Simulation Study on the Impact of Uneven Fuel Injection of Each Hole of the Diesel Engine Injector on the Combustion Process

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Abstract. The spray impulse and injection pressure of each hole of the 4-hole injector of F186 engine were tested by using the transient test system for flow coefficient and injection rate of each hole of the injector, and the injection rate, fuel injection quantity and flow coefficient of each hole were obtained. According to the measured injection rate of each hole and cycle fuel injection quantity, a 3D model of the diesel engine was established with the FIRE software, and the uniform injection rate and uneven injection rate of each hole were made as the injection setting for the combustion simulation to comparatively analyze the influence of the uneven injection rate of each hole on the combustion process of diesel engine. As the injection of each hole is uneven, some holes with high injection rate have long fuel spray penetration distance and the fuel spray is fully mixed with the air, and the ignition starting point is moved ahead. When compared with the case of uniform injection rate, the phase corresponding to the heat release rate in the case of uneven injection rate is moved forwards, the maximum cylinder pressure and temperature rise fast, the maximum cylinder pressure and maximum average temperature in cylinder are higher, the NO generation is larger, and the Soot generation is slightly larger. In the case of uneven injection rate from four holes, as the utilization of air in the hole-located cylinder space by the fuel spray is uneven, the hole with a large quantity of injection makes the oxygen in the hole-located cylinder space relatively low, the wall collision of the hole with high injection rate is more, and the diffusion combustion is incomplete and insufficient.

1. Introduction

The spray and combustion of diesel are important factors affecting engine emission and fuel economy. As the terminal of the fuel injection system of the diesel engine, the injection characteristics of the nozzle have a direct impact on the distribution of fuel in the combustion chamber, the fuel atomization quality, and the injection duration, thus affecting the combustion in cylinder and the performance of the engine [1-3].

Researchers have carried out a lot of research on the impact of injection rate on the diesel engine combustion process from the aspects of test and simulation calculation, but most of them are based on...
the general injection rates of the fuel injector [4, 5]. However, due to the difference in the structure, processing and high-pressure hydraulic conditions during use, the injection rate of each hole of the multi-hole injector is inconsistent, and this will lead to uneven fuel space and time distribution in the combustion chamber, thus resulting in changes in the spray and combustion process.

The spray impulse and injection pressure of each hole of the 4-hole injector of F186 engine are tested by using the transient test system for flow coefficient and injection rate of each hole of the injector, and the injection rate, fuel injection quantity and flow coefficient of each hole are obtained. According to the measured whole injection rate and cycle fuel injection quantity, a 3D model of the diesel engine is established with the FIRE software. Based on the uniform injection rate and uneven injection rate of each hole made as the injection setting, the combustion process is simulated to comparatively analyze the influence of the uneven injection rate of each hole on the combustion process of diesel engine, so as to provide a basis for more accurate description of its combustion process.

2. Combustion model

The geometric model of the combustion chamber at TDC (top dead center) is drawn by ProE software, as shown in Figure 1, and it is saved as a STEP format file. The geometric model is imported into hyper mesh software for mesh division and saved as a mesh file in the form of NAS. The mesh file is imported into AVL FIRE software for mesh inspection, refinement, dynamic mesh setting, selection of sub-models and parameter setting [6].

The 4-hole injector adopted by the F186 diesel engine has 4 evenly-distributed holes, but the injection direction is inconsistent with the angle of the cylinder section. The center of the pit of the combustion chamber has a 3 mm offset from the center of the piston, and the airflow movement in cylinder has different impact on the fuel sprays of each hole, so the whole combustion chamber modeling is adopted. The mesh is encrypted in the area close to the hole and the boundary, and the mesh model at TDC is shown in Figure 2. There are 140448 and 343488 mesh cells at TDC and BDC (bottom dead center) respectively.

The parameters of the diesel engine are shown in Table 1. The position and direction settings of the injector are as follows: X-coordinate (0.003 m), Y-coordinate (-0.003 m), Z-coordinate (0 m), X-
direction (0.007), Y-direction (0.0397), Z-direction (0). The position setting of each hole is shown in Table 2. The uniform injection rate and measured uneven injection rate of each hole are made as the injection setting, and the injection rate is shown in Figure 3. The standard component transport model of diesel fuel is used for chemical reaction kinetics calculation, and the calculation model involved is shown in Table 3 [7, 8].

### Table 1. The main parameters of diesel engine

| Parameters                      | Value                                      |
|---------------------------------|--------------------------------------------|
| Type                            | vertical, wind cooled, naturally aspirated, direct injection, four-stroke |
| Cylinder bore × stroke / mm×mm  | 86×72                                      |
| Length of the connecting rod/mm | 115                                        |
| Compression ratio               | 19                                         |
| Rated rotation speed / r·min⁻¹   | 3000                                       |
| Compression chamber type        | ω                                          |
| Fuel supply advance angle (ºCA in front of TDC) | 20                                          |
| Inlet valve closing (ºCA behind BDC) | 54                                         |
| Exhaust valve open (ºCA in front of BDC) | 54                                         |
| Injector nozzle number          | 4                                          |
| Nozzle diameter/mm              | 0.32                                       |

### Table 2. Nozzle whole data

| Hole | Nozzle diameter at hole center positions / m | Number of nozzle holes | Spray angle delta 1 | Spray angle delta 2 | Circumferential hole distribution |
|------|---------------------------------------------|------------------------|---------------------|---------------------|-----------------------------------|
| 1    | 0.003                                       | 1                      | 160                 | 135                 | 0                                 |
| 2    | 0.003                                       | 1                      | 160                 | -135                | 0                                 |
| 3    | 0.003                                       | 1                      | 140                 | -45                 | 0                                 |
| 4    | 0.003                                       | 1                      | 140                 | 45                  | 0                                 |

### Figure 3. Injection rate of each hole
Table 3. Computational models

| Computational Model                  | Selection                          |
|--------------------------------------|------------------------------------|
| Turbulence model                     | K-Zeta-F                           |
| Fuel wall interaction model           | Bai Gosman                         |
| Particle interaction model            | Schmidt                            |
| Fuel evaporation model                | Dukowicz                           |
| Fuel spray breakup model              | KHRT                               |
| Combustion model                     | Coherent Flame Model               |
| Auto-ignition model                  | Two-Stage                          |
| Nitrogen oxide model                 | Extended Zeldovich+prompt+fuel    |
| Soot model                           | Kinetic Model                      |

3. Simulation results and analysis

For ease of description, the working condition simulated by uniform injection rate of each hole is referred to as the “Even Condition”, and the working condition simulated by the measured uneven injection rate of each hole is referred to as the “Uneven Condition”.

Figure 4 shows fuel spray in each hole. Figure 5 shows the mass concentration distribution of fuel in cylinder at 350°CA, 360°CA and 400°CA. Figure 6 shows the temperature distribution in cylinder at the ignition starting point, 360°CA and 380°CA. Figure 7 and Figure 8 respectively show the mass concentration distribution of NO and Soot in cylinder at 400°CA.

Figure 4 shows that, the fuel spray is deflected along the circulation direction driven by the gas circulation in cylinder. The fuel injection has lasted 3°CA by 345°CA, due to uneven fuel injection, some holes have longer penetration distance during the early injection period, its space distribution area is wider, the interaction with air is more sufficient [9], the fuel particle crushing, evaporation and atomization are quicker, and the combustible mixture is formed; accordingly, the fuel particles sprayed by this fuel spray in the early period have become the fuel components in the air at 350°CA [10].

Figure 5 shows that, under the uneven injection rate, there is a relatively high concentration of fuel components around the fuel spray of some holes at the crankshaft angle of 350°CA. The high temperature area in Figure 6 shows that, as the fuel vaporization and atomization of some fuel sprays are faster around the fuel spray with high injection rate in the early period, the ignition occurs at 348°CA [11]. However, under the uniform injection rate, a significant high temperature area occurs at 350°CA, and the fuel ignition occurs in cylinder. It can be found out that, under the uneven fuel injection rate, some holes with high injection rate shorten the ignition delay period and make the combustion starting point earlier. After the start of combustion, it is in the stage of piston upward approaching the top dead center [12]. The temperature and pressure in cylinder rise rapidly, the turbulence of air flow is strengthened, the fuel vaporization, atomization and mixing, and the ignition condition are accelerated, so the combustion is faster [13].

The high temperature and pressure in cylinder accelerate atomization of the fuel particles. Figure 4 shows that, most of fuel particles sprayed in the early period at Uneven Condition have been vaporized and atomized at 355°CA; therefore, a large number of fuel can be used for the combustion, and the temperature and pressure in cylinder are significantly higher than those at Even Condition.

The fuel particles are significantly reduced, the concentration of fuel components close to the wall surface in combustion chamber is relatively higher, the high temperature area in cylinder is widened, the NO generation is increased due to higher and wider in-cylinder temperature distribution when compared with those at 360°CA at Even Condition [14]. At 380°CA, the high temperature area at Even Condition and Uneven Condition is almost the same, compared with the more fuel components for the early combustion at Uneven Condition, more fuel components are used for the combustion at Even Condition, the fuel component in areas outside of the hole is relatively even, the air volume is relatively abundant, so the combustion is sufficient.
As some holes have high injection rate and large fuel injection quantity and the fuel attached on the wall surface is increased at Uneven Condition, and the air-fuel ratio in the corresponding area is relatively low, the diffusion combustion is incomplete. At 400°CA, in the pit wall of combustion chamber and near the wall at the top of piston top, the concentration of fuel components is higher than that at Even Condition [15]. These fuel components cannot be easily burnt completely, so the HC and CO emission are higher than those at Even Condition.

Figure 7 and Figure 8 show that, due to high temperature in cylinder during the rapid combustion period, the NO generation and Soot concentration at Uneven Condition are higher than those at Even Condition.

![Figure 4. Spray cloud at even condition and uneven condition](image)

![Figure 5. C13H23 mass fraction distribution at 350°CA, 360°CA and 400°CA](image)
Figure 6. Temperature distribution at the ignition starting point, 360°CA and 380°CA

Figure 7. NO mass fraction distribution at 400°CA

Figure 8. Soot mass fraction distribution at 400°CA

Figure 9 and Figure 10 respectively show the average temperature in cylinder, accumulated heat, cylinder pressure and heat release rate at Even Condition and Uneven Condition.
Figure 9. Average temperature in cylinder and accumulated heat release at Even Condition and Uneven Condition

Figure 10. Cylinder pressure and heat release rate at Even Condition and Uneven Condition

The previous analysis can be verified in Figure 9 and Figure 10. The ignition at Uneven Condition is slightly moved forwards, the combustible mixture formed during the ignition delay period is increased, the heat release rate is higher during the early combustion period, and the cylinder pressure rises faster and the maximum cylinder pressure is increased due to the fact that it is close to TDC. In addition, the combustion heat release rate and the combustion process at Uneven Condition are also ahead of those at Even Condition. The temperature in cylinder in the early period and the maximum cylinder pressure at Even Condition are higher, but the combustion heat release rate and the combustion temperature in cylinder in the later period are lower than those at Even Condition [16]. From the perspective of the accumulated heat release rate, the heat release in the early combustion stage at Uneven Condition is larger, but it is slightly reduced in the later period, so the combustion at Uneven Condition is not as sufficient as that at Even Condition.

Due to the uneven injection rate of each hole, some holes have high injection rate and large fuel injection quantity, and some holes have low injection rate and small fuel injection quantity. For the holes with high injection rate, as the fuel spray distance is longer and the space distribution within the same time is wider, fuel can be mixed with the air to form more mixtures in a relatively short period; however, due to the excessive fuel injection quantity, the fuel attached on the wall surface is increased, and the air-fuel ratio in the corresponding area is relatively low, so the diffusion combustion is incomplete [17]. For the holes with low injection rate, as the evaporation, atomization and mixing of fuel spray is slightly
slower but the air in the area where the fuel spray is located is relatively sufficient, the combustion is complete and sufficient. Under the combined effect of these situations, the combustion starting point is moved ahead, the maximum cylinder pressure and temperature are increased, the NO generation is larger, the Soot generation is slightly larger, the combustion is incomplete and insufficient, and the HC and CO emission is slightly higher when compared with those at Even Condition.

4. Conclusion
The spray impulse and injection pressure of each hole of the 4-hole injector of F186 engine are tested by using the transient test system for flow coefficient and injection rate of each hole of the injector. According to the measured whole injection rate and cycle fuel injection quantity, the uniform injection rate and measured uneven injection rate of each hole are made as the injection setting for the combustion simulation and the analysis of the impact of uneven injection rate of each hole on the diesel engine combustion process. Based on the model-based engine parameter characteristics and the uneven injection rate of the tested diesel injector, the following conclusions can be drawn.

(1) As the injection rate of each hole is uneven, some holes with high injection rate have long fuel spray penetration distance, and the fuel spray is fully mixed with the air, so the ignition starting point is moved ahead.

(2) The phase corresponding to the heat release rate at Uneven Condition is moved forwards when compared with that at Even Condition. The early combustion period is in the late compression stroke period, which makes the maximum cylinder pressure and temperature rise fast, the maximum cylinder pressure and the maximum average temperature in cylinder higher than those at Even Condition, the NO generation larger, and the Soot generation slightly larger.

(3) The utilization of air in the hole-located cylinder by the fuel spray at Uneven Condition is uneven, a large injection quantity of the holes makes the oxygen of the fuel spray space relatively low, and the wall collisions of the hole with high injection rate are more, so the combustion is incomplete and insufficient.

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