The Effect of Dual-injector on Combustion Process of 396 Series Diesel Engine with Shallow Basin-shaped Combustion Chamber

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Abstract. The 396 series diesel engine has high performance and reliability and long service life, and it has been widely used in many areas, especially in the field of military and industrial power plants. By applying shallow basin-shaped combustion chamber, the original fuel injection system of the 396 series diesel engine can be improved easily. With two symmetrical injectors in each cylinder, two injectors can be used to spray diesel at the same time, or one injector can be used to spray ignition diesel and the other injector can be used to spray biodiesel or alcohol fuel. A 3D combustion model of the 396 series diesel engine with shallow basin-shaped combustion chamber was established by using the computational fluid dynamics software FIRE. When 8-hole single-injector and 4-hole dual-injector were respectively adopted, the combustion process was simulated to compare and analyze the fuel spray, ignition start point, combustion pressure, combustion heat release rate, average temperature in cylinder and NO emission, and the impact of injection duration and fuel injection advance angle on the combustion process were discussed. By increasing fuel injection pressure, shortening fuel injection duration and increasing fuel injection advance angle properly, the combustion process of 396 series diesel engine can be improved when an 8-hole single-injector was adopted. When a dual-injector was applied, the fuel spray space distribution area was wide, combustion process was improved, cylinder pressure and temperature became high, combustion was relatively sufficient and thermal efficiency got high. Proper reduction of fuel injection advance angle and extension of injection duration can mitigate the condition of large NO emission and higher cylinder pressure when the dual-injector was adopted. The combustion process of the 396 series diesel engine with shallow basin-shaped combustion chamber can be improved obviously and the thermal efficiency can be improved by adopting the dual-injector and selecting proper injection duration and fuel injection advance angle. This research result is conductive to improve the combustion process of the 396 series diesel engine with shallow basin-shaped combustion chamber and provides a basis for using biodiesel and alcohol fuel in the diesel engine.
1. Introduction
With the increasing scarcity of petroleum resources, the application of biodiesel and alcohol fuels (such as methanol and ethanol) in the diesel engine is increasing gradually [1, 2]. It is recommended to apply alcohol fuel in the diesel engine by dual-injection, and the common form is to spray alcohol fuel in the intake manifold and spray diesel in the cylinder as the ignition fuel [3, 4]. However, if this method is adopted, the proportion of alcohol fuel cannot be adjusted easily. Another method is to directly spray alcohol fuel and diesel in the cylinder by different injectors and alcohol fuel is ignited by diesel [5]. The 396 series diesel engine is widely used in fields including military and industrial power unit, and it adopts shallow basin-shaped combustion chamber with small heating area, thus reducing the heat load of the piston. In addition, because of its large cylinder diameter, it is easy to arrange two injectors on one cylinder for diesel spraying, and both injectors can inject diesel fuel when alternative fuels are not used [6].

When shallow basin-shaped combustion chamber is adopted, the formation of mixture mainly depends on the spray atomization of fuel, and this requires high spray quality and the fuel should be distributed to the whole combustion space as far as possible to avoid direct contact of oil bunches with cylinder walls. If dual-injector is adopted, the fuel spray will be more widely distributed, thus ensuring easier mixture formation and rapid and complete combustion [7-9].

A 3D combustion model of the 396 series diesel engine with shallow basin-shaped combustion chamber is established by using the computational fluid dynamics software FIRE, and the combustion process when 8-hole single-injector and 4-hole dual-injector are adopted is simulated and calculated with different injection duration and fuel injection advance angle, so as to improve the combustion process of the 396 series diesel engine with the shallow basin-shaped combustion chamber with the dual-injector as well as provide a basis for using biodiesel and alcohol fuel in the future.

2. Combustion model
The characteristic parameters of the 396 series diesel engine with shallow basin-shaped combustion chamber are shown in Table 1. The geometric model is drawn by ProE software, the mesh division is completed by hyper mesh software, and then the mesh is optimized and encrypted by the AVL FIRE, and the dynamic mesh is set for calculation and post-processing analysis [10]. The model is established for the whole combustion chamber. There are 72576 and 223104 mesh cells at TDC (top dead center) and BDC (bottom dead center) respectively, and the combustion chamber model at TDC is shown in Figure 1.

| Table 1. Summary of engine specifications                  | Value                                      |
|------------------------------------------------------------|--------------------------------------------|
| Parameters Type                                           | vertical, water cooled, turbocharged, direct injection, four-stroke |
| Cylinder bore × stroke / mm×mm                             | 165×185                                    |
| Length of the connecting rod / mm                         | 341                                        |
| Compression ratio                                         | 12.3                                       |
| Rated rotation speed / r min⁻¹                             | 2000                                       |
| Diesel injection advance angle (°CA in front of TDC)      | 8                                          |
| Inlet valve closing (°CA behind BDC)                      | 68                                         |
| Exhaust valve open (°CA in front of BDC)                  | 75                                         |
| Pressurization ratio                                      | 2.9                                        |
The diameter of the hole of the 8-hole single-injector and 4-hole dual-injector is 0.419 mm, the injection cone angle is 15°, the oil spray angle is 152°, and the total circulation injection amount is 0.484 g. The distribution of spray particles in the cylinder after fuel injection of 1°CA, 3°CA and 5°CA is shown in Figure 2. The eddy current ratio in the cylinder is set to 2.9, and the airflow in the cylinder is asymmetric due to the position of the inlet valve. The figure shows that the fuel spray has been affected by the airflow in the cylinder.

The chemical reaction dynamics calculation is carried out with the diesel standard component transport model of the FIRE, and the main calculation model selection is shown in Table 2 [11].

| Computational Model                        | Selection                     |
|--------------------------------------------|-------------------------------|
| Turbulence model                           | K-Zeta-F                      |
| Fuel wall interaction model                | Bai Gosman                    |
| Fuel 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 when adopting the 8-hole single-injector

Figure 3, Figure 4 and Figure 5 respectively show the pressure in cylinder, heat release rate, average temperature in cylinder, accumulated heat release and NO mass fraction when the 8-hole single-injector is adopted.

![Cylinder pressure and heat release rate](image)

(a) 8°CA fuel injection advance angle  
(b) 10°CA fuel injection advance angle  

**Figure 3.** Cylinder pressure and heat release rate when adopting the 8-hole single-injector

![Average temperature and accumulated heat release](image)

(a) 8°CA fuel injection advance angle  
(b) 10°CA fuel injection advance angle  

**Figure 4.** Average temperature in cylinder and accumulated heat release when adopting the 8-hole single-injector

![Average NO mass concentration](image)

(a) 8°CA fuel injection advance angle  
(b) 10°CA fuel injection advance angle  

**Figure 5.** Average NO mass concentration in cylinder when adopting the 8-hole single-injector

Figure 3 shows that the heat release start point is moved forwards slightly after the injection duration is shortened. This is because that the injection rate is increased, the penetrating distance is increased.
slightly, the fuel atomization is strengthened, and the ignition delay period is shortened. When the injection duration is shortened, the amount of fuel sprayed through the same crankshaft angle is increased, the combustion heat release is more concentrated, the peak value of combustion heat release rate is increased, the rapid combustion period is shortened accordingly, and the highest combustion pressure in cylinder is increased. After the fuel injection advance angle is increased to 10°CA, the peak value of combustion heat release rate is unchanged, but the heat release is more concentrated close to TDC, and the highest combustion pressure in cylinder is increased.

Figure 4 and Figure 5 show that, after the injection duration is shortened, as the ignition start point is slightly moved forwards, the rapid combustion period is shortened, the maximum average temperature in cylinder is increased accordingly, and the phase corresponding to the maximum temperature is moved forwards. This results in the increase of NO production with the shortening of injection duration [12]. From the perspective of accumulated heat release, when the injection duration is shortened, the accumulated heat release is slightly increased. This is due to the increase of the penetration distance of the oil beam, which makes it easier to use the air at the far end of the injector to make the combustion more full [13]. After the fuel injection advance angle is increased to 10°CA, as the maximum average temperature in cylinder only has minor change, NO emission is only increased slightly.

4. Simulation results and analysis when adopting the 4-hole dual-injector

Under the condition that the effective flow area is unchanged, a 4-hole dual-injector is adopted and two injectors are arranged symmetrically on the center plane passing through the cylinder, with an interval of 60 mm.

Figure 6, Figure 7 and Figure 8 respectively show the pressure in cylinder, heat release rate, average temperature in cylinder, accumulated heat release and NO mass fraction when the 8-hole single-injector and 4-hole dual-injector with different injection duration and fuel injection advance angle are adopted. In the figures, ID is the abbreviation of injection duration, and FIAA is the abbreviation of fuel injection advance angle.

(a) single-injector VS dual-injector                        (b) dual-injector with different injection timing

Figure 6. Cylinder pressure and heat release rate when adopting the 8-hole single-injector and 4-hole dual-injector
Figure 7. Average temperature in cylinder and accumulated heat release when adopting the 8-hole single-injector and 4-hole dual-injector

Figure 8. Average NO mass concentration in cylinder when adopting the 8-hole single-injector and 4-hole dual-injector

Figure 6 (a), Figure 7 (a) and Figure 8 (a) show that, for the case of the 8-hole single-injector, if the injection duration is shortened and the fuel injection advance angle is increased, the combustion start point is moved forwards, the peak value of combustion heat release rate, the maximum average temperature in cylinder, the maximum combustion pressure and the accumulated heat release are significantly increased, the thermal efficiency is improved, but NO emission is increased [14]. After the adoption of the 4-hole dual-injector, the combustion start point is slightly moved forwards, the peak value of combustion heat release rate, the maximum average temperature in cylinder, the maximum combustion pressure and the accumulated heat release are significantly increased, the fuel atomization, mixing and diffusion are accelerated, the rapid combustion period is significantly shortened, the thermal efficiency is improved, but the NO emission is also significantly increased by about a magnitude.

After the 4-hole dual-injector is adopted, the penetrating distance is almost the same as that of the case of the 8-hole single-injector, however, as these two injectors are separated by certain distance, the fuel space distribution area is wider, the mixing action of fuel spray and air in cylinder is strengthened, the air in cylinder is more completely utilized, the fuel evaporation, atomization and diffusion are accelerated, the combustion speed is higher, and the combustion is more complete [15].

Figure 6 (b), Figure 7 (b) and Figure 8 (b) show that, when compared with the condition that the 4-hole dual-injector is applied with 22°CA injection duration and 8°CA fuel injection advance angle, when the fuel injection advance angle is reduced by 2°CA, the combustion start point is delayed by about 2°CA, the peak value of combustion heat release rate, the maximum average temperature and the accumulated heat release are basically unchanged, the peak value of maximum combustion pressure is slightly reduced, the corresponding phase is delayed accordingly, and NO emission is slightly reduced.
When the injection duration is extended by 6°CA, the combustion start point is delayed by about 2°CA, the peak value of combustion heat release rate is reduced, the combustion duration is extended, the post-combustion is intensified, the maximum average temperature and the maximum pressure in cylinder are significantly reduced, but the accumulated heat release is basically unchanged, the combustion is still complete, and NO emission is significantly reduced.

5. Conclusion
When the 396 series diesel engine is adopted with the shallow basin-shaped combustion chamber, it is conducive to arrange two injectors on one cylinder. One injector can be used to spray biodiesel or alcohol fuel, and the other injector can be used to spray ignition diesel. Two injectors can be used to spray diesel when no alternative fuel is used.

A 3D combustion model of the 396 series diesel engine with shallow basin-shaped combustion chamber is established by using the computational fluid dynamics software FIRE, and the combustion process is simulated and calculated when 8-hole single-injector and 4-hole dual-injector are adopted. According to the model-based engine parameter characteristics, the following conclusions can be drawn.

(1) For the case of the 8-hole single-injector, if the injection duration is shortened and the fuel injection advance angle is increased, the combustion start point is moved forwards, the peak value of combustion heat release rate, the maximum average temperature in cylinder, the maximum combustion pressure, and the accumulated heat release are increased, the thermal efficiency is improved, but NO emission is increased.

(2) After the adoption of the 4-hole dual-injector, the combustion start point is slightly moved forwards, the peak value of combustion heat release rate, the maximum average temperature in cylinder, the maximum combustion pressure and the accumulated heat release are significantly increased, the fuel atomization, mixing and diffusion are accelerated, the rapid combustion period is significantly shortened, the thermal efficiency is improved, but NO emission is also significantly increased.

(3) For the phenomenon that the pressure, temperature and NO emission in cylinder are significantly increased after the adoption of the 4-hole dual-injector, the advance angle of the injector can be properly reduced and the injection duration can be properly extended to reduce the pressure and temperature in cylinder, thus to reduce NO emission and obtain relatively complete combustion.

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