mixture mass, basic specific fuel consumption, exhaust temperature raised, combustion duration and the length of ignition delay shortened. In three late intake valve timing conditions, the combustion characteristics were unchanged with the postponement of exhaust valve timing. The effect of dual variable valve timing on scavenging and combustion process was similar. Intake valve timing played a determinate role in the combustion performance of gasoline direct injection engine. The optimized scavenging process could lower the super-knock frequency and improve combustion characteristics.

1. Introduction

In recent years environmental and energy problems have become a major concerned all over the world. There are more than 1 billion automobiles worldwide and over 60% are equipped with gasoline engine [1,2]. The fuel consumption of gasoline engine is normally 20%–30% higher than that of diesel engine [3]. Therefore, improving the efficiency of gasoline engine is vital for energy saving and emissions reduction.

The combination of direct injection, high boost and dual variable valve timing (DVVT) technologies have become the main development trend of gasoline engine. Although these techniques have great benefits in lowering fuel consumption and improving power density, they also bring some harmful effects on engine performance, especially the knock. A new engine knock mode, called super-knock [4] which occurs in boosted gasoline direct injection (GDI) engine at low-speed high-load working condition has been studied recently. The super-knock is a phenomenon of rapid multipoint auto-ignition of plenty of end gas before normal spark timing and it can seriously destroy the components and parts near the combustion chamber (e.g. spark plug, the valve and piston) because of the especially high peak pressure and the pressure oscillation amplitude [5]. In addition, the control strategies on common knock, such as enriching mixture, retarding spark timing and shortening flame propagation distance are not valid for super-knock [6]. Therefore, the super-knock is the major obstruction for further improving power density and lowering fuel consumption in gasoline engine.

Many researchers have investigated the occurrence mechanism of super-knock. Inoue et al. revealed that the tendency of super-knock was not affected by different structural parameters of spark plug [7]. Dahnz et al. found that the pre-ignition origins were spread throughout the cylinder evenly and there was no apparent relevance between the working conditions and the distribution of pre-ignition origins [8]. More studies have indicated that the auto-

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Table 1
Engine specifications.

Engine type	4 cylinder, Water-cooling
Displacement	1.5 L
Bore/stroke	75.0 mm/84.8 mm
Compression ratio	11.5:1
Connecting rod length	133.86 mm
Cylinder distance	83 mm

ignition of oil droplet induced super-knock. The oil droplet became a trigger when the temperature of combustible mixture around it achieved the auto-ignition point [9]. Dingle et al. found that when the oil was injected into the cylinder directly, pre-ignition could be induced [10]. Further investigation found that the basic oil properties and additives compositions also influenced the frequency of super-knock [11,12].

In addition to the oil droplet, suspending and glowing solid particles are also the possible origins to super-knock. The pre-ignition frequency decreased when the combustion chamber was clean or under the condition which had less spray/wall interaction [11,13]. The deposits formed by wall wetting could form an ignition kernel, the pre-ignition occurred when the kernel size became bigger than the laminar flame thickness at local pressure and temperature [14].

From the above research, it can be concluded that the super-knock can be attributed to the auto-ignition of the nonstructural hot-spots (e.g. oil droplets, oil/fuel mixture droplets or carbon particles). Thus eliminating these nonstructural hot-spots is a valid method to restrain super-knock.

Some actual measures have been applied to suppress super-knock. The light to moderate levels of cooled EGR improved the brake mean effective pressure and thermal efficiency and reduced super-knock frequency by lowering the thermal load on the combustion chamber [15]. Two-stage injections in which the first and second injection occurred in the middle and late stage of intake stroke could also decrease the super-knock tendency due to the alleviation of cylinder liner wall wetting [16,17]. Further, the integration of high tumble ratio of 2.8, EGR, high compression ratio and miller cycle or late IVC (intake valve close) Atkinson cycle suppressed super-knock occurrence under high load operating regime [18,19].

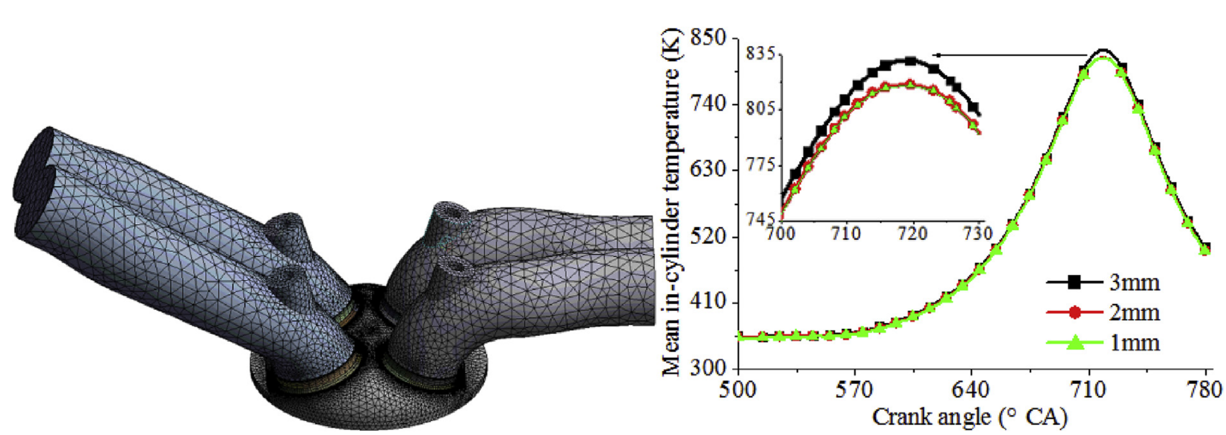
GDI engine could realize scavenging effect with a proper duration of valve overlap under full load operating regime [16]. The scavenging process can reduce the in-cylinder temperature and clear the residual particles formed from the first pre-ignition cycle [20]. Therefore, scavenging may be another effective measure to suppress super-knock by reducing in-cylinder thermal load and clearing non-structural hot-spots. However, in previous investigations, the study of scavenging concentrated on the optimization of combustion and emissions [21,22]. Rational use of scavenging to restrain super-knock in 4-stroke GDI engine was seldom involved. Further, the study of DVVT mainly focused on improving charge efficiency and reducing pumping losses [23,24]. The mechanism of DVVT on improving scavenging was also rarely explored. This study is dedicated to evaluate scavenging effect in reducing the thermal load of combustion chamber and cleaning the non-structural hot spots in cylinder. Valve overlap duration and the positive scavenging pressure difference among the intake port, cylinder and exhaust port during valve overlap are two determinate factor of scavenging. Different DVVT strategies represent different valve overlap duration and different pressure difference during valve overlap. Therefore, in this work, the effect of DVVT on scavenging process in a production 1.5 L 4-stroke GDI engine was performed through numerical simulation to study the possible way to suppress super-knock through optimizing scavenging. In addition, in order to investigate the additional influence of scavenging on engine performance, the effect of DVVT on combustion characteristics were also carried out by experimental study.

2. Engine and computational model

The GDI engine used in this study is a 4 cylinder, 1.5 L production engine with compression ratio of 11.5. It incorporates a pent-roof cylinder head, an intake-side-mounted six-hole high-pressure fuel injector and a centrally located spark plug. The research engine is equipped with the technology of continuously DVVT. The adjustment ranges of intake VVT and exhaust VVT are 50°CA. The maximum injection pressure for fuel pump is 28 MPa and the actual injection pressure is varied according to different working conditions based on the original engine map. The maximum boost pressure for turbocharger is 250 KPa. Detailed engine specifications are shown in Table 1.

2.1. Establishment and validation of grids

In this study, for the engine considered, the sizes of the cylinder



a) Grids for calculation b) Comparison of in-cylinder temperature

Fig. 1. Grid independence.