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Analysis of homogeneous charge compression ignition combustion strategy and its current application

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Abstract. Under the pressure of energy and environmental problems, people's demand for high-efficiency and low-pollution power sources is becoming more and more urgent. In this case, the HCCI combustion engine was developed. A new combustion method combining premixed combustion gas and low-temperature combustion was developed: it relies on a uniform formed mixture by premixed combustion gas and the lower cylinder temperature when combustion happened to reduce PM and NOX emissions simultaneously. The HCCI combustion adopts high compression ratio ignition and multi-point combustion in the cylinder, which makes its lean mixture have high thermal efficiency, and the engine performance can reach a better condition.The research and development goal of HCCI technology is to surpass compression ignition and spark ignition engines in performance and emissions. Because HCCI engine has the advantages of the first two, and its emission control system only needs to rely on its own operating characteristics and emission characteristics to reduce pollutant emissions.So if HCCI combustion can be truly mature and commercialized on a large scale, it will be a major innovation in the development history of internal combustion engines.

Keywords: Energy and environmental problems, Power sources, HCCI combustion engine.

1. The first section in your paper

With the rapid development of society, the increasing number of vehicles not only provide convenience to people's life, but also promote the vigorous development of social production efficiency [1]. But at the same time, under the pressure of energy and environmental problems, people's demand for high-efficiency and low-pollution power sources is becoming more and more urgent, especially the requirements for the engine with high performance and low emission are becoming more and more strict [2]. At present, there is still a big emission problem in the combustion process of the traditional diesel engine. During the combustion process, the emission of NOX and PM can not be effectively suppressed at the same time, because NOX is mostly generated under high temperature and oxygen enrichment conditions, but the generation of NOX is suppressed by reducing the combustion and emission temperature, which is not good to the oxidation reaction of PM [3]. Therefore, although this method can suppress NOX production, it makes carbon smoke emissions increase instead [4].

In this case, a new combustion method combining premixed combustion gas and low-temperature combustion was developed: it relies on a uniform formed mixture by premixed combustion gas and the lower cylinder temperature when combustion happened to reduce PM and NOX emissions simultaneously. This combustion mode is called Homogeneous Charge Compression Ignition (HCCI).

2. HCCI combustion

2.1. HCCI theory

The HCCI theory mainly improves the temperature and pressure of the gas mixture in the cylinder by increasing the compression ratio, using exhaust gas re-circulation, intake air heating and supercharging, and forms multi-point ignition in the cylinder to promote the homogeneous gas mixture to burn uniformly and stably [5]. The combustion in the cylinder of HCCI is more uniform and stable which is different from the single point ignition mode of the normal internal combustion engine [6]. It also reduces the propagation of flame and combustion duration, therefore, effectively suppressing vibration and impact during combustion. Thereby, ignition and combustion process of HCCI engine is essentially different from that of traditional spark ignition and compression ignition engines (Fig.1). The appearance of HCCI combustion effectively suppresses the shortcomings of the traditional homogeneous gas ignition combustion, such as slow combustion speed, incomplete combustion and non-uniform combustion [7].

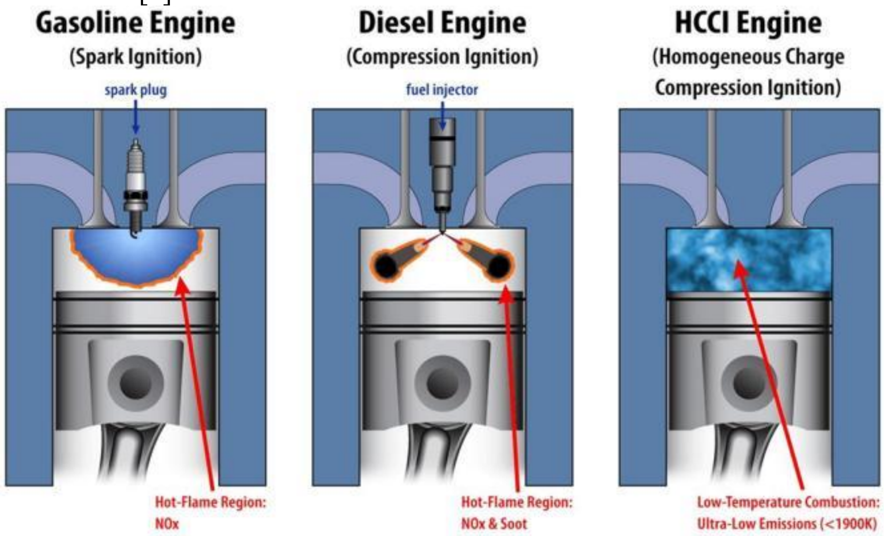

Figure 1. Three types of ignition.

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2.2. Characteristics of combustion

2.2.1. Homogeneous mixture. The homogeneous mixture of most HCCI engines is premixed in the gas intake system and sucked into the cylinder for compression and combustion. There are also fuel injected directly into the cylinder and mixed with air in the cylinder [8].

2.2.2. Compression ignition. In the compression stroke, a series of pressurization measures such as piston compression raise the temperature of the mixture to reach the spontaneous combustion temperature and ignite.

2.2.3. Higher compression ratio. The compression ratio of HCCI engine is generally much higher than that of ordinary spark ignition engine (SI) [9]. Because HCCI needs to ensure that the mixture can ignite spontaneously, and SI engine has an spark ignition system to help the mixture ignite .So that the compression ratio of HCCI is higher. In addition, the mixture of HCCI is very thin(lean) compared with that of ordinary engines (its air-fuel ratio can be 2-3 times larger than that of ordinary engines). Therefore, HCCI needs to provide a larger compression ratio in order to make the mixture burn spontaneously.

2.3. Advantages

2.3.1. Excellent power generation and fuel consumption. HCCI adopts high compression ratio ignition and multi-point combustion in the cylinder, which makes its lean mixture have high thermal efficiency, and the engine performance can reach a better condition. At the same time, the content of air in the lean mixture is too high, so the specific heat of gas mixture can be very high, which will make the power performance of the engine to be correspondingly better. High power performance and fuel economy can be maintained at the same time.

2.3.2. Less pollutants. HCCI combustion can reduce the emission of NOx and PM at the same time, because it can maintain the combustion temperature below 2000K by using lean mixture or EGR (Exhaust gas re-circulation) system. At the same time, due to the homogeneous mixture and multi-point simultaneous ignition in the combustion chamber under the action of piston compression makes the combustion more uniform and reduces the flame propagation distance and combustion duration. So that the temperature in a certain part of the combustion chamber is prevented from being too high and NOx emission can be greatly reduced [10].

Since there is no ignition system, HCCI engines only rely on compression to ignite the fuel mixture. Therefore, the combustion of the mixture is only related to its physical and chemical properties, and is not affected by the ignition system parameters. Its combustion parameters are only controlled by the chemical reaction of fuel oxidation At the same time, because the mixture used is relatively lean and the homogeneous premixed mixture process is relatively simple, the HCCI combustion mode can simplify the combustion system and combustion chamber structure of the engine.

3. HCCI in practical use

3.1. Control strategies of HCCI engines

The temperature in the cylinder has a great influence on the ignition of HCCI engine. Low temperature makes HCCI engine easy to misfire, resulting in insufficient power generation; If the temperature is too high, the ignition will be advanced. So the combustion duration will be shortened and the cylinder will knock. Therefore, the combustion temperature control of HCCI engine is very important, and the ignition time needs to change with the change of engine operating conditions. There are various strategies to achieve the goal.

3.2. Fuel supply and combustion control strategies

3.2.1. Direct injection. Direct injection is one of the most effective means to control engine combustion temperature. Direct injection can form different kinds of combustion mixture in the cylinder to match different working conditions, by changing the injection time, injection amount and injection ratio. “Injection in advance” can gain more time for fuel evaporation and to form a homogeneous mixture; “Late injection” delays fuel injection after TDC. It can use EGR and high swirl ratio at the same time to extend ignition delay duration and improve mixing rate, so that fuel injection can be completed by these ways and the temperature will be controlled.

So the direct injection can effectively increase the compression ratio, thereby expanding the engine's payload range. It also provides the ability to control the combustion phase under different conditions.

In addition, the direct injection technology can inject a small amount of fuel into the cylinder during the NVO (Negative Valve Overlap) period and mix it with the high-temperature exhaust gas in the cylinder, which can greatly reduce the fuel self-ignition temperature and improve the HCCI ignition performance and combustion stability. Moreover, the pre-injection can play a good role in regulating the ignition starting point and combustion rate of HCCI, making it possible to precisely control the combustion of HCCI.

3.2.2. Intake gas pressurization. Intake air pressurization is considered to be one of the most effective methods to expand the working range of HCCI engine. The HCCI engine's operating range will broaden to the heavier and lighter load when the inlet pressure increased or decreased. Fig. 2 shows the engine load in different pressures and various exhaust valve timings.

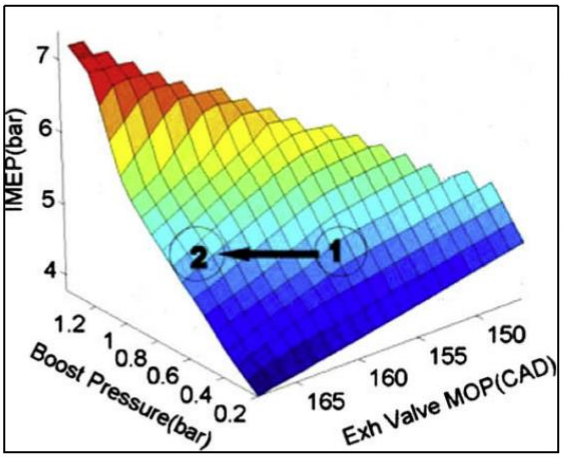

Figure 2. The engine load in different pressures and various exhaust valve timings.

Supercharging can significantly increase the average pressure in the engine cylinder. And turbocharging produces less power loss than supercharging, and has better efficiency than non-supercharged engines. So charge boost can expand the load range of HCCI engine.

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3.2.3. Variable compression ratio. A higher compression ratio can increase the temperature of the mixture during ignition, thereby reducing the demand for inlet air temperature, increasing the intake air density and increasing the power generation. However, for fuels with poor anti-knock performance, increasing the compression ratio will easily lead to engine detonation and cylinder knock at high load. Therefore, in order to meet the requirements of different loads of vehicle engines, variable compression ratio (VCR) technology can be used for engines. In addition, HCCI engines also use VVT (Variable Valve Timing) technology to change the closing time of the intake valve to change the compression ratio.

3.2.4. EGR. EGR can rise the inflation temperature to the ignition temperature. The residual exhaust gas in the cylinder stores a large amount of compounds, which can make the ignition of the mixture happens in advance; At the same time, EGR enables significant increase in engine power output. This supplementary of cold gas helps to delay ignition. And the inert gas in the exhaust gas slows down the chemical reaction when combustion happened and increases the specific heat of the mixture, thereby inhibiting rapid combustion, reducing the maximum combustion pressure, and improving the anti-knock ability of HCCI under high load.

4. Future development of HCCI engine

4.1. Goals of HCCI

The research and development goal of HCCI technology is to surpass compression ignition and spark ignition engines in performance and emissions. Because HCCI engine has the advantages of the first two, and its emission control system only needs to rely on its own operating characteristics and emission characteristics to reduce pollutant emissions, HCCI does not need to face the challenges of NOx and PM emissions and fuel purification. The traditional compression ignition engine will be difficult to meet the future harmful NOx and PM emission standards.

4.2. Research directions in future

4.2.1. Instant combustion mode switching. It can be applied different ignition methods in different combustion phases, so that engines will find a best working conditions under different loads, so as we call this ---- The Dual Combustion which is feasible and reasonable. Spark ignition or compression ignition is used for startup and heavy load, because this will request a very high torsion, and HCCI combustion mode is for idling and partial load so that it can save unnecessary fuel consumption and reduce emissions. Combining the dual combustion technology with EGR, the emissions of PM and NOx will reach a very low level. Because of the homogeneous combustion mixture, the characteristics of the ordinary gasoline engine with high power consumption are still the same on the HCCI engine; On the other hand, the throttling loss is eliminated because of without any spark generation components. The multi-point simultaneous ignition combustion mode makes the energy release rate in a rapid pace, which is similar to the ideal constant volume combustion, so the thermal efficiency can reach a considerable level. Maintaining the characteristics of good fuel economy under partial load of the diesel engine.

4.2.2. Wider operating range. HCCI engine can perform very well under medium and low load. However, at high load, the mixture is enriched, the combustion speed will be much faster, so the pressure will rise in a rapid pace, which leads to detonations of cylinder. At the same time, the emission of NOx will maintain in a unfavourable level due to the rapid raising of the temperature inside of the cylinder; Also, the thermal efficiency when combustion happened under light or idle load is too low and it is going to be very hard to ignite the combustion mixture. In this case, HCCI combustion is limited from an extreme operating condition.

The operational range of HCCI combustion also needs to be extended to the low load range to improve the stability of HCCI combustion, fuel economy and emission performance at low load, including low idling and start-up conditions.

4.2.3. Precise ignition control. The ignition timing of internal combustion engine is controlled by spark ignition or fuel injection, while the ignition HCCI engine is determined by the auto-ignition characteristics of air and fuel mixture. In a wide range of speed and load, especially in the fast transient conditions, the control of HCCI engine ignition timing has become a major challenge. To solve this problem, the solution of control the ignition timing is being proposed. The temperature and composition of the mixture in the cylinder are adjusted by directly adjusting the intake air temperature and changing the EGR rate. The residual exhaust gas volume and effective compression ratio in the cylinder are changed by variable valve timing (VVT). The fuel injection timing (in the direct injection system) and the use of fuel additives change the activity of the mixture. Variable compression ratio and variable valve timing are the most promising, but further research is needed in terms of cost and feasibility. The temperature of the mixture at TDC is controlled by variable compression ratio (VCR).

5. Conclusion

HCCI combustion can be controlled through EGR, supercharging, direct injection in cylinder and other means. The operation range of HCCI can be expanded through the cooperation of various technologies, and its combustion can be effectively controlled gradually. The research and development goal of HCCI technology is to surpass compression ignition and positive ignition engines in performance and apply it to high load engines. The realization of this goal must depend on the solution of such technical problems as fast and reliable combustion mode switching, accurate control of ignition, widening of operating range, and separate cylinder closed-loop independent control.

The improvement of the combustion mode also will be the most important tasks in the future though the electrical motor is taking the high ground. In the pursuit of lower the emission of the combustion engine, improve the thermal efficiency and gain a broader operational range, the HCCI combustion must be a key solution for the revolution of internal combustion engines. If HCCI combustion can be truly mature and commercialized on a large scale, it will be a major innovation in the development history of internal combustion engines.

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