Experimental study on the influence of injection advance angle to diesel engine equipped with electronic unit pump

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Abstract. The fuel injection advance angle of electronic unit pump fuel injection system has a great influence on the running performance of diesel engine as well as the energy consumption, environmental and global warming issues. For a supercharged diesel engine equipped with electronic unit pump, the influence of injection advance angle on the injection characteristics, specific fuel consumption, combustion characteristics and reliability have been studied in this paper, which has important reference significance for the optimization of injection strategy of diesel engine.

1. Introduction

The problem of diesel emission and efficiency has always been the focus in tackling the energy consumption, environmental and global warming issues [1-2]. Fuel injection system plays one utmost important role in diesel engine’s general performance, high-pressure direct injection associated with electronic control system has been widely regarded as one promising injection manner to modern diesel engines for its advantages in dynamic power and raw emissions [3-5]. In all diesel fuel injection systems, EUP system has variable and flexible injection timing and high injection pressure, it is one of the main technologies to increase power per engine displacement and meet emission requirements [6-9].

The fuel injection advance angle has a great influence on the running status of diesel engine. If the fuel injection advance angle is too large, it will lead to a longer preparation period, which will lead to rough engine operation [10-11]. However, if the injection advance angle is too small, the combustion process will be delayed too much, and the maximum pressure value will drop, which will obviously reduce the thermal efficiency of diesel engine. The best injection advance angle can help obtain the maximum power and the minimum fuel consumption rate under the condition of constant speed and oil delivery [12].

The optimal injection advance angle of diesel engine changes with oil delivery and crankshaft speed, and increases with the increase of diesel engine speed [13-14]. In addition, the structure of diesel engine also has a certain influence on the optimal injection advance angle. For example, the optimal injection advance angle is different with different combustion chambers; Generally, the best injection advance angle of diesel engine with direct injection combustion chamber is larger than that with separated combustion chamber [15].

In this paper, a V-type eight-cylinder supercharged diesel engine matched with electronic unit pump fuel system is taken as the research object. Firstly, the influence of injection advance angle on injection characteristics have been studied. Then, the change trend of specific fuel consumption and
combustion characteristics with injection advance angle have been analyzed. Finally, the influence of injection advance angle on the reliability and working safety of diesel engine have been discussed, which has important reference significance for the optimization of injection parameters of diesel engine.

2. Experiment facilities
As a typical time controlled fuel injection system, as shown in Figure 1, the electronic unit pump system has good working characteristics, including flexible and controllable injection timing and quality, more prominently high injection pressure and better working reliability. The normal injection pressure is between 160Mpa and up to 220MPa. Electronically controlled fuel injection works: the components of EUP fuel system are driven by a cam, and the movement of plunger is determined by cam contour. When the plunger moves upward, the solenoid valve is energized and closed, the passage between the high-pressure and low-pressure oil chambers will be cut off, and the oil will be pressed down by the plunger. The high-pressure fuel opens the outlet valve, enters the fuel injector through the high-pressure oil pipe, and is injected into the cylinder through the atomizing nozzle; When the solenoid valve is disconnected, the oil chamber between high pressure and low pressure is connected, the fuel is unloaded quickly, and the nozzle stops injection.

![Figure 1. Electronic control unit pump diagram.](image1.png)

![Figure 2. The characteristics of deceleration cam.](image2.png)

A Delphi EUP system was used in this study and its main parameters are shown in Table 1. In order to measure the injection characteristics a Kistler pressure sensor was placed on the high-pressure tube and a needle lift sensor was installed in the injector.

| parameter               | value       |
|-------------------------|-------------|
| plunger diameter       | 11mm        |
| open injection pressure | 28MPa       |
| injector hole number   | 8           |
| Injector hole diameter | 0.27mm      |

As analyzing the EUP injection characteristics with the injection advance angel, combining the cam contour to the fuel supply system is very necessary. One kind of deceleration cam has been designed by Qiu Tao, Liu Xing-hua and Liu Fu-shui from Beijing Institute of Technology based on the research of the EUP oil supply system and cam profile matching characteristics. It realized the balance between fuel injection capacity and fuel supply ability [16-18]. Consequently, the fuel delivery per cycle and maximum injection pressure will not change dramatically with the injection advance angle. In this situation, More flexible adjusting methods can be provided for the match work between EUP system and diesel engines. The profile lift and speed curves of the deceleration cam used in this paper are shown in Figure 2.

The cam lift at this moment when the piston arrives at the TDC, is defined as Pre-lift and the segment of deceleration is regarded as working segment or constant pressure segment. At the designed speed (2200r/min crankshaft speed), the fuel delivery per cycle and maximum injection pressure will not vary with different injection advance angles. Theoretically, if the crankshaft speed is smaller or larger than the designed value, the fuel supplying ability will be less or more than the fuel injection
capacity. Therefore, the fuel delivery per cycle and the maximum injection pressure will change as the injection advance angle moves. Moreover, due to some uncertain factors, such as velocity fluctuation and pressure oscillation in high-pressure pipe, it is necessary to study the actual injection characteristics experimentally.

The test prototype is a V-type eight-cylinder supercharged diesel engine, and its main parameters are shown in Table 2.

### Table 2. The diesel engine main parameters.

| Parameter                        | Value               |
|----------------------------------|---------------------|
| Bore diameter (mm)               | 132                 |
| Stroke (mm)                      | 145                 |
| Compression ratio                | 14:1                |
| Combustion chamber               | double swirl        |
| Ignition sequence                | 1-8-4-5-7-3-6-2     |
| Start injection pressure (MPa)   | 20                  |
| Nozzle number                    | 8                   |
| Nozzle diameter (mm)             | 0.27                |
| Max torque (N.m)                 | 2415@(1800r/min)    |
| Max power (kW)                   | 500@(2100r/min)     |

A large number of sensors are installed on the test bench to monitor the state of the engine, Kistler pressure sensors measure the in-cylinder pressure, oil supply pressure in the high-pressure oil pipe, oil pressure and intake and exhaust pressure; The needle valve lift sensor monitors and adjusts the injection position; K-type temperature sensor measures inlet and outlet temperature and inlet and outlet water temperature, etc. The fuel consumption rate of engine is measured by using the Tongyuan transient fuel consumption meter. DEWECA combustion analyzer is used to calculate in-cylinder heat release rate and display combustion pressure curve, oil supply pressure curve and needle valve lift. All measurement results have been calibrated and checked, and the errors are within the reasonable range.

### 3. Experiment results and analysis

In this part, Firstly, the influence of injection advance angle on injection characteristics have been studied. Then, the change trend of specific fuel consumption and combustion characteristics with injection advance angle have been analyzed. Finally, the influence of injection advance angle on the reliability and working safety of diesel engine have been discussed.

#### 3.1. Influence of injection advance angle on fuel injection characteristics

The experimental results of the EUP with the crankshaft speed 1800r/min and 2500r/min are shown in Figures 3 to 6, where Figure 3 and Figure 4 are the experimental results of injection pressure, and Figure 5 and Figure 6 are the experimental results of the maximum injection pressure and the fuel delivery per cycle, respectively.
As shown in Figure 5 and Figure 6, with both the crankshaft speed of 1800r/min and 2500r/min, the injections start too early and the whole process of injection locate in front of the constant pressure segment when the injection advance angle is before 18° CA BTDC. Consequently, both of the fuel delivery per cycle and the maximum injection pressure show a clear downward trend. This is an abnormal working status and can cause more difficulties for the diesel engine mapping process. It is needed to note that for the smaller injection advance angle in the case of 2500r/min, the fuel delivery per cycle begins to drop, although the maximum injection pressure keep the same which did not appear in the case of 1800r/min. It is because that the injection pressure decrease in the late stage of injection process. In other words, although the early injection stage happens in the constant pressure segment, the later stage goes beyond that. Therefore, with the pre-lift increases, the maximum critical value of injection advance angle will increase accordingly. Moreover, a minimum critical value of injection advance angle can be found, if the injection begins after the minimum critical one, the fuel delivery per cycle will decrease, and that happens a little more early than that of the maximum injection pressure. Additionally, the injection duration has a direct impact on the minimum critical value: it gets smaller with a shorter injection duration, which means the fuel delivery per cycle can keep the same in a wider range of the injection advance angle.

3.2. Influence of injection advance angle on fuel consumption and combustion characteristics
Figure 7 to Figure 9 show the test results of fuel consumption, combustion duration and E50 position with injection advance angle under different loads.
As shown in Figure 7, for different loads, with the increase of injection advance angle, the specific fuel consumption decreases first and then increases, that is, for each load, there is a most economical injection advance angle. With the increase of load, the most economical injection advance angle increases correspondingly. And when the load is 350kW, the best specific fuel consumption is the smallest, which shows that when the engine speed is constant, the specific fuel consumption decreases first and then increases with the increase of load. As shown in Figure 8, with the increase of the injection advance angle, the combustion duration increases linearly, and the combustion duration increases by about 0.4° CA for every 1° CA increase of the injection advance angle. And when the load is small, the relationship between combustion duration and load is obvious, that is, the greater the load, the more fuel injection and the longer the combustion duration. However, for medium and large loads, the combustion duration remains basically unchanged, because when the load increases, the combustion temperature in the cylinder increases, so the combustion speed increases and the time required for combustion remains basically unchanged. As shown in Figure 9, with the increase of injection advance angle, the position of E50 decreases, and for every 1° CA increase of injection advance angle, E50 decreases by about 0.8° CA. This is mainly because the fuel injection position is advanced and the combustion duration is slightly increased, so the change of E50 position is smaller than that of fuel injection advance angle.

The above three test results show that when the engine speed is constant, for different loads, the influence laws of fuel injection advance angle on fuel consumption, combustion duration and E50 position are basically the same, but the most economical fuel injection advance angle increases with the increase of load. Figure 10 is a graph showing the relationship between specific fuel consumption and the position of E50 under different loads.

As shown in Figure 10, when E50 appears at about 8.5° CA after TDC, the minimum specific fuel consumption appears for four different loads at 1800rpm. This shows that the position of E50 determines the combustion efficiency of the engine, and when the engine speed is constant, the optimal position of E50 is basically unchanged, which is of great significance for improving and
optimizing the combustion efficiency and specific fuel consumption of the electronically controlled unit pump diesel engine.

3.3. Influence of injection advance angle on combustion pressure and exhaust temperature

The above research shows that the combustion duration and E50 position can be changed by adjusting the injection advance angle, and the specific fuel consumption can be optimized. However, the injection advance angle also affects the combustion pressure and exhaust temperature of the engine, and these two parameters have an important influence on the reliability of the engine. Excessive maximum combustion pressure will increase the mechanical load of the cylinder head, while excessive exhaust temperature will increase the heat load of the exhaust system. During the operation of the engine, they need to be strictly controlled and cannot exceed the specified limit for a long time. The maximum combustion pressure of the prototype can not exceed 170 bar, and the exhaust temperature before turbine can not exceed 700℃.

Figure 11. The test result of combustion pressure.  Figure 12. The test result of exhaust temperature.

Figure 11 and Figure 12 show the test results of maximum combustion pressure and exhaust temperature before turbine changing with injection advance angle. It can be found that under different loads, with the increase of injection advance angle,

the maximum combustion pressure and exhaust gas temperature before turbine basically change linearly. When the injection advance angle increases by 1° CA, the maximum combustion pressure increases by 2-3bar, and the exhaust gas temperature before turbine decreases by 2-5℃. The higher the load, the faster they change with injection advance angle. This is because the larger the injection advance angle is, the longer the post combustion will be, and the more fuel will be burned during the lag period, which will cause the increase of combustion pressure. At the same time, the smaller the proportion of post combustion, the lower the exhaust energy, so the exhaust temperature decreases gradually.

In addition, With the increase of injection advance angle, the exhaust temperature decreases slowly, and the maximum combustion pressure increases significantly. Therefore, it is difficult to reduce the exhaust temperature by adjusting the injection advance angle. If the exhaust temperature is too high, we should mainly consider increasing the intake pressure and reducing the intake temperature in order to increase the intake air volume, increase the excess air coefficient, shorten the combustion duration and reduce the exhaust energy. In addition, measures such as optimizing valve timing and increasing injection pressure can be taken.

4. Conclusion

For supercharged diesel engine equipped with electronic unit pump, Firstly the influence of injection advance angle on the injection pressure and fuel delivery per cycle have been studied. Then the change trend of specific fuel consumption, combustion duration and E50 position with injection advance angle have been analyzed. Finally the influence of injection advance angle on the maximum combustion pressure and exhaust temperature have been discussed. The main conclusions drawn from this research are:

(1) When the EUP works in the constant pressure segment, the fuel delivery per cycle and the
maximum injection pressure nearly keep constant, otherwise, both of them decrease dramatically with the injection advance angle.

2) A minimum critical value of injection advance angle can be found, if the injection begins after the minimum critical one, the fuel delivery per cycle will decrease, and that happens a little more early than that of the maximum injection pressure. Additionally, the injection duration has a direct impact on the minimum critical value: it gets smaller with a shorter injection duration, which means the fuel delivery per cycle can keep the same in a wider range of the injection advance angle.

3) Combustion duration, position of E50, maximum combustion pressure and exhaust temperature injection advance angle all nearly show linear trend with injection advance angle. The position of E50 determines the combustion efficiency of the engine, when E50 appears at about 8.5° CA after TDC, the minimum specific fuel consumption will be obtained.

4) The injection advance angle has an important influence on the combustion efficiency, economy and safety of diesel engine. When the specific fuel consumption is optimized by adjusting the injection advance angle, the best injection advance angle can be determined according to the economy for medium and small loads, but for large loads, it is necessary to monitor the highest combustion pressure at the same time to prevent the reliability from dropping significantly.

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