The Influence of Nozzle Parameters on the Atomization Performance of Non-normal Fuel based on the Super-high Pressure Common Rail System

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Abstract. The uniformity of the fuel and air mixture in the cylinder of diesel engine directly affects the smooth running of the combustion process. In order to improve the atomization effect of the fuel in the cylinder, the super-high injection pressure exceeding 180MPa was used. The changing relationship between the physical properties of the non-normal fuel and the pressure under the influence of the super-high injection pressure was derived. The three-dimensional combustion model of TBD620 diesel engine is constructed on the FIRE software platform. A numerical simulation of the two injectors’ fuel injection process under different load conditions has been done in the research work. The fuel spray characteristics has been simulated. The results show that the special fuel injector has a good performance under low loading conditions, but the standard fuel injector has better performance for oil and gas fully mixed under high loading conditions.

1. Introduction
Because of its high thermal efficiency and good reliability, diesel engine has become the main choice for ships’ power system in the world. At the same time, it is also widely used in power generation, construction machinery, railway transportation and other fields [1]. The atomization effect of the fuel in the cylinder is very important to the performance of diesel engine. Reasonable nozzle parameters are favorable to the uniform mixing of fuel and air in the cylinder, which is a prerequisite to improve the combustion process. Recent studies showed that the fuel injection pressure of super-high pressure common rail system has been a trend of further improvement. In some diesel engines, the super-high pressure injection exceeding 180MPa has been realized [2]. When the pressure increases, the physical property parameters of the fuel would change. In this paper, the atomization process of fuel and gas mixing process of TBD620 diesel engine is simulated on the AVL FIRE software. The fuel spray characteristics test is carried out, and the dynamic process of the whole oil and gas mixture is given, and a good result is obtained.

2. Variation of fuel physical properties
The variations of temperature of the fuel can be neglected when the diesel engine is running because the fuel injection duration of each working cycle is short. But the pressure has changed a lot when it flows from the rail chamber through the injector to the outlet of the orifice. Most of the physical parameters of the fuel are also changed simultaneously. In order to study the variation of each physical parameter and reduce the impact of each variable. The density, sound speed and bulk modulus are
expressed as a function of pressure and temperature as the independent variable. Other parameters have little effect on the fuel flow characteristics, so it is not necessary to go into details here.

2.1 Density
For mineral oil, Donson D and Higginson G R found that the following relationship exists between dimensionless density \( \bar{\rho} \) and pressure \( p \):

\[
\bar{\rho} = \frac{\rho}{\rho_0} = 1 + \frac{0.6 \times 10^{-3} p}{1 + 1.7 \times 10^{-3} p} - 3.0 \times 10^2 \cdot \frac{p}{\rho_0}
\]

where \( \rho \) and \( \rho_0 \) are the density under pressure \( p \) and atmospheric pressure, respectively. The unit of pressure is MPa.

![Figure 1. Density variation with pressure](image)

After summarizing and analyzing, the effect of temperature on the density is taken as a correction factor. Taking into account the other characteristics of diesel, the following empirical formula is put forward by Wang et al.:

\[
\rho = \rho_0 \left[ 1 + \frac{0.69 \times 10^{-3} p}{1 + 3.23 \times 10^{-3} p} - \lambda_f (t - t_0) \right]
\]

where \( t \) is 60°C after experimental testing. \( \lambda_f \) is the coefficient of thermal expansion. The relationship between density and pressure is shown in figure 1.

2.2 Speed of sound
According to the theory of fluid dynamics, the equation of the speed of sound is:

\[
a = \left( \frac{dp}{d\rho} \right)^{\frac{1}{2}} = \left\{ \rho_0 \left[ \frac{0.69 \times 10^{-3} p}{1 + 3.23 \times 10^{-3} \rho} \right]^2 + 1.8 \times 10^{-4} \times a \left( \frac{t - 138}{t_0 - 138} \right)^{\frac{1}{2}} (t - t_0) \right\}^{\frac{1}{2}}
\]

\[
s = \frac{\lambda (t_0 + 135.15)}{\ln \eta_0 + 9.67}
\]

\[
\eta_0 = \rho_0 \times 10^{\left( \frac{1.305 \eta_0 - 1000}{1000 \rho_0 - 6} \right)}
\]

Where \( a = (1 - 3) \times 10^{-8} \, Pa^{-1} \) is the viscosity pressure coefficient. \( \lambda = 0.03 - 0.06 \) is the viscosity temperature index. The relationship between speed of sound and pressure is shown in Fig 2.
Figure 2. Speed of sound variation with pressure

2.3 Bulk modulus

According to the definition\(^\text{[7-8]}\), the expression of bulk modulus is:

\[
B = \rho \frac{dp}{d\rho} = \frac{1 + \frac{0.69 \times 10^{-3}}{1 + 3.23 \times 10^{-3} p} - \frac{\lambda}{\rho} (t - t_0)}{\frac{0.69 \times 10^{-3}}{1 + 3.23 \times 10^{-3} p} + 1.8 \times 10^{-4} \alpha \left( \frac{t - 138}{t_0 - 138} \right) (t - t_0)}
\]  

(6)

The relationship between bulk modulus and pressure is shown in Fig. 3.

Figure 3. Bulk modulus variation with pressure

3. Simulation model

3.1 Calculation model

The three-dimensional geometry model including inlet, valve and combustion chamber is established on the AVL FIRE software, as shown in Fig. 4. The crank rotation angle is set to 360° while the piston in the intake stroke TDC position, and the inlet valve opening and closing moments are set to 315° and 580°\(^\text{[9]}\).
In order to improve the fuel atomization effect, the TBD620 diesel engine matches two different injectors. As shown in Fig. 5, the diameter of the standard injector used in the high load is 0.48mm. The diameter of the special injector used in the low load is 0.46mm. The diameter of the pressure chamber at the bottom of the nozzle reduces from 1.8mm of the standard injector to 1.5mm of the special injector, and the height reduces from 1.78mm to 1.36mm.

3.2 Parameter setting
The swirl intensity in cylinder is equal to the atomization effect of two kinds of injector, so the $k-\varepsilon$ model is chosen for the turbulence model. Fuel atomization using WAVE discrete model, fuel evaporation using Dukowicz model. The ECFM-3Z model is chosen for the combustion model \[10\]. The cycle fuel injection quantity of the 25% load condition and the 100% load condition are respectively set to 0.133g and 0.47g. The speed of diesel engine is set to 1500r/min. The calculation angle is set to 360°CA—850°CA.

4. Simulation results and analysis
Fig. 6 and Fig. 7 show the development of in-cylinder fuel from different injectors at 25% load. Fuel moves forward in bulk form after they leave injectors. At this time the oil beams are relatively concentrated. Two kinds of oil beams motion are the same. With the fuel injection process, the oil beam tips appears mutual movement with air, and it begins to disperse. Then fuel continue to move forward and gradually close to the cylinder wall, spreading around under the effect of high velocity airflow near the cylinder wall. Part of the fuel is heated up, and changing from liquid to gaseous. Gaseous fuel mixed with air rapidly is fully atomized. Only in the oil beams internal, due to low temperature, oil droplets that are far away from airflow haven’t mixed with air yet. Comparison of two different injectors shows that special fuel injector has smaller nozzle and higher injection pressure. Fuel from special fuel injector begins to disperse and mix with air earlier in the middle of spray process. Atomizing effect is better than the standard fuel injector. There are less in-cylinder residual oil beams in the end of injection process \[11\].
Fig. 6. Spray processes of standard fuel injector under 25% load

Fig. 7. Spray processes of special fuel injector under 25% load

Fig. 8. Variation of penetration and sauter mean diameter under 25% load

Fig. 8 shows the variation of penetration and sauter mean diameter under 25% load. Under low load condition, the fuel spray penetration increases gradually throughout the development process. Shortly after the start of the spray, the spray penetration of the special nozzle is smaller than that of the standard spray nozzle, and continued until the end of the spray process. This is mainly because the nozzle diameter of the special nozzle is relatively small. When the oil droplets are ejected, the mixture can be formed rapidly with air. When the oil droplets are ejected, the mixture can be formed rapidly with air.[12]

Fig.9 and Fig.10 show the development of in-cylinder fuel from different injectors under 100% load. In this condition, injection pressure is very high at this time. Effects of in-cylinder swirl on the two injectors are relatively the same. The shapes of in-cylinder oil beams from two injectors have no obvious difference. But after the injection process, oil droplets of standard fuel injector have smaller volume. There are less residual oil beams in the cylinder. For special fuel injector, because of its longer injection duration, there are more residual oil beams in the cylinder. So the atomization effect of the special fuel injector is not good.
Fig. 11 shows the variation of penetration and sauter mean diameter under 100% load. It can be seen that the spray penetration of the two kinds of injectors showed a trend of first increasing and then decreasing under high load. In the early and middle stage of fuel injection, because of the smaller size of the oil droplets ejected from the special injector, its spray penetration is smaller than the standard injector, and the atomization effect is better. However, in the later period of fuel injection, due to the long duration of the special injector, there are more residual oil beams, which is not conducive to the atomization of the fuel. So the spray penetration is larger than the standard injector[13].

5. Test results and analysis

5.1 Test principle

1. high pressure vessel 2. injector 3. flash lamp 4. digital camera 5. safety valve 6. pressure relief valve 7. high pressure gas cylinder 8. compressor 9. fuel filter 10. oil pump 11. tubing 12. fuel tank 13.、14. overflow valve 15. test control console

Figure 12. Schematic of the spray experimental setup
Simulation experiment of spray characteristic is to simulate the fuel injection process as the object, using high speed flash photography technology, makes a comprehensive and accurate description of the characteristics of fuel spray. The spray images are obtained through the analysis and understanding of the characteristics of fuel spray.

First of all, open the shutter of the digital camera. The control system sends a pulse to control the electronic flash at the T time after the injection. When the oil beam image of the flash time is captured by the digital camera, the fuel spray image of the T time after the injection is obtained. For each injection, adjusting the delay time of the flash lamp to get the spray images with different time intervals, then the whole development process of fuel spray can be obtained.

5.2 Test result analysis

![Figure 13. Compare of spray penetration](image)

Fig.13 is the comparison of the simulation value and experimental value of the spray penetration of the special injector under the 100% load. The difference between the simulation value and the experimental value is very small in the whole process of fuel injection. They are basically the same in the range of error tolerance. It shows that the simulation model can well reflect the actual situation.

6. Conclusion

Under different load conditions, the fuel injection quantity of diesel engine is different. So the fuel injection pressure is different. Thus, the atomization effect of the fuel in the cylinder will be affected. Under the condition of low load, the diameter of the oil droplet from special nozzle is smaller. The atomization effect is better and the cylinder mixture distribution is more uniform. It has a better affect to the combustion process. However, under the condition of high load, the injection rate of standard nozzle is fast. The duration has been shortened and there is less residual oil in the cylinder. So the mixing effect of oil and gas is more ideal.

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