Analysis on Combustion Process of a 396 Series Diesel Engine with Flat-top Convex Basin Combustion Chamber

Yu Liang¹, Liying Zhou¹,², *, Mingfei Xu¹, Guwen Yao¹

¹School of Mechanical Engineering, Guiyang University, 103 Jianlong Road, Guiyang, 550005, China
²School of Mechanical Engineering, Guizhou Institute of Technology, 1 Caiguan Road, Guiyang, 550003, China

*Corresponding author e-mail: zhouliying0330@163.com

Abstract. The 396 series diesel engine has been widely used in many fields in China. The combustion process of the 396 series diesel engine with flat-top convex basin combustion chamber is analyzed by using the computational fluid dynamics software FIRE, and a 3D combustion model was established. The fuel spray, ignition start point, combustion pressure, combustion heat release rate, average temperature in cylinder and NO emission were compared and analyzed when the 5-hole, 6-hole and 8-hole uniformly distributed injectors were adopted. When injectors with different injection holes are adopted, the ignition delay period is basically the same and the fire occurs in the same place. The proper number of injector hole shall be selected to enlarge the space area occupied by fuel spray. The 6-hole injector is featured by higher pressure in the combustion cylinder, higher average temperature, better combustion process, higher thermal efficiency and higher NO emission. This research result provides a basis for selecting suitable injector for the 396 series diesel engine with flat-top convex basin combustion chamber.

1. Introduction

The MTU396 series diesel engine has excellent dynamic performance indexes, high running efficiency, compact structure, long life, etc. After years’ development and sales since its introduction, it has been widely used in domestic ship hosts, ship generating sets, submarine power supplies, heavy dump trucks, train engine sets, special vehicles and industrial power units, etc.

The combustion process of the 396 series diesel engine with flat-top convex basin combustion chamber was analysed by using the computational fluid dynamics software FIRE, and a 3D combustion model was established to study and discuss the impact of the 5-hole, 6-hole and 8-hole injectors on ignition, combustion heat release and NO emission to provide a basis for selecting suitable injector for the combustion chamber.¹

2. Combustion model

The characteristic parameters of the 396 series diesel engine are shown in Table 1. The geometric model is drawn by ProE software, and the mesh division is completed by hyper mesh software. The mesh is optimized and encrypted by the AVL FIRE, and 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, the model is established for the whole combustion
chamber. There are 56050 and 158900 mesh cells at the TDC (top dead center) and BDC (bottom dead
center) respectively, and the geometric model and combustion chamber mesh model are shown in Figure
1.

**Table 1. Summary of engine specifications**

| 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                                       |
| Combustion chamber type                   | Type ω                                     |
| Diesel injection advance angle (ºCA in front of TDC) | 8                                           |
| Inlet valve closing (ºCA behind BDC)      | 68                                         |
| Exhaust valve open (ºCA in front of BDC)  | 75                                         |
| Pressurization ratio                      | 2.9                                        |

**Figure 1.** Geometric model at 350ºCA and combustion chamber mesh at 440ºCA

The main parameters of the 5-hole, 6-hole and 8-hole injectors are shown in Table 2. In order to
match with the injection pump, 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 5ºCA is shown
in Figure 2. The swirl ratio in cylinder is set to 2.9, and the airflow in cylinder is asymmetric due to the
position of the inlet valve. The figure shows that the airflow in cylinder has a similar impact on fuel
spray particles of injectors with different injection holes.

**Table 2. Summary of injector specifications**

| Parameters                  | 5-hole injector | 6-hole injector | 8-hole injector |
|-----------------------------|-----------------|-----------------|-----------------|
| Cycle fuel injection / g    | 0.484           | 0.484           | 0.484           |
| Fuel injection duration / ºCA| 26.84           | 26.84           | 26.84           |
| Oil beam angle / º          | 152             | 152             | 152             |
| Nozzle diameter / mm        | 0.53            | 0.4838          | 0.419           |
| Number of nozzles           | 5               | 6               | 8               |
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 $C_2$ is set to 12.4.

| 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. Combustion 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 the 5-hole, 6-hole and 8-hole injectors are adopted.

#### 3.1. Cylinder pressure and heat release rate
As shown in Figure 3, when the 5-hole and 6-hole injectors are adopted, the curve of the pressure in cylinder and the combustion heat release rate curve are close. However, when the 6-hole injector is adopted, both the combustion heat release rate and the combustion pressure are higher. When the 8-hole injector is adopted, both the combustion heat release rate and the pressure in cylinder are significantly reduced and the combustion duration is extended.

3.2. Average temperature in cylinder and accumulated heat release

![Figure 4. Average temperature in cylinder](image)

Figure 4 shows that, when the 5-hole and 6-hole injectors are adopted, the curve of the average temperature in cylinder and the accumulated heat release curve is also close. However, when the 6-hole injector is adopted, both the average temperature in cylinder and the accumulated heat release are higher. When the 8-hole injector is adopted, both the average temperature in cylinder and the accumulated heat release are significantly reduced.

Under the condition that the injection duration and the effective flow area are unchanged, the atomization quality of fuel injection and the penetrating distance of oil beam are changed accordingly because the injector with different number and diameter of the hole is adopted. When the number of the hole is 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 and the spatial distribution area of the fuel are reduced. 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, and then the pre-mixed gas volume during the ignition delay period is reduced and the combustion duration is extended.

Combining the cases shown in Figure 3 and Figure 4, the 6-hole injector has the highest thermal efficiency while the 8-hole injector has a significantly reduced thermal efficiency. When the 6-hole injector is adopted, the atomization is better. Although the penetration distance is smaller than that of the 5-hole injector, there is one more nozzle, and the fuel distribution area is wider, which is conducive to diesel premixing and diffusive combustion. However, 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 intensifying the after-combustion and extending the combustion duration.
3.3. NO concentration

Figure 5 shows that, when the 6-hole injector is adopted, the average temperature in cylinder is high and the NO emission is the largest due to high combustion pressure. However, when the 8-hole injector is adopted, the NO emission is the lowest.10

3.4. Discussion and analysis

Figure 6 shows the temperature distribution in cylinder taken from the longitudinal section at 359.5°CA, and Figure 7 shows the temperature distribution in cylinder taken from the cross section at the same height as the nozzle hole at 359.5°CA. The 359.5°CA is the crank angle when the temperature area above 1000K begins to appear in cylinder. Therefore, the crank angle of 359.5°CA is determined as the ignition start point.

Figure 6 and Figure 7 show that ignition occurs at 359.5°CA in all these three cases, indicating the same ignition delay period. Under the condition that the total effective flow cross section area of the injector is unchanged, the more holes bring the smaller initial particle size of fuel spray and the shorter penetrating distance of oil beam. The initial particle size and penetrating distance restrict each other and affect the fuel-gas mixture jointly. These two figures show that the ignition area at the ignition start point of the 6-hole injector is slightly larger than that of the 5-hole injector, while the 8-hole injector has the smallest ignition area. This indicates that the case of the 6-hole injector is conductive to the evaporation, atomization and mixing of fuel, the formation of pre-mixed gas, and the acceleration of diffusion combustion.
**Figure 7.** Temperature distribution in cylinder taken from the cross section at the same height as the nozzle hole at 359.5°CA

Figure 8 shows the fuel component distribution at 362°CA (10°CA behind injection) taken from the cross section at the same height as the hole. It can be found out that, due to the effect of the combustion chamber structure and the airflow in cylinder, the mixed ignition combustion of fuel during the ignition delay period and the initial combustion period occurs in the same area. The more holes bring the more oil beams, and the distribution area of the fuel components around the injector is wider. This is conducive to make full use of the air around the injector. However, as the area of fuel component with higher concentration is concentrated near the hole and fuel component cannot mix with the air away from the injector, the combustion process is decelerated. The main purpose of selecting the proper number of nozzle holes is to enlarge the space area occupied by fuel spray.

**Figure 8.** Fuel component distribution at 359.5°CA taken from the cross section at the same height as the hole

4. Conclusion
A 3D combustion model is established for the cylinder of the 396 series diesel engine with flat-top convex basin combustion chamber. On the premise of matching with the injection pump, the combustion process of the engine with the 5-hole, 6-hole and 8-hole injectors is simulated and analyzed. The following conclusions can be drawn based on the engine parameter characteristics for the model.

1) When the 6-hole injector is adopted, the pressure in combustion cylinder is larger, the average temperature is higher, the combustion speed is faster, the combustion process is sufficient and proceeds well, the thermal efficiency is higher, but the NO emission is larger.

2) If the injectors with different holes are adopted, both the ignition delay period and the combustion start point are basically the same, and the ignition occurs in the same position. However, due to the
effect of the initial particle size of spray and the penetrating distance of oil beam, the pre-mixed gas formed in the ignition delay period and the condition required for the later diffusion combustion are different and then affect the combustion process. The proper number of injection hole shall be selected to enlarge the space area occupied by fuel spray.

(3) The case with 6-hole injector is conducive to the evaporation, atomization, mixing and the formation of pre-mixed gas, thus accelerating the diffusion combustion.

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