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High-Pressure Common-Rail Fuel Injection System with Electronic Control System in Diesel Engine

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ABSTRACT: High-Pressure Common-Rail Fuel Injection System is the most common technique of fuel injection used in diesel engine of automobiles. High-Pressure Common-Rail Fuel Injection System refers to a new method of fuel supply which can entirely separate the process of generation of inject pressure and the process of fuel inject under the control of a close-loop system which contains high-pressure oil pump, pressure sensor and electronic control unit. During the working process of diesel engine, the time of injection is extremely short which costs only a few milliseconds due to the high rate of rotation of the engine, meanwhile, in the process of injection, the pressure of every point of the high-pressure oil pipe is fluctuated with the change of position and time. Besides, because of the compressibility of diesel itself, the real situation of fuel injection is quite different from the regularity of fuel supply of the ram pump controlled by high-pressure fuel pump. What’s more, the fluctuation of pressure in high-pressure oil pipe may also cause secondary injection which will sharply reduce the performance of emission and economy. If the unusual injection is severe, it may not only cause the non-uniform of fuel injection but also lead to a phenomenon of intermittent inject failure. The engine equipped with common-rail technique can effectively solve these defects that traditional engine may have.

Keywords: Diesel Engine; High-pressure Common-rail;Fuel injection system; Electronic control

I. INTRODUCTION

Electronic control technique is now wildly used in modern automobile industry, especially in engine industry due to its high control precision, short response time, high capacity of resisting disturbance. Electronic control technique becomean important symbol of modern automotive industry, it also shows the way of how automobile industry will develop in the future. Electronic control technique can be found almost everywhere within a vehicle. It can be found in the systems of fuel injection, ignition, intake, exhaust, self-diagnosis. It is also commonly used in powertrain system, steering system, brake system and also the body and support systems[1].

We are facing the serious problem of lacking resources, as a matter of fact,diesel engine has been highly regarded in this condition due to its high efficency. Diesel engine, however, has a lot of problems when used as vehicle engine, such as heavy noise and high exhaust of particulate matter (PM). During the working process of traditional diesel engine, the time of injection is extremely short which costs only a few milliseconds due to the high rate of rotation of the engine,meanwhile, in the process of injection, the pressure of every point of the high-pressure oil pipe is fluctuated with the change of position and time. Besides, because of the compressibility of diesel itself, the real situation of fuel injection is quite different from the regularity of fuel supply of the ram pump controlled by high-pressure fuel pump. What’s more, the fluctuation of pressure in high-pressure oil pipe may also cause the pressure in the high-pressure oil pipe rise up again after main injection, if this pressure reach the thread value that could make the needle valve open once again which will make the oil that should not be injected get into the cylinder, this is called the secondary injection. Because the oil injected by the secondary injection can’t be combusted totally, the carbon black and hydrocarbon in the emission gas will sharply increasing, it will cause the carbon particulate more easily deposit on the wall of cylinder as well as increase the cost of oil. At the end of each cycle of injection, the pressure left in the high-pressure oil pipe will never be the same. The difference of pressure will cause unstable injection; this phenomenon appears more often within the low rotate speed area. If the unusual injection is severe, it may not only cause the non-uniform of fuel injection but also lead to a phenomenon of intermittent inject failure.

Diesel engine is being higher and higher regarded for people are now facing up with a more and more serious environment of lacking resource. Diesel engines however, have some significant problems when being used as vehicle engine, especially as saloon cars’ engine, such as the large noise and high exhaust of particulate matter (PM). During the working process of diesel engine, the time of injection is extremely short which costs only a few milliseconds due to the high rate of rotation of the engine, meanwhile, in the process of injection, the pressure of every point of the high-pressure oil pipe is fluctuated with the change of position and time. Besides, because of the compressibility of diesel itself, the real situation of fuel injection is quite different from the regularity of fuel supply of the ram pump controlled by high-pressure fuel pump. What’s more, the fluctuation of pressure in high-pressure oil pipe may also make the pressure of high-pressure oil pipe rise again after the main injection finished, if this

pressure is enough to force the needle valve of the injector open, the valve will open again and inject the gas, which should not be injected, into the cylinder and cause the secondary injection. Those gas injected by secondary injection will certainly not be combusted completely due to short time of combustion, thus this will significantly increase the content of Hydrocarbon (HC) and smoke within exhaust gas, and carbon deposition is more easily built in cylinder, these will increase the oil consumption. Besides, at the end of every injection cycle, the residual pressure in high-pressure oil pipe will always fluctuate which will cause unstable injection, the lower speed the engine operates on, the easier this problem happens. If the unusual injection is severe, it may not only cause the non-uniform of fuel injection but also lead to a phenomenon of intermittent inject failure. Through in recent years, with the new technology used on diesel engine, its comprehensive performancehas already been improved[2][3],the diesel engine meet a significant innovation when common-rail injection system came into use. The high-pressure common-rail injection system of diesel engine has been regarded as one of the three breakthroughs in 20th century[4], which has become the most commonly used fuel injection system in diesel engine.

II. INTRODUCTION OF HIGH-PRESSURE COMMON-RAIL INJECTION SYSTEM

High-pressure common-rail (HPCR) injection system is a new method of oil supply for diesel engine, it is a close-loop system that contained with high pressure oil pump, pressure sensor and electronic control unit (ECU). In this method, the build-up of inject pressure and the process of injection will be totally separated. Compared with the last two generations of injection system, the electronic common-rail injection system overcame the deficiency that oil pressure is influenced by engine speed. Common-rail system replaced the traditional piston pump with a commonly controlled oil pipe which is called Common-Rail. High pressure oil pump send oil to the pipe to maintain the pressure common-rail need. In order to meet the need of working condition, injection pressure is controlled by regulate the common-rail pressure continually. This also make it possible to control the pressure and speed of oil injection, meanwhile, the control freedom and accuracy of the system has been significantly improved [5].

There are three main parts in diesel engine high-pressure common-rail injection system: the low-pressure module, the high-pressure module and the electronic control module. The low-pressure module is the oil supply system; the high-pressure module is made up with high-pressure oil pump, oil rail (high-pressure accumulator),injector and oil pipe; the electronic control system contained with sensors, ECU, and actuators. The typical structure of HPCR injection system is shown in Fig.1.

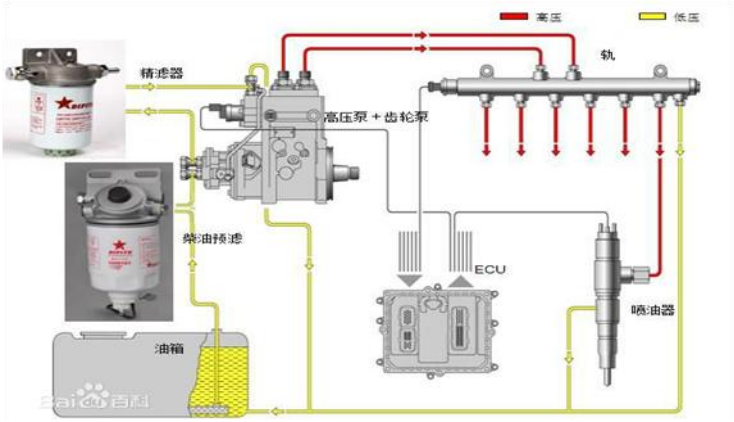

Fig.1 The typical structure of HPCR injection system

Diesel is pumped out from the tank by low-pressure oil pump, then it will be filtered and pumped into high-pressure oil pump under the control of the solenoid valve within the low-pressure oil pump. The pressure sensor equipped on common-rail will monitor oil pressure in real time and feed it back to ECU. According this pressure, ECU will calculate the best value of oil flow and send signal to oil pump to control the oil flow. According the need of injection pressure in different engine working conditions, the injection pressure is different from 200 to 1800 bar, then oil will be injected into the cylinder controlled by ECU. In this process, the common-rail not only maintains the oil pressure, but also eliminates the fluctuation of pressure.

III. THE CURRENT RESEARCH STATUS OF HPCR

Among the world, some reference enterprises and laboratories have studied HPCR technology for pretty long time, they have accomplished many achievements in this realm, there are many famous companies contribute to this research, such as BOSCH from Germany, FIAT from Italy, DELPHI from the US, NIPPONDENSO from Japan, LUCAS VARITY from the UK etc. [4][5] Among these companies, BOSCH made the most significant achievement. BOSCH replaced the high speed solenoid valve with piezoelectric quartz as actuator; this would

increase the injection pressure up to 180MPa, the speed of needle valve up to 1.3m/s, and made it possible to control the accuracy of oil pre-injection value to 1 mm3. As for control strategy, the open-loop control system and close-loop control system based on classical control theory and modern control theoryhave been widely used[6].

The research of HPCR injection system is now in the development phase due to its late start. Among these researchers, the FIRCRI HPCR system developed by Tianjin University is now in the phase of hardware in loop simulation and real machine test. The GD-1 HPCR system developed by Shanghai Jiao Tong University is now in the phase of preparation for matching up with YuChai 6110. Some universities such as Beijing Institute of Technology and Central China University of Science and Engineeringare also developing their own HPCR system. Weifu Group from Wuxi have cooperated with BOSCH to set up a new company called Wuxi BOSCH diesel engine system Limited and start to produce HPCR system. As for control strategy, the classic PID control is now commonly used in China. This control strategy is simple, easy to implement and stable, it also has some problems such as need to be regulated in different working conditions and it cannot be regulated online [7].

Now, the research of HPCR injection system in China is still in initial stage, diesel engine injection method is in transition of mechanical injection to electronic injection, which is relied on foreign technology. In order to improve the independent research and development capability of Chinese company, the core competence of China, we should pay much more attention on how to producing electronic injectors,hydraulic control valves, injector nozzle matching parts, high-speed actuators and the hardware/software of ECU etc. Researches on control strategy and its functions, the technique of matching and calibration, improve the stability and safety, reduce the cost must be valued[7].

IV. BOSCH HPCR INJECTION SYSTEM

Until now, BOSCH has designed and developed 3 generations of HPCR system. One of the BOSCH HPCR systems is shown in Fig.2.

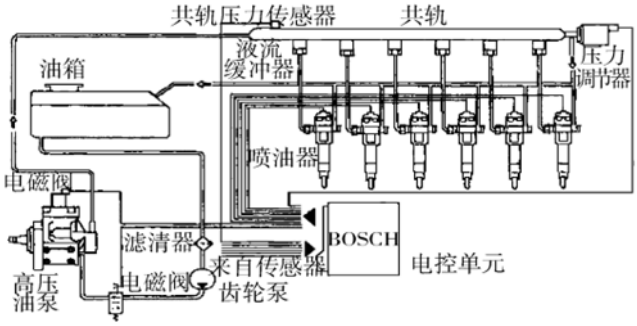

Fig.2 Bosch Hpcr injection system

A. The 1st and 2nd generation of BOSCH HPCR system

Fig.3 is the 1st generation of Common-rail injection system equipped on saloon cars, which were produced by Alfa Romeo and Mercedes-Benz, produced by BOSCH in 1997.Diesel is pumped from the tank by gear pump driven by camshaft of the engine, after being purified by the filter, diesel is sent to the high pressure pump under a pressure of 0.2MPa through an electric emergency disconnecting valve. Then oil is separated into two flows, one is sent to the lumen of camshaft to cool the regulation valve down and then flows back to the tank; the other is sent to the common-rail after being compressed by three plunger chambers until its pressure reaches 135MPa[8].This flow of oil is separated into two parts again, one is sent to the combustion room, the other is sent back to the tank through the opened solenoid valve. The structure of a high pressure injection pump with oil cutting device is shown in Fig.4.The valve is a radial Piston Pump made up with three pump parts driven by eccentric camshaft. There is a piston at the oil inlet of the valve which is controlled by spring. When the pressure forced on piston is low, the inlet is closed by the piston. The inlet will not open until the pressure is large enough. Based on this principle, together with the emergency disconnecting valve, they could cut the oil supply off in emergency situations. There is a bypass hole on the piston with spring;the cam shell is flushed by oil through the hole. There is an inlet valve and an outlet valve on every plunger matching parts, the consumption of the parts can be reduced by cut certain inlet valve off.

The injection module of common-rail system is made up of injector, control piston, control orifice and solenoid valve, the structure of the module is shown in Fig.5.When the solenoid valve is powered off, the valve will close the orifice A on the top of control piston, the injector is forced close by the pressure forced on the piston build by common-rail. When the solenoid valve is powered, the orifice A is opened, the pressure in control room will reduce sharply, the control piston rises up, the injector begins to inject; When the solenoid valve is closed, the pressure in control room will rise again and force the piston went down and close the injector to finish the injection. The spring on injection module is used to avoid the backflow of fuel when the pressure of the common-rail has not

been built.

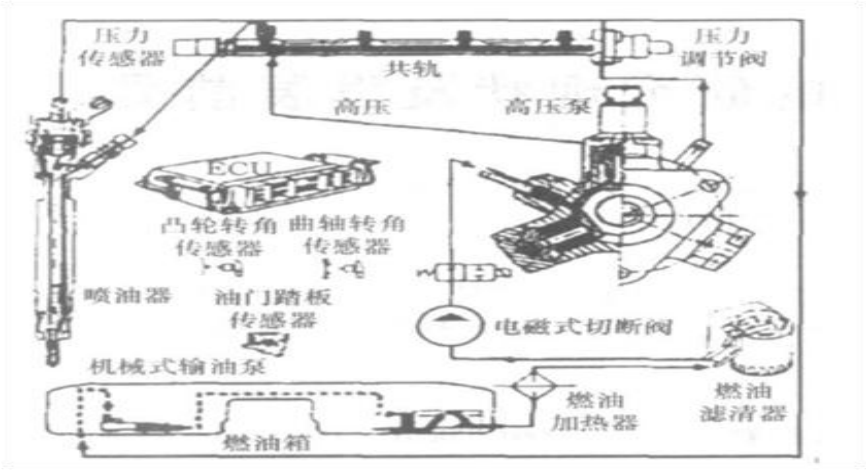

Fig.3 The 1st generation of BOSCH HPCR system

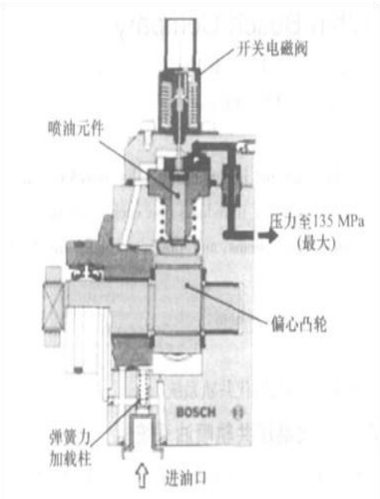

Fig.4 BOSCH high pressure pump

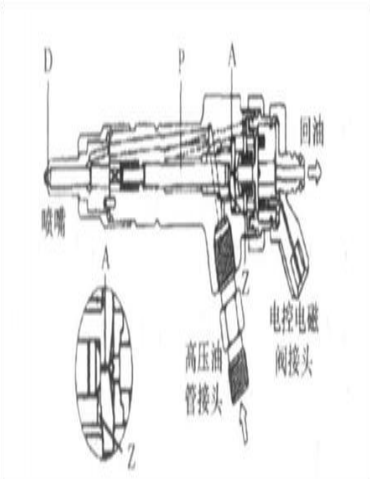

Fig.5 BOSCH injector

The pipe of common-rail is a kind of forging part on which equipped pressure sensor and pressure regulating valve used to regulate the pressure of the common-rail. The regulating value, which is shown in Fig.6, controls the open and close of globe valve’s inlet by the force of spring. The force is strengthened by magnet which is controlled by duty cycle of related signal. Common-rail is connected to high-pressure pump and injector through high-pressure oil pipe with larger internal diameter. The volume of common-rail can keep the pressure fluctuation caused by oil pump and oil injection as small as possible, meanwhile it can also help to build the pressure quickly when engine is starting.

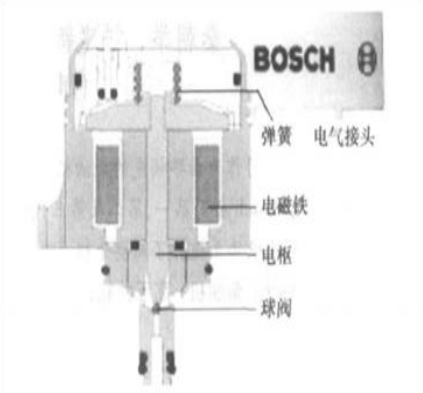

Fig.6 BOSCH pressure regulating valve

Fig.7 The injector of 3rd BOSCH HPCR system

BOSCH made their 2nd generation HPCR injection system into mass production in 2000(equipped on vehicles produced by Volvo and BMW). This generation of system made the maximum pressure up to 160MPa, there were also many new technologies used on it such as high-pressure pump with oil regulator, updated solenoid valve injector and multiple injection. This kind of system has higher injection pressure, compactly injector, smaller size, small fluctuation of oil injection; it also used close-loop control and multistage injection technology.

B. The 3rd generation of BOSCH HPCR system

Which is shown in Fig.7 is the 3rd generation HPCR injection system BOSCH made into mass production on May, 2003(equipped on vehicles produced by Audi). This was a breakthrough in realm of diesel common-rail injection technology. Injection pressure is the characterization parameter of the 1st and 2nd generation system, the injection of 1st system can reach to 135MPa, 160Mpa the 2nd generation can reach. For the 3rd generation, the characterization parameter is high technology. The pressure of this generation is maintained on 160Mpa. Due to the use of highly integrated piezoelectric injector, the piezoelectric actuator is more close to the needle valve, which make the hydraulic response time of the system more reasonable. The mass of injector's moving parts has been decreased by 75%; the number of parts in needle valve has decreased from 4 to 1.Thus, the response time of the piezoelectric injector is twice quicker than any other electromagnetic injector. In old common-rail system, the injection process can only be separated into 5-7 parts; it can be separated into any amount of parts in the 3rd generation. Through the quantity of oil set for partial load is decreased, the accuracy is increased. According to BOSCH, the result of this change is the exhaust decreased by 15%-20%, the power of engine increased by 5%-7%; the noise decreased by 3dB (A) [9]. In late 2006, BOSCH produced a new HPCR system which injection pressure can reach up to 180MPa, could be a new choice for more powerful and more limited designed emission diesel engine.

What shown in Fig.8 is a system structure of 3rd generation common-rail system for V6 diesel engine [10]. Oil is sent to high-pressure pump with oil regulator by low-pressure electric oil pump. The allocation unit separates the oil into to flows, one flow is sent to the pump, the other flow is used to cool the transmission structure and lubricate the gear. The oil is sent to common-rail after its pressure is built to 160MPa by the high pressure oil pump. The pressure sensor tightly equipped on the rail can get the pressure of common-rail in real time;the allocation unit integrated on high pressure pump can regulate the quantity of oil based on this pressure. The pressure regulation valve is used for sending more quantity of oil to the injector in acceleration condition. This valve is controlled by ECU according to working condition to regulate the start time and duration of injection; it can also shape the injection curve (the phase, inject time and quantity)softy. The pipe of common-rail takes high strength modular laser welded rail (LWR) as structure method, its surface coating is off with Cr^{6+}. In order to regulate the pressure of the oil rail, two sides of the rail are both equipped the newest pressure sensor and pressure regulation valve.

C. The next generation of BOSCH HPCR system

As for the 4th BOSCH HPCR injection system which is still in developing phase, its important characteristic will be changeable coaxial injector and supercharger of oil [11]. Compared with classic injector, the changeable coaxial injector will be totally different in orifices, including number, location,diameter, shape etc. The classic injector has 5-7 one-channel orifices, oil is sent to combustion room only by single open/close control. The changeable coaxial injector shown in Fig.9 has two coaxial needle valves meshed by a piezoelectric actuator, the open/close of two sides of orifices are controlled individually. The first side of orifices are lower flow ones, they supply the little amount of oil which is needed in the early phase of combustion, this can make the combustion process more stable, thus the noise during combustion will be decreased. Besides, it can also help to make the fuel mix better with air in partial loadcondition, this will decrease the emission significantly, an experiment showed that the noise has been decreased distinctly; the exhaust of HC and NOx has been decreased by 70%. When the engine is in full load, the second side of orifices with bigger diameter will open, this make it possible to inject accuratelyquantity of oil into the combustion room in a very short time, this can meet the need of the largest power of diesel engine.

BOSCH is developing another kind of common-rail system with hydraulic intensifier. The design is that the high pressure oil pump force the oil into common-rail until its pressure reaches 135MPa, then the oil flows through high-pressure oil pipe into the injector, after flowing over a special convert piston, the pressure of oil will increase to more than 250MPa. Due to the high pressure, a large amount of oil that the combustion need could be inject through very tiny orifices, which means the thin spray of oil will be more easily to mix with the air, the combustion will surely be cleaner and more efficient [13].

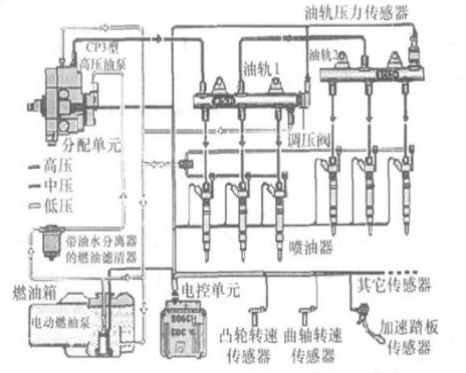

Fig.8 The system structure of 3rd BOSCH HPCR system

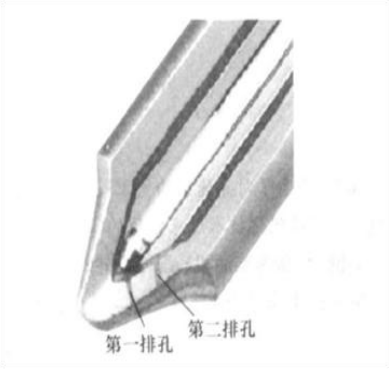

Fig.9 The changeable coaxial injector

V. CONCULSION

Engine is the heart of vehicle, improve the performance of engine is the best and important way to increase the capability of the vehicle. How to make the engine operate more stable, efficient, flexible is the most important question we are going to solve. In diesel engines, high-pressure common-rail injection system is the best way to improve the capability of combustion and emission, the pressure of injection can now be increased up to over 200Mpa, on a certain rate, the larger pressure the injection built, the accurate the quantity of oil will be injected, the more efficientthe engine will be, and the less exhaust of PM and HC will be. The present situation of the research on HPCR system in China is not so satisfactory, thus, we need to pay more attention on this research to help our country's engine manufacture industries have the ability to stand against the world.

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