Effect of Double Injector on Combustion Process in a 396 Series Diesel Engine

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Abstract. The 396 series diesel engine has high performance, reliability and long service life, which has been widely used in many fields including ship, vehicle and industrial power unit. With the improved injection system and dual-injector in each cylinder, two injectors of the diesel can spray diesel at the same time; or one injector sprays ignition diesel and the other injector sprays biodiesel or alcohol fuel. A 3D combustion model of the 396 series diesel engine with flat-top convex basin combustion chamber is established by using the computational fluid dynamics software FIRE, and the combustion process when uniform 5-hole and 8-hole injectors and 4-hole dual-injector are adopted is simulated to compare and analyze the fuel spray, ignition start point, combustion pressure, combustion heat release rate, average temperature in cylinder and NO emission. Compared with the diesel engine adopting 8-hole injector, the diesel engine adopting 4-hole dual-injector has a wide spray space distribution area, high pressure and temperature in cylinder, and high thermal efficiency. The combustion process with injection duration of 26.84°CA, 22°CA and 20°CA for 396 series diesel engine adopting 4-hole dual-injector is simulated respectively, and the simulation result shows that the shorter injection duration can bring the higher maximum pressure and the maximum average temperature in cylinder, the shorter ignition delay period, the advanced ignition start point, the larger peak value of combustion heat release rate, the more concentrated combustion heat release, the higher NO emission. These three cases have almost the same accumulated heat release and the relatively complete fuel utilization. The proper injection duration shall be selected based on comprehensive consideration of the pressure in cylinder, effective power and NO emission. This research result is conducive to improve the combustion process of the 396 series diesel engine with the dual-injector and provides a basis for using biodiesel and alcohol fuel in the diesel engine.

1. Introduction

The 396 series diesel engine has been widely used in domestic ships, vehicles and industrial power units, etc., because the engine has the reliable performance, long service life, high power and economy and can be converted into utilizing alternative fuels such as natural gas.1-3
With the increasing reduction of petroleum resources, the application of biodiesel and alcohol fuels (such as methanol and ethanol) in the diesel engine is increased. As alcohol fuel is not miscible with diesel, the proportion of alcohol fuel in the mixed fuel of alcohol fuel and diesel is generally less than 10%. The mixed fuel has low stability, is easily layered and cannot be stored for a long time even with the addition of cosolvent.4-6

It is recommended to use alcohol fuel in the diesel engine by dual-injection. One method is to spray alcohol fuel in the intake manifold and spray diesel as ignition fuel in cylinder, and another method is to directly spray alcohol fuel and diesel into cylinder by different injectors, with diesel igniting alcohol fuel. The fuel injection system of the original 396 series diesel engine was modified, and two identical 4-hole injectors were installed in each cylinder. Therefore, the diesel can be sprayed by two injectors, or one injector can be used to spray diesel and the other injector can be used to spray biodiesel or alcohol fuel.

A 3D combustion model of the 396 series diesel engine is established by using the computational fluid dynamics software FIRE, and the combustion process when uniform 5-hole and 8-hole injectors and 4-hole dual-injector were adopted was compared and analyzed by simulation method so as to improve the combustion process of the 396 series diesel engine with dual-injector as well as to provide a basis for using biodiesel and alcohol fuel in the future.7, 8

2. Combustion model

The characteristic parameters of the 396 series diesel engine with flat-top convex basin combustion chamber are shown in Table 1. The geometric model is drawn by ProE software, the mesh division is completed by Hypermesh software, and then the mesh is optimized and encrypted by the AVL FIRE. The dynamic mesh is set for calculation and post-processing analysis. As the airflow movement in cylinder is asymmetrical and it has impact on the spatial distribution of the fuel spray and then on combustion process, the model is established for the whole combustion chamber. There are 56050 and 158900 mesh cells at TDC (top dead center) and BDC (bottom dead center) respectively, and the combustion chamber model at TDC is shown in Figure 1.9

| Parameters | Value |
|------------|-------|
| 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 main parameters of the 5-hole and 8-hole injectors and 4-hole dual-injector are shown in Table 2, and injectors with different injection holes have the same total effective flow cross section area. The distribution of spray particles in cylinder after fuel injection of 5°CA is shown in Figure 2. The eddy current ratio in cylinder is set to 2.9, the airflow movement in cylinder is asymmetric due to the position of the inlet valve, and the fuel spray is also impacted by airflow movement accordingly.10

Table. 2 Summary of injector specifications

| Parameters                        | 5-hole injector | 8-hole injector | 4-hole dual-injector |
|-----------------------------------|-----------------|-----------------|----------------------|
| Cycle fuel injection / g          | 0.484           | 0.484           | 0.484                |
| Fuel injection duration / °CA     | 26.84           | 26.84           | 26.84                |
| Oil beam angle / °                | 152             | 152             | 152                  |
| Nozzle diameter / mm              | 0.53            | 0.419           | 0.419                |
| Number of nozzles                 | 5               | 8               | 4×2                  |

Figure. 2 Diesel injection position and fuel spray at 357°CA

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 3. In the KHRT spray breakup model, the value of coefficient C2 is set to 12.

Table. 3 Computational models

| 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

Figure 3, Figure 4 and Figure 5 respectively show comparison and analysis of the pressure in cylinder, heat release rate, average temperature in cylinder, accumulated heat release and NO mass fraction when 5-hole and 8-hole injectors and 4-hole dual-injector are adopted.

**Figure. 3** Cylinder pressure and heat release rate when adopting 5-hole and 8-hole injectors and 4-hole dual-injector

**Figure. 4** Average temperature in cylinder and accumulated heat release when adopting 5-hole and 8-hole injectors and 4-hole dual-injector

**Figure. 5** Average NO mass concentration in cylinder when adopting 5-hole and 8-hole injectors and 4-hole dual-injector

Figure 3 and Figure 4 show that, when compared with the case of adopting 5-hole injector, the case of adopting 8-hole injector has lower combustion heat release rate, pressure in cylinder, average temperature in cylinder, accumulated heat release and thermal efficiency, and combustion process becomes incomplete. In addition, when compared with the case of adopting 8-hole injector, the case of adopting 4-hole dual-injector has better combustion process, and the pressure in cylinder and
combustion heat release rate are between those of the case of adopting 5-hole and 8-hole injectors. However, when compared with the case of adopting 5-hole injector, the case of adopting 4-hole dual-injector has lower maximum average temperature in cylinder, slightly higher average temperature in cylinder during the latter combustion period and basically the same accumulated heat release.

Under the condition that the injection duration and the effective flow area are unchanged, when the holes are increased and the diameter is reduced, the size of fuel spray particles is smaller, the atomization quality is improved, but the penetrating distance of oil beam is decreased. The distribution of fuel in space is synthetically determined by the number of nozzles and the fuel penetration distance. The improvement of atomization quality is conducive to the formation of more pre-mixed gas during the ignition delay period and the acceleration of the diffusion combustion. However, as the penetrating distance is reduced, the fuel is concentrated near the nozzle and fails to mix with the fresh air at the far end. This results in reduced pre-mixed gas volume during the ignition delay period and extended combustion duration.

When the 8-hole injector is adopted, the impact of the reduced penetrating distance on the combustion process is intensified, the total fuel distribution area and the pre-mixed combustion are reduced, and the diffusion combustion is decelerated, thus making the combustion incomplete and thermal efficiency lower. After the 4-hole dual-injector is adopted, as the two injectors are separated by a certain distance, the spatial distribution area of the fuel is widened, and the mixing effect between fuel spray and air in cylinder is intensified. Although the penetrating distance is still shorter and the pre-mixed combustion is still less than that of the 5-hole injector, the accumulated heat release is equivalent to that of the 5-hole injector because the air in cylinder is fully utilized, the combustion duration of diffusion combustion is slightly longer and the combustion is more complete.

Figure 5 shows that, when the 8-hole injector is adopted, the combustion is incomplete, the combustion pressure and average temperature in cylinder and the NO emission are lower. When the 4-hole dual-injector is adopted, the NO emission is about 60% of that of the 5-hole injector due to the low maximum combustion temperature.

4. Simulation results and analysis of shortening injection duration of the 4-hole dual-injector

Under the condition that the injection duration and the effective flow area are unchanged, the thermal efficiency is reduced when changing the 5-hole injector to the 8-hole injector. However, if the 4-hole dual-injector is adopted, the thermal efficiency is kept the same as that of the 5-hole injector. If the injection pressure is increased, the injection duration is shortened and the penetrating distance of oil beam is increased, the mixing of fuel and air is further increased and the combustion process is improved.

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 injection angle of the 4-hole dual-injector is 26.84°CA, 22°CA and 20°CA.
Figure 6, Figure 7 and Figure 8 show that, when the injection duration is shortened, the ignition delay period is slightly shortened and the combustion start point is advanced. The higher the peak combustion heat release rate is, the earlier the corresponding phase is. When the maximum combustion pressure is increased, the corresponding phase is advanced. When the maximum average temperature in cylinder is increased, the corresponding phase is advanced but the average temperature in cylinder during the latter combustion period is slightly reduced. The combustion heat release is concentrated, the accumulated heat release is basically the same, but the NO emission is significantly increased.13

As the injection start point is maintained at 352°CA, with the shorter injection duration, the fuel sprayed into the cylinder is increased through the same crank angle and the penetrating distance is increased.14 This is conducive to the more fuel mixing with air and better fuel atomization, so the ignition delay period is shortened, the pre-mixed combustion of fuel is increased, and the diffusion combustion gets quicker. As a result, combustion heat release is concentrated, combustion pressure and cylinder temperature are increased, and NO production is increased accordingly15. Figure 9 shows the diesel component distribution taken from the cross section at the same height as the nozzle hole at 380°CA. It can be found out that as the injection duration is shortened, the combustion starts earlier and is more concentrated; in addition, the residual diesel component is reduced at 380°CA and the post-combustion part is also reduced. This is conductive to the improvement of effective power.
5. Conclusion

The injection system of the 396 series diesel engine with flat-top convex basin combustion chamber is improved and a dual-injector is adopted in each cylinder. A 3D combustion model is established for simulated calculation and analysis of the combustion process of the engine when the 5-hole and 8-hole injectors and 4-hole dual-injector are adopted. The following conclusions can be drawn based on the parameter characteristics of the base engine:

1. The result of the case adopting 4-hole dual-injector shows that, when compared with the case of adopting 8-hole injector, the spatial distribution area of the fuel is widened, the mixing effect between fuel spray and air in cylinder is intensified, and the combustion is relatively complete, so the combustion process of the case of adopting 8-hole injector is improved.

2. The result of the case of adopting 4-hole dual-injector shows that, when the injection duration is shortened, the ignition delay period is slightly shortened, the peak combustion heat release rate, the maximum combustion pressure and the maximum average temperature in cylinder are increased, the combustion heat release is concentrated, the accumulated heat release is equivalent, and the NO emission is significantly increased.

3. The result of the case of adopting 4-hole dual-injector shows that the proper injection duration shall be selected based on comprehensive consideration of the pressure in cylinder, effective power and NO emission. According to the operation parameters and structural characteristics of the 396 series diesel engine, 22°CA injection duration is more suitable.

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