Simulation Study on the Effect of Uneven Fuel Injection of Each Hole on the Combustion Process of Ethanol-Diesel Blend Fuel

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Abstract. The small diesel generator has been widely used. When compared with vehicle diesel engine, it has stable working speed, small load variation range and lower requirements for fuel performance, so the fuel ethanol can be more easily applied for the diesel generator. The blend fuel containing 5% ethanol and 95% diesel (E5D95) is tested on a generator powered by F186. A 3D combustion model based on the injection position and angle of each hole of the diesel engine is established and verified by using the test data. Based on the measured injection rate of each hole of the 4-hole diesel injector, the even injection rate of each hole and the measured uneven injection rate of each hole are made as the injection settings for the combustion simulation. The effect of the uneven injection rate of each hole on the combustion process of ethanol-diesel blend fuel is comparatively analyzed. Due to the uneven injection of each hole, the ignition starting point is moved forwards, the maximum pressure and temperature in the cylinder are higher, NO generation is larger, soot generation is slightly smaller, and the emission of HC and CO is higher.

1. Introduction

The fuel ethanol is a kind of renewable energy and one of the alternative fuels with early considerable attention for diesel engines. Due to the characteristics of 34.8% oxygen content, high volatility, high octane number, high gasification latent heat, low viscosity, low cetane number and poor miscibility with diesel, many researchers have focused on the application of ethanol in diesel engines and the more concentrated application is diesel blended with ethanol. Some studies show that the blend fuel with a small amount of ethanol can obtain the equivalent dynamic performance of the original engine, higher combustion speed, slightly improved thermal efficiency and lower carbon smoke emission [1, 2].

The greatest advantage of the blend fuel is that it can be directly used in the original engine without any modification to the structure. The small diesel generator has been widely used, which has stable working speed, small load variation range, lower requirements for fuel performance and simple exhaust gas treatment device when compared with vehicle diesel engine; therefore, the fuel ethanol can be more easily applied in the diesel generator [3].
Oil-gas mixing process is the most direct and important influence factor of the diesel engine combustion, and the oil-gas mixing quality is controlled by fuel injection, air flow, turbulence in the cylinder and fuel atomization quality. The fuel injection, atomization, evaporation, interaction between fuel and air in the cylinder, oil-gas mixing, ignition of combustible mixture, combustion and emission formation are all closely related to the injection characteristics of the injection system, and the injection rate including injection speed, duration and timing has important impact on the spray characteristics of the diesel engine [4, 5].

The injection rate of each hole of the injector is different due to different structures, processes and hydraulic conditions during the use no matter whether the hole nozzles are evenly distributed; therefore, the injection characteristics of each hole become different, thus affecting the atomization and evaporation of all oil beams and the interaction between the oil beam and the gas in the cylinder, and finally affecting the combustion and emission performance of the diesel engine.

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, 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 is established with the FIRE software, and the even 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 of each hole on the ethanol-diesel blend fuel combustion process, so as to provide a basis for the application of ethanol blended fuel in the diesel engine.

2. Combustion model

The geometric model of the combustion chamber at TDC (top dead center) is drawn by ProE software, the mesh division is completed by Hypermesh software, and then it is imported into AVL FIRE software for dynamic mesh setting. The four holes are evenly distributed, but the angle between the injection direction of each hole and the cross section of the cylinder is not the same, so the whole combustion chamber modeling is adopted. The area close to the hole and the boundary was densely meshed. 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 physical and chemical characteristics of the fuel are shown in Table 2, the injection rate is shown in Figure 1, and the mesh model of the combustion chamber at TDC is shown in Figure 2. The chemical reaction kinetics calculation was achieved with the standard ethanol and diesel transportation sub-model in AVL FIRE [6]. The main sub-models selected for the computation are shown in Table 3.

| 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                       |
| Combustion chamber type      | ω                           |
| Fuel supply advance angle (°CA in front of TDC) | 20                        |
| Inlet valve closing (°CA behind BDC) | 54                        |
| Exhaust valve open (°CA in front of BDC) | 54                        |
| Injector nozzle number       | 4                           |
| Nozzle diameter/mm           | 0.32                        |
Table 2. Physical and chemical properties of fuels

| Parameters                                      | Ethanol | 0\textsuperscript{a}diesel | E5D95 |
|------------------------------------------------|---------|-----------------------------|-------|
| Density\(^{30\,\text{℃}}\)/g·cm\(^{-3}\)     | 0.789   | 0.839                       | 0.832 |
| Kinematic viscosity\(^{30\,\text{℃}}\)/mm\(^{2}\)·s\(^{-1}\) | 1.152   | 3.321                       | 3.174 |
| Cetane number                                   | 8.0     | 49.1                        | 47.8  |
| Oxygen content /%                               | 34.78   | 0.00                        | 1.64  |
| Low calorific value /MJ·kg\(^{-1}\)            | 26.80   | 42.50                       | 41.76 |

Figure 1. Injection rate of each hole

Figure 2. Combustion chamber mesh at top dead center

Table 3. Computational models

| Computational Model                        | Selection                               |
|--------------------------------------------|-----------------------------------------|
| Turbulence model                           | K-Zeta-F                                |
| Fuel wall interaction model                | Bai Gosman                              |
| Fuel evaporation model                     | Multi-component                         |
| 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

The working condition simulated by the even 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 3, Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8 respectively show the mass fraction of diesel and ethanol in the cylinder, in-cylinder pressure, heat release rate, average temperature in the cylinder, accumulated heat, NO mass fraction, soot mass fraction and CO mole fraction at Even Condition and Uneven Condition.
Figure 3 shows that, at Uneven Condition, the change of fuel component concentration in the cylinder is ahead of that at Even Condition. There are more diesel and ethanol in the cylinder during early period at Uneven Condition, therefore, the ignition is slightly ahead, the combustible mixture formed during the ignition delay period is increased, the heat release rate is higher during the early combustion period, the pressure in the cylinder is increased quickly, and all of these can be proved from Figure 4. The uneven injection rate of each hole makes the combustion starting point earlier and the initial heat release rate higher [7]. At this time, it is close to TDC, so the in-cylinder pressure rises faster and the maximum in-cylinder pressure increases. The peak value of fuel component at Uneven Condition is lower than that at Even Condition but the fuel component at Uneven Condition is slightly higher than that at Even Condition in the late combustion period, which means that its combustion is incomplete [8].

Figure 3. Diesel mass fraction and ethanol mass fraction

Figure 4. In-cylinder pressure and heat release rate

Figure 5. Average temperature in the cylinder and accumulated heat release
The combustion heat release at Uneven Condition is ahead of that at Even Condition, and the combustion process proceeds slightly earlier. Figure 5 shows that the in-cylinder temperature at Uneven Condition in the early period is higher than that at Even Condition, the maximum in-cylinder pressure is higher, but the combustion heat release rate in the late period is lower and the in-cylinder temperature in the late combustion period is lower than that at Even Condition. The accumulated heat release rate shows that the heat release at Uneven Condition in the early period is higher but that in the later period is slightly lower, which also means that the combustion at Uneven Condition is not as sufficient as that at Even Condition.

Figure 6. NO mass fraction at Even Condition and Uneven Condition

Figure 7. Soot mass fraction at Even Condition and Uneven Condition

From Figure 6 and Figure 7, it can be seen that the NO mass fraction is significantly higher than that at Even Condition and soot mass fraction is slightly lower than that at Even Condition because the maximum in-cylinder pressure and the maximum average in-cylinder temperature are higher at Uneven Condition.

Figure 8. CO mole fraction at Even Condition and Uneven Condition
As shown in Figure 8, the CO emission at Uneven Condition is higher than that at Even Condition. The fuel combustion is incomplete, the HC emission is high, and the combustion is insufficient.

When the injection of each hole is uneven, during the early injection period, the instantaneous injection rate of some holes is lower, while that of some holes is higher. For the hole with higher instantaneous injection rate, the fuel spray has a long penetration distance, and it is sufficiently mixed with air to quickly form the combustible mixture. In addition, the fuel components are distributed in the wider space, thus slightly shortening the ignition delay period [9]. The rise of in-cylinder temperature after the ignition accelerates the atomization, evaporation, mixing of fuel components, so there are more fuel components involved in combustion during the early combustion period, the heat release increases, and the temperature and pressure in the cylinder rise rapidly [10].

In the case of uneven injection of each hole, the injection speed of each hole is uneven and cycle injection quantity of each hole is different, which makes the utilization of air in the hole-located cylinder by the fuel spray uneven. In case of low injection rate, the penetration distance is short, so full contact with the air at the far end is difficult and the air utilization rate is insufficient. In case of large injection quantity, the air-fuel ratio of the spray area is relatively lower and full combustion is affected. In case of excessive injection rate, the penetration distance is long, so more fuel components hit the wall and adhere to the cylinder wall, and there is more components of diffusion combustion with incomplete combustion in the later stage [11, 12]. Under the combined effect of these factors, the combustion starting point is advanced at Uneven Condition, the maximum in-cylinder pressure and temperature are higher, NO emission is larger, soot emission is slightly lower, the combustion becomes incomplete and insufficient, and HC and CO emission is slightly higher.

4. Conclusion
A three-dimensional combustion model of F186 diesel engine fueled with 5% ethanol and 95% diesel blended fuel was established and the combustion process was analyzed. The following conclusions can be drawn based on the characteristics of engine parameters on which the model is based and the non-uniform injection rate of each hole of the diesel injector used in the test.

(1) Due to the uneven injection rate of each hole, the hole with higher injection rate has long fuel spray penetration distance and the fuel spray is fully mixed with the air, and the ignition starting point is moved forwards.

(2) The heat release rate is higher and the heat release is larger at Uneven Condition during the early combustion period. At this time, it is close to TDC, so the maximum in-cylinder pressure and temperature are high, NO generation is increased.

(3) As the utilization of air in the hole-located cylinder by the fuel spray at Uneven Condition is uneven, the holes with a large quantity of injection make the oxygen of the fuel spray space relatively low, and the wall collisions of oil beam is more for the hole with high injection rate, so the combustion is incomplete and insufficient and HC and CO emission is higher.

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