Research on Mechanism of Low Speed Pre-Ignition and Knock Process in Boosted Direct Injection Spark Ignition Gasoline Engines

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Abstract. The mechanism of low speed pre-ignition (LSPI) and knock process in boosted direct injection spark ignition (DISI) gasoline engines are researched in this study. A single cylinder boosted DISI engine test bench was set up and operated at LSPI caused by oil, whose results are used to verify the feasibility of the calculation models. The geometric model is therefore established and the numerical simulation working at different injection times when the engine speed at 1200rpm and 1600rpm are conducted with the AVL FIRE CFD software.

1. Introduction

Under the circumstance about the increasingly austere energy crisis and environmental pollution which mankind cannot avoid, the turbocharged directly injection technology has become the mainstream developing tendency in the field of spark ignition gasoline engines, which could boost the volume power and reduce the harmful exhausts.

Boosted DISI engines, however, are suffering from a series of abnormal combustion problems and the LSPI is an important part of them. LSPI means that mixture in cylinder begins to burn before the spark plug igniting in low-speed and high load operating condition [1]. This undesirable phenomenon will have serious effects on the boosted DISI engines that are prevalent today. LSPI can engender knock or ever super knock result in overall efficiency losses and possible damage to the engine. However, the LSPI can lead to super knock not exactly, but it must happen before the super knock phenomenon.

The results of endoscopy optical imaging experiment of engine cycle by Zahdeh A, Dahnz C and Peters N [2]–[5], show the LSPI is caused by unstructured hot spots (suspended oil droplets and carbon particles) in cylinder stochastic and sporadic. In consideration of the fact that different engines have a variety of operating conditions, the LSPI caused by carbon deposition cannot be studied and numerically analyzed with uniform standards. Therefore, this paper only research the mechanism of LSPI caused by oil drops.

Takeuchi K [6], the researcher of Toyota has researched the process of the oil droplets causing LSPI: Fuel spray impinges the cylinder wall, so the wall film of oil is diluted because of wall wetting phenomenon. The oil-fuel mixture accumulates in the piston crevice volume due to the decreased adhesiveness. With the driving by inertia, some particles release from mixture and become suspending
oil droplets in cylinder, when the piston moves close to TDC in the compression stroke. The droplet-stripping was gradually evaporated and a layer of mixture, which includes oil, fuel and air around this drop, was produced. The spontaneous ignition takes place in this mixture region in high temperature and pressure. The flame nucleus, furthermore, ignite the surrounding fuel-air mixture and lead to flame propagation. Qi Y L and Wang Z from Tsinghua University [7]–[8] has proved rationalization of this conclusion by engine bench test and result shows that both the position of oil droplets are also influent LSPI and knock phenomenon.

Although the mechanism of LSPI has been preliminarily studied, the process of knock, or ever super knock, has not been researched systematically, especially by the method of numerical simulation. Therefore, this study researched the knock phenomenon after the LSPI firstly on an engine test bench with the support of Tsinghua University; then, according to the engine bench test data, the feasibility verification of calculation models selected by numerical simulation work has carried out; finally, this study simulated the processes of LSPI and super knock using AVL FIRE, a CFD software, under different working condition of engine speed and oil quantity.

2. The feasibility verification of calculation methods

The result of high-speed photography, from Dingle S F, shows the multi-point LSPI phenomenon could be simulated truly by injecting oil into cylinder [9]. Hence, this study researches the phenomenon of oil self-ignition by this method in order to get the curves of pressure and simulate the LSPI process. Table 1 lists main technical parameters of test engine.

A super knock dynamometer engine test bench was built using the test engine, and the device composition in shown in the Fig. 1. This bed includes the single-cylinder engine, oil injection system, ECU, dynamometer and control system, combustion data acquisition system etc.

**Table 1. Test engine technical parameters.**

| Description              | Unit | Parameter |
|--------------------------|------|-----------|
| Displacement             | cm³  | 815.145   |
| Bore×Stroke              | mm   | 95×115    |
| Connecting rod length    | mm   | 215       |
| Compression ratio        | -    | 14        |
| Rotate speed             | r·min⁻¹ | 1200       |
| Number of cylinders      | -    | 1         |
| Number of stroke         | -    | 4         |

**Figure 1.** Schematic diagram of experimental set-up.

AVL FIRE software was used to numerically analyze the oil auto-ignition in cylinder. In addition to basic control equations such as mass conservation equation, momentum conservation equation and energy conservation equation, k-ε model and standard wall function are also selected to close the turbulent kinetic energy equation. The spray process was simulated by AVL FIRE’s own model, like the Amsden O’Rourke spary/wall interaction submodel [10]. In the simulation of combustion process, the CFM model was selected. In addition, Extented Zeldovich and Kinetic Model emission submodels were eventually selected in this study to meet the simulation requirements of NOₓ and Soot.
According to the data report of engine bench test whose the start injection time at 40°CA BTDC, the model is verified in this study, Fig. 2. The result shows maximum pressure in cylinder is over 130bar that appears near the TDC, which agrees well with the maximum pressure of test (120bar).

![Figure 2. Results of engine bench test and feasibility verification.](image)

3. Numerical simulation of LSPI and knock process

3.1. Preprocessor

The geometric model and the grid model were established according to the test single-cylinder engine by 3D modeling software. The FAME ENGINE PLUS (FEP) module of AVL FIRE is used to generate the moving mesh and the moving boundary is adopted at the top of piston. In order to obtain more accurate flow field in cylinder, the local area of valves seats should be refined locally during the generation process of moving meshes. The Fig. 3 a) and b) are the solid model and the grid model, the sectional drawing and the local refinement of valves seats area are shown at Fig. 3 c) and d).

![Figure 3. Grid model and computational domain.](image)
The computational domain discretization and solution methods of governing equations were worked by AVL FIRE. The discretization equation uses a finite volume method based on the control volume. The SIMPLE method is used to resolve pressure-velocity decoupling of flow field. The discretization method of energy equation, turbulence equation and scale equation is the first order upwind scheme. Furthermore, the central difference method and MINMOD method were selected for purpose of solving the continuous equation and the momentum equation.

3.2. Results of numerical simulation
The work of numerical simulation about the influence of LSPI and knock process on different injection times was carried to when the engine speed at 1200 rpm and 1600 rpm. It can be obtained clearly in the curves figures of pressure and rate of heat release that all the curves deviate from the compression line. It means that the mixture gas is ignited by oil before the spark plug fires. Detonation also occurred in each set of test because acute fluctuation appeared in peak position of all curves as shown as Fig. 4.

The result shows that injecting oil later can lead to the increase of maximum peak pressure of detonation at the same engine speed. When the injection time at -40°CA ATDC, the peak pressure of knock can be reached 140 bar which is similar to -30°CA ATDC. The maximum peak pressure when the injection time is -50°CA ATDC, however, is only half the maximum pressure at -40°CA ATDC injection time, as shown as Fig. 4 a).

The reason of this phenomenon is that the oil can impinge and adhere to the surface of piston and wall of cylinder so that the oil cannot form suspending droplet at -50°CA ATDC injection time, which cannot happen when the injection time is -40°CA ATDC or -30°CA ATDC. In other words, it is the suspending droplet of oil into cylinder that can cause LSPI and knock phenomenon.

The turbulence can also influence the LSPI and knock process of boosted DISI engines. The Fig. 4 b) shows the simulation result at 1600 rpm engine speed, and the maximum peak pressure are lower than 1200 rpm. The turbulence intensity can be increased when the engine speed is up, which will accelerate the diffusion of oil and restrain the formation of droplet. This also explains the pre-ignition often occurs at low-speed working condition.

![Figure 4. Pressure and rate of heat release of numerical analysis results.](image-url)
4. Conclusions
The LSPI and super knock phenomenon of boosted DISI engine were studied by the method of numerical simulation in this paper. The conclusions are summarized as follows:

Under the conditions of high temperature and pressure, the oil after injected into cylinder can form suspending droplets and burn spontaneously regardless of the injection time and speed, which can cause the LSPI and subsequent detonation.

Injecting earlier can cause the oil to crash and stick to the wall of cylinder and the top surface of piston, so that the formation of oil droplets is inhibited. The intensity of knock caused by the LSPI is also decreased.

The increase of turbulence because of higher engine speed in cylinder could accelerate the expansion of oil, hence it can also restrain the formation of droplets and self-ignition of oil. The intensity of knock in 1600rpm engine speed is lower than 1200rpm working condition.

Acknowledgments
This work was financially supported by National Science Foundation of China(NSFC) fund [Grant number 51376113].

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