# Measurement and analysis of cycle fuel injection quantity for electronic unit pump

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**Abstract**: The cycle fuel injection quantity is accurately measured for electronic unit pump (EUP) operating at high, middle and low speeds by using displacement method based on EFS instantaneous mono-injector qualifier. On the basis of the experimental data about fuel injection quantity and fuel pressure, the variation of inconsistency in fuel injection quantity of EUP and the influence factors in different operating conditions are concluded. The results show that the inconsistency is lowest in maximum torque condition, while on the start and maximum power conditions, it is higher.

**Key words**: diesel engine; fuel injection quantity; electronic unit pump (EUP)

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## 0 Introduction

Diesel engine has lower fuel consumption and higher torque characteristic in contrast with gasoline engine with the same power[1]. Therefore, diesel engine is widely used in automobile, vessel, high duty truck, military vehicle, engineering machine, dynamotor unit, and so on. Using the advanced emission control technology in diesel engine, the application area of diesel engine can be enlarged gradually.

In diesel engine, air-fuel mixing rate is a key factor which can influence power, heat efficiency and emission performance. The air-fuel mixing process is determined by three aspects: fuel injection, flow discharge and effect of combustion chamber. Once the three aspects are well-matched, the diesel will obtain an optimized performance.

Fuel injection system is one of the most important parts in diesel engine with the highest manufacturing accuracy and adjustment accuracy. With the continuous deterioration of environment and increasingly stringent emission regulations, the emission performance of diesel engine need to meet more stringent requirements[2-3].

The improvement in emission performance of diesel engine can not be separated from good match and continuous innovation. Nowadays, the fuel injection system mainly consists of high pressure common rail system, electronic unit injector (EUI) system and electronic unit pump (EUP) system. The EUP system has good reliability, flexible injection control and low modification cost. While it is difficult for domestic oil quality to meet the required conditions. Therefore, the EUP system is a superior system[4-5].

The cycle fuel injection quantity is the most important performance indicator for high pressure EUP system, which is the third generation pulsation control system. And it is also the main test factor in the stages of product design and performance test, which directly influences the engine dynamic characteristic. Considering machining accuracy, there are some difference among the cycle fuel injection quantities of different EUP systems, which would have an adverse effect on diesel operation[6-8].

This paper has measured a lot of cycle injection quantities about EUP, and analyzed the inconsistency in different operation conditions. This paper has also proposed the corresponding control pulse width correction factor to improve the operation stability of diesel engine.

## 1 Experiment equipment and bench

### 1.1 Test bench

The experiment was carried out on the pump drive control platform of Beijing Institute of Technology Engine Laboratory. Fig. 1 shows the schematic diagram of the drive control platform of EUP system.

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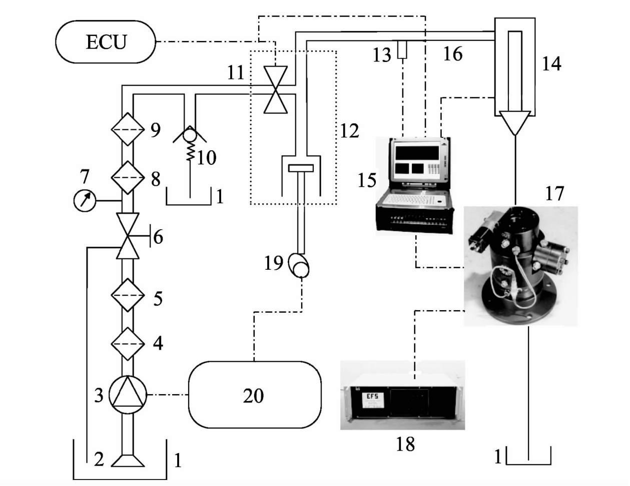


1 – Fuel tank; 2 – Filter; 3 – Oil pump; 4 – 1st stage of coarse filter; 5 – 2nd stage of coarse filter; 6 – Pressure regulating valve; 7 – Oil pressure indicator; 8 – 1st stage of fine filter; 9 – 2nd stage of fine filter; 10 – Check valve; 11 – Electromagnetic valve; 12 – EUP; 13 – Oil pressure sensor; 14 – Injector; 15 – Dewetron-5000 combustion analyzer; 16 – High-pressure injection pipe; 17 – EFS; 18 – EFS control unit; 19 – Camshaft; 20 – Control system

**Fig. 1 Schematic diagram of drive control platform of EUP system**

The test bench controls oil pressure and camshaft speed by using pump station control system. Dewetron-5000 combustion analyzer is used to collect data about pump pressure, drive current and injector needle valve lift signals. Needle valve lift signal is characterized by truncated signal, of which the curve cannot reflect the real displacements. EUP system delphi-E1 is selected with plunger diameter 11 mm and stroke 18 mm. The electronic control unit (ECU) controls the solenoid valve to open and close to generate high pressure. The Bosch mechanical injector was chosen with injection staring pressure 2.8 MPa. The fuel pressure of high-pressure oil pipe is acquired using Kistler4067BB2000 oil pressure sensor and electric charge amplifier. The cycle fuel injection quantity is collected using EFS-8246. Low oil supply pressure is 0.6 MPa, drive current peak is 11 A and holding current is 5 A.

## 1.2 Measurement principle for cycle fuel injection quantity

The measurement instrument is EFS-8246. The accuracy of EFS is 0.6 $mm^3$ and the measurement range is 0 – 600 $mm^3$. Figs. 2 and 3 show the mechanical structure and measurement principle of EFS-8246, respectively.

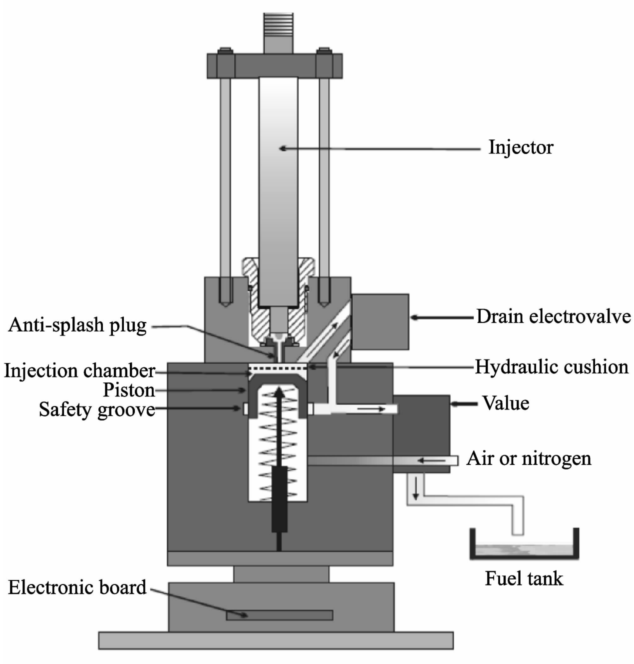


**Fig. 2 Mechanical structur diagram of EFS**-8246

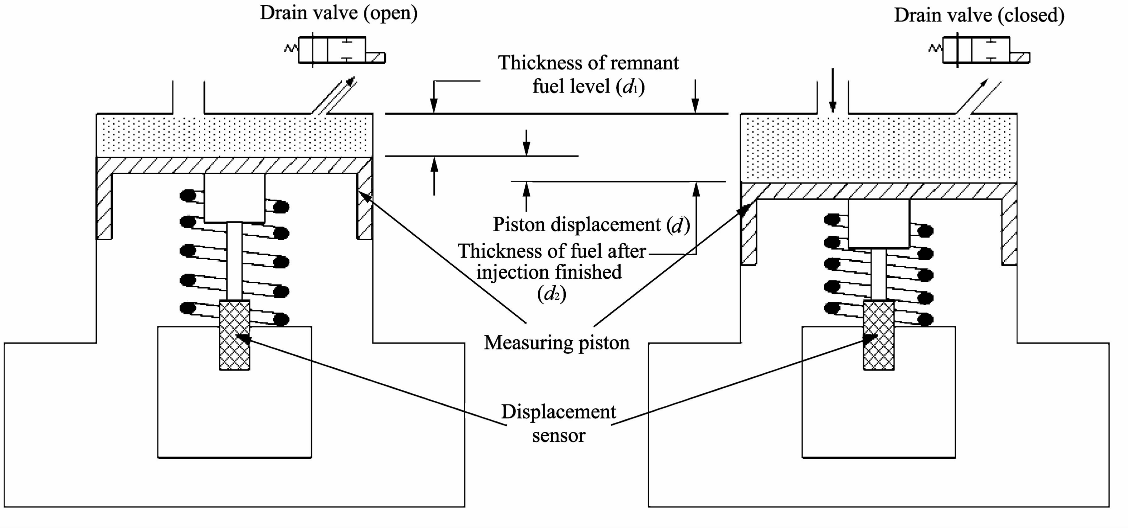


**Fig. 3 Measurement principle of displacement method**

The measurement principle is based on the displacement of a piston with the force of the injected fluid. The equipment is synchronized with the rotation of the camshaft of an injection pump. An injector installed on the top of the equipment fills a variable volume injection chamber. As long as the pump is in the injection phase, the drain eletrovalve remains closed and the piston lowers with the thrust of injected fluid. The position change of the piston graphically expresses the injected fluid volume exactly. It is permanently measured by the electronics and volumes are calculated at various angles in the injection phase.

When the injection begins, the drain valve is opened, at this time the thickness of the remnant oil level in the measuring cylinder is $d_1$; in the injection process, the drain valve is closed, the measuring oil is injected into the cylinder and pushes the piston down; when the injection over, the thickness of the remnant oil level in the measuring cylinder is $d_2$, therefore the displacement of the piston is $d = d_2 - d_1$. This displacement is the direct parameter for oil injection volume, which could be accurately measured by displacement sensor. After the measurement finished, the piston will be reset, the drain valve is opened and the oil in measurement cylinder is discharged.

The EFS system collects piston lift signal and injection parameters five times in each crank angle to ensure accuracy. In the initial phase of measurement, angle domain is automatically set at starting signal(the maximum angle of 90°), which is actually the starting point of injection parameters. The system synchronically generates a cursor. When a signal of each piston lift is measured, the system adds a level signal onto the cursor. The highest level corresponds to the end of the sampling piston and the lift oil chamber containing the starting point of the drain. In addition, the system can differentiate piston motion rate according to piston lift signal which indirectly reflects the injection rate.

### 1.3 Delay analysis of characteristic parameters

There will be a time delay between control parameters and characteristic parameters while EUP system works. Fig.4 shows the test results of characteristic parameter systems.

There is an electronic delay of power drive module when electric control system outputs control signal to generate driving current. Delay time is $t_2 - t_1$ (The results can be converted according to the camshaft angle and speed). After the solenoid valve driving current has been generated, the solenoid valve attracts armature to close return pipe and the piston compresses the fuel in chamber to generate high pressure fuel which may spread to the high-pressure tubing. The duration of this process is $t_3 - t_2$. When the fuel pressure reaches the opening pressure for needle valve, the fuel will spread into fuel injector pin valve to open and start injection. The duration of this process is $t_4 - t_1$. The delay time extends from the end of driving current to the fuel pressure decreasing, and the time of the needle seated is $t_6 - t_5$.

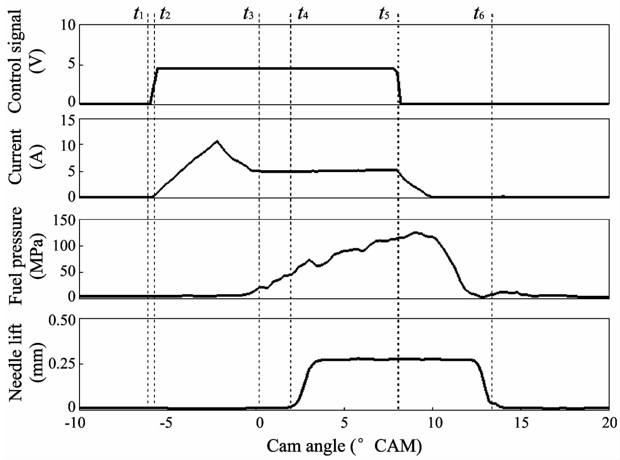


**Fig.4 Relationship between the measured signals' delays**

## 2 Inconsistency analysis of cycle fuel injection quantity

### 2.1 Operation conditions

The experiment measures the cycle injection quantity in different operation conditions for 36 EUP systems. The operation conditions include low-, middle- and high-speed external characteristic conditions[9]. The drive parameters consistes of injection timing and pulse width. The injection timing for all experiments is set at 0°CA. Table 1 shows the operation conditions.

**Table 1 Operation conditions of experiment**

| Speed (r/min) | Condition | Injection pulse width (°CA) |
|---|---|---|
| 200 | Start | 16 |
| 1 800 | Maximum torque | 35 |
| 2 500 | Maximum power | 30 |

### 2.2 Experiment results and analysis

The number of experimental EUP systems is No.1 to No.36. Fig.5 shows the cycle injection quantity of 36 EUP systems in different operation conditions.

The average values of injection quantity on different conditions are 245.3 $mm^3$, 410.6 $mm^3$, 270.2 $mm^3$ (100 cycles) and the relative standard deviation of cycle injection quantity has been calculated as the evaluation criteria. The formula of the standard deviation is

$$S = \sqrt{\frac{\sum (Q_i - \bar{Q})^2}{N-1}}, \tag{1}$$

where $Q_i$ is injection! quantity of one single EUP system in corresponding condition, $\bar{Q}$ is average value of all EUP systems in a corresponding condition, $N$ is all quantities of EUP systems.

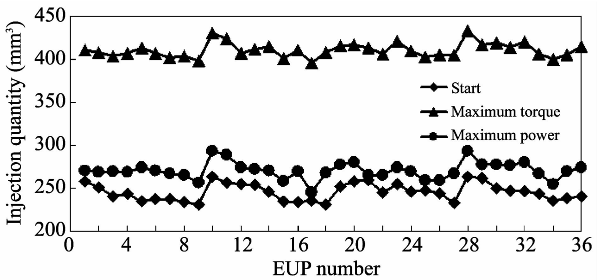


**Fig. 5 Cycle fuel injection quantity of EUP systems No. 1-36**

Fig. 6 shows the relative standard deviation of injection quantity of EUP systems No. 1-36.

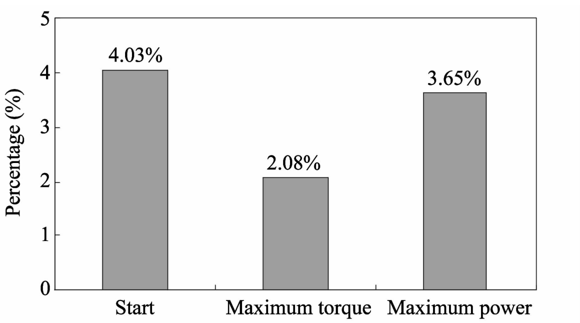


**Fig. 6 Percentage of cycle fuel injection quantity standard deviation**

Fig. 6 shows that the inconsistency is lowest in maximum torque condition, but it is higher in the start & maximum power conditions. Fig. 5 also shows that there are two factors that have the effect on the inconsistency, one is engine speed, and the other is injection pulse width. Meanwhile, both factors are influenced by the characteristic parameter of solenoid valve response time. Fig. 7 shows the timing characteristic of EUP solenoid valve.

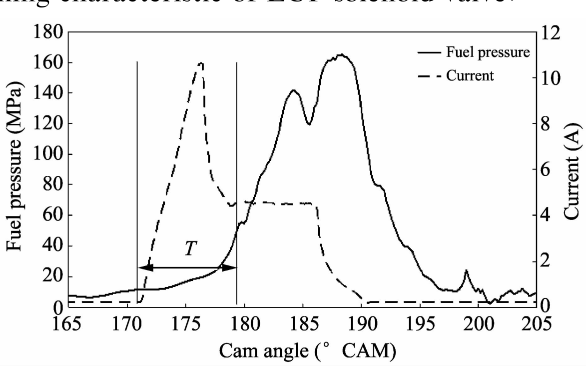


**Fig. 7 Timing characteristic of EUP solenoid valve**

In high-speed condition, the relative time (expressed by crank angle) of solenoid valve response time increases. As a result, the discrepancy of timing characteristic will enhance the injection quantity inconsistency. Fig. 8 shows the driving current and fuel pressure curves of No. 20 and No. 34 EUP system (2 500 r/min, 30°CA).

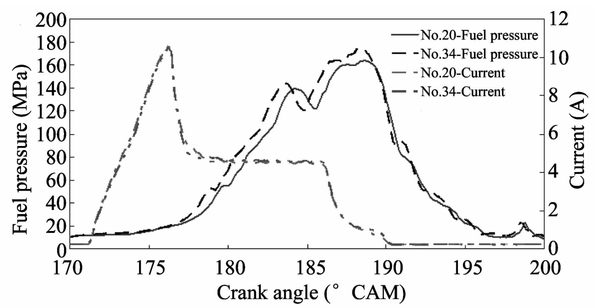


**Fig. 8 Driving current and fuel pressure curves of No. 20 and No. 34 EUP system (2 500 r/min, 30°CA)**

Fig. 8 shows that No. 20 EUP system has the faster solenoid valve response time than No. 34 EUP system, and the former advances 0.6°CAM (1.26° CA) than the latter. Sometimes, the characteristics of EUP injection makes the fuel injection pressure lift with the speed increasing, therefore, the injection quantity is more in high-speed condition than in low-speed condition, which will result in the worse consistency of injection quantity because relative standard deviation increases.

When the engine runs at a low speed, due to low pressure, the injection quantity is affected by speed fluctuation. The lower injection pressure makes the pressure fluctuate more violently, which leads to much worse injection consistency with the low speed. Fig. 9 shows the driving current and fuel pressure curves of No. 20 and No. 34 EUP systems (200 r/min, 16°CA), and the dotted line means the nozzle open pressure.

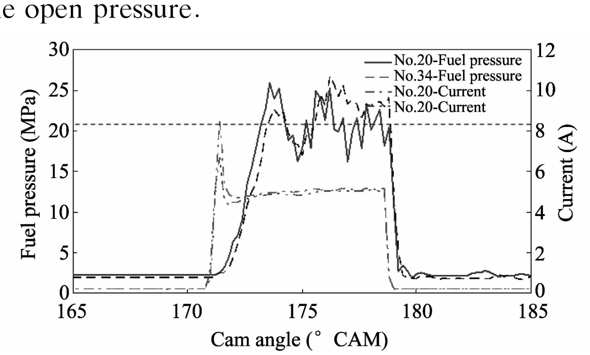


**Fig. 9 Driving current and fuel pressure curve of No. 20 and No. 34 EUP systems (200 r/min, 16°CA)**

As Fig. 9 shows, the fuel injection pressure fluctuates more violently, and furthermore the characteristic of solenoid value response time would increase the inconsistency of injection quantity. The statistical results also show that the consistency with the middle speed is better than the low and high ones[7].

Because of the inconsistency of EUP injection quantity, the power of ever cylinder can be non-uniform, which will result in less stability, vibration and reliability[8-10]. In the engine system, the factors which affect the inconsistency include machining accuracy and hydraulic delay. The former cannot be improved, and the improved effect of the latter is not well. By analyzing injection pressure curve, it can be seen that the difference of solenoid valve response characteristics is the main factor affecting the consistency of EUP injection quantity. Therefore, it is reasonable to use sub-cylinder independent control strategy to improve the consistency of EUP injection quantity.

## 3 Conclusions

1) Because of machining accuracy and hydraulic delay, the inconsistency of cycle fuel injection quantity always exists, which can be reduced by sub-cylinder independent control strategy.

2) In low-speed and high-speed operation conditions, the inconsistency of cycle fuel injection quantity is higher. In low speed operation condition, the main factor is the speed fluctuation which causes the change of injection pressure. In high speed operation condition, the main factor is solenoid valve drive characteristic.

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# 电控单体泵循环喷油量测量方法及分析

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**摘　要：** 基于先进的EFS瞬时喷油量测量仪，采用位移法分别对电控单体泵不同转速工况进行循环喷油量的精确测量。依据循环喷油量及喷油压力的试验数据，得到了电控单体泵喷油量不一致性变化规律以及不同转速下的主要影响因素。分析结果表明，在最大扭矩工况，各单体泵循环喷油量不一致性最低，而启动工况和最大功率工况的不一致性较高。

**关键词：** 柴油机；循环喷油量；电控单体泵

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