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Homogeneous Charge Compression Ignition (HCCI) Combustion: Combustion Process and Control Strategies

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Abstract: *Homogeneous Charge Compression Ignition (HCCI), a low temperature combustion technology, is believed to be a promising technology due to low NOx and PM emissions and better fuel economy. HCCI combustion can realize homogeneous charge preparation in the cylinder and promote combustion auto-ignites in multiple spots by cooperative control of fuel chemistry and boundary conditions, such as Intake temperature, pressure, mixture concentration and EGR, which can short the flame propagation distance and accelerate the ignition and combustion speed. HCCI combustion control technology can be divided into two categories: one is to change the air/fuel mixing characteristics; the other is to change the working and design parameters of the engine. This paper reviews the establishment, improvement and development of HCCI combustion indirect control technology through the experimental research results of researchers in recent years.*

Keywords: *Diesel engine, HCCI, Combustion Process, Control Technology, Heat Release Rate*

1. Introduction

Homogeneous Charge Compression Ignition (HCCI), as a new combustion technology, has attracted wide attention due to its high thermal efficiency and low oxides of nitrogen (NOx) and particulate matter (PM) emission. Compared with the spark ignition (SI) of gasoline engines and compression ignition (CI) of diesel engines, HCCI combines the advantages of SI and CI, which can improve the power performance and fuel economy of the engine, and greatly reduce the emission of NOx and PM. In the traditional spark ignition engine, the homogeneous charge is ignited by the spark plug, and the flame front propagates in the homogeneous charge. The local temperature of the flame front and combustion products is much higher than other unburned mixture, which leads to combustion process and temperature distribution being very uneven, and the significant formation of NOx in the local high temperature. Diesel engine is diffusion combustion, the chemical reaction rate is much higher than the fuel and air mixing and diffusion rate, combustion speed is determined by the mixing and diffusion rate. In this type of combustion, the mixture and temperature distribution are very uneven, and accordingly, the high temperature oxygen-rich zone produces NOx, and high temperature anoxic zone produces PM. The above two traditional combustion methods have the problem of uneven temperature distribution, which is local high temperature and overall average low temperature [1].

Characteristics of high viscosity, low volatility and low spontaneous combustion temperature of diesel oil limit the development of HCCI combustion process and combustion control technology using diesel fuel. At the same time, the high vaporization temperature and low intake temperature of diesel fuel make it difficult to form a homogeneous mixture. In addition, the spontaneous ignition temperature of diesel fuel is low. If the compression temperature exceeds 800 K, there will be obvious pre-flame reaction, leading to earlier burning time and faster burning rate. Therefore, the first condition for the realization of HCCI combustion in diesel engine is the preparation of mixture, including the improvement of the mixing rate of fuel and air to achieve rapid mixing. At the same time, whole-process control of mixture concentration and composition and the whole-process combustion temperature is needed. In addition, the control of the combustion process and the ignition time of HCCI are equally important. On the one hand, it is to control the start of combustion (SOC) which occurs near TDC. On the other hand, it is to control the heat release rate of combustion to avoid rough combustion and knock. Many researches have been conducted to investigate HCCI and have been made a lot of progress in HCCI combustion technology.

The combustion process of HCCI is mainly controlled by chemical kinetics [2]. The research shows that spontaneous combustion of a fuel depends mainly on its composition, molecular size and structure. Meanwhile, the nature of the mixture and the change of temperature in the cylinder also affect the spontaneous combustion of the combustible mixture. Therefore, the factors affecting the combustion process of HCCI include the spontaneous combustion characteristics of the fuel, the fuel concentration, the residual exhaust gas rate, the reactivity of the residual exhaust gas, the homogeneity of the mixture, the compression ratio, the inlet temperature, the latent heat of the fuel vaporization, the temperature in the cylinder, the heat transfer of the wall around the cylinder, and other parameters related to the engine. Since the HCCI combustion occurs almost simultaneously, it can be controlled by an indirect method. There are two types of indirect control of HCCI combustion: one is to change the air/fuel mixture characteristics, such as intake temperature, air fuel ratio, EGR and fuel properties. The other is to change the operating and design parameters of the engine, such as variable compression ratio, variable valve timing, supercharge and the use of different fuel injection methods.

As HCCI combustion technology has the potential to replace conventional CI or SI engines, this paper aims to review peer-reviewed articles, which report recent advancements of combustion control methods and expansion of operating range of HCCI. This review focuses on improving HCCI combustion and emissions by more appropriate fuels and indirect control of combustion boundary conditions, such as fuels with different physical and chemical properties, reactants such as ozone and nitric oxide, injection strategies, intake pressurization, EGR, variable valve mechanism, intake heating, fuel modification, etc.

2. Changes in Air/Fuel Mixing Characteristics

2.1. Intake Temperature

Higher intake temperature can lead to higher heat release rate and advance the ignition of the first stage cold flame shortening the ignition delay. Adjust the intake temperature is a common method to achieve HCCI combustion and ignition time control. Higher intake temperature can promote HCCI combustion, but the adjust range is limited. Thus, outside the adjust range, the ignition time too early will cause a large negative work on the piston, which will lead to a significant reduction in the volume efficiency and thermal efficiency of the engine. Christensen [3-6] et al. controlled the HCCI combustion process by combining adjusting the intake temperature and changing other parameters.

2.2. Air-Fuel Ratio

The air-fuel ratio directly affects the ignition time and heat release rate of HCCI combustion. HCCI combustion rate can be controlled well under the conditions of high air fuel ratio and high EGR rate, which can stable HCCI combustion. However, too high an air-fuel ratio will cause misfire, and too low an air-fuel ratio will cause knock. Therefore, the variation range of the air-fuel ratio is limited.

2.3. Exhaust Gas Recirculation (EGR)

There are two methods for EGR to control HCCI combustion process: internal EGR and external EGR. Internal EGR has two effects on HCCI combustion, namely, thermal and chemical effects. Therefore, the effect of EGR on HCCI combustion is the result of the combined action of thermal and chemical action. The thermal action is associated with the high temperature of the EGR, which increases the temperature of the total intake charge, making it more likely to ignite, and thus to ahead of ignition timing. The chemical action comes from the types of chemical activity that EGR contains. When the intake temperature is maintained constant, the more chemical active species EGR contains, the earlier ignition occurs. When the quantity and mass of EGR are fixed, the higher the intake temperature causes the earlier Ignition timing. Accordingly, mixing the air/fuel mixture with thermal EGR can increase the engine charge temperature in the combustion process. The ignition delay and heat release rate of HCCI combustion can be controlled by adjusting the amount of EGR.

Compared with the internal EGR, the external EGR tends to have a lower intake temperature by external cooling, which reduces chemical reaction rates, delays ignition timing, and reduces the heat release rate and the peak cylinder pressure. Based on the study of external EGR, Christensen et al. found [7] that under the conditions of engine compression ratio of 18.1, indicated mean effective pressure (IMEP) of 0.5 MPa and intake temperature of air/fuel mixture of about 120 C, 110 C and 150

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C, respectively. Stable HCCI combustion can be achieved by using 57 % EGR in isooctane, 62 % EGR in ethanol and 48 % EGR in natural gas. When the fuel is diesel, stable HCCI combustion can be achieved with a certain load range at higher air/fuel intake temperature (175 C~240 C), lower compression ratio (8:1), and EGR of 50%. Yoshinori Iwabuchi et al. studied the influence of EGR on the combustion process of HCCI and found that the ignition time was delayed with the increase of EGR rate, and this trend became more obvious when the fuel-air equivalence ratio (Φ) was 2 or lower.

2.4. Additives

In the first stage of combustion, some chemicals have the ability to delay or increase the heat release rate. Therefore, the composition of the fresh charge of the engine changed by additives will affect the combustion heat release of the first stage of HCCI, and then affect the combustion characteristics of the main combustion period. DME, when mixed with conventional fuels, can increase the heat release rate of the first stage ignition and stabilize HCCI combustion due to low octane number. The test results of a dual fuel engine show that adding DME can improve the combustion of HCCI [7,8]. Water can be used as a potential additive due to its inactive chemical properties, which can also affect the ignition time and heat release rate of HCCI combustion. The test results [9] show that water spraying in the cylinder can delay the ignition time of HCCI combustion and slow down the heat release rate, but this only operates within a narrow load range and also causes an increase in the emissions of unburned hydrocarbon (UHC) and carbon monoxide (CO).

2.5. Mixtures of Different Fuels

The physical and chemical properties of fuel play a decisive role in the combustion process of HCCI, of which the composition, molecular size and structure of the fuel will directly affect the spontaneous combustion characteristics of the fuel. Therefore, mixing of different fuels can better adapt to HCCI combustion and control the combustion process. Since HCCI combustion is homogeneous charge compression ignition, it requires not only the formation of homogeneous mixture but also the higher octanes number and lower boiling point of the fuel. Studies show that HCCI can be applied to a variety of fuels, of which gasoline, diesel, alcohol and natural gas have significant effects on HCCI combustion and emissions. The conventional fuel octane number cannot represent the knock resistance of HCCI [10], so lowering the octane number of gasoline and the cetane number of diesels at the same time is more conducive to expanding the operating range of HCCI [11,12]. Since the HCCI operating range of alcohol fuel is larger than that of gasoline, adding some alcohol fuel into gasoline can significantly expand the HCCI operating range.

Compression ignition requires high ignition property of fuel, namely high cetane number. For this reason, if a special fuel suitable for HCCI combustion can be prepared in advance, the combustion process will be better controlled. Mixing fuels with different spontaneous combustion characteristics can greatly change the combustion performance of HCCI. Methane HCCI operating range can be extended and emissions can be reduced by mixing DME with methane, especially at low load. However, an inappropriate fuel mix ratio can also limit the operating range of the HCCI engine. Experimental studies show that the range of air fuel ratios suitable for HCCI combustion for mixed fuel is narrower than that for pure diesel with the compression ratio increases.

2.6. Fuels Reformation

Fuel reformation is an effective way to extend the operating range of HCCI engine. Fuel reformation can provide additional active radicals to the homogeneous combustible charge, so that the chemical reaction path of the homogeneous combustible charge in the cylinder can be changed, and the ignition time can be accurately controlled, which is conducive to the expansion of the operating range of HCCI engine. In addition, the mixed fuel also plays a role in the expansion of the operating range of HCCI engine. In addition, the dual-mode operation scheme is also a research hotspot expanding the operating range of HCCI engine, of which HCCI combustion mode is used under medium and low load conditions to effectively utilize the combustion advantages of HCCI and then switch to traditional ignition and compression ignition under large and too low load conditions. However, the use of this operation scheme will make the engine more complex.

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3. Changes in Engine Operating and Design Parameters

The aim of changing engine operating and control parameters is to optimize HCCI combustion by changing the temperature variation of the engine charge to adapt different engine operating ranges.

3.1. Compression Ratio

The higher compression ratio can increase the inlet terminal temperature and advance the ignition phase of HCCI combustion. Besides, the higher compression ratio and expansion ratio contribute to the improvement of thermal efficiency. However, knock is a problem when high compression ratios are used, especially with lower octane number fuels. Christensen et al. proved that almost any liquid fuel can adopt HCCI mode under the condition of variable compression ratio by adjusting the intake temperature without the use of EGR and fixed excess air ratio (λ=3) [6].

3.2. Engine Speed

The ignition delay of an HCCI engine is largely dependent on the degree of air/fuel mix and is less affected by the engine speed. However, the ignition time is closely related to the engine crankshaft Angle, in which when the engine speed increases, the ignition time is delayed. When the ignition occurs before TDC, the increase of the mixture compression temperature will compensate for the ignition delay caused by the high speed. However, when the ignition occurs after TDC, the increase of the speed will cause a significant lag in the ignition timing or even misfire.

3.3. Variable Valve Timing

Lotus University controls the HCCI combustion process through variable valve timing. The internal combustion engine can take in a certain amount of residual exhaust gas during the intake stroke by changing the valve timing of the engine. Sequential or simultaneous inhalation of EGR and fresh charge are the two basic modes of using variable valve timing. The sequential intake of EGR and fresh charge is to retain a certain amount of residual exhaust gas by prematurely closing the exhaust valve. During the later exhaust stroke, the residual exhaust gas remaining in the cylinder is compressed. When the piston runs down in the intake stroke, the intake valve opens, and fresh charge enters the cylinder and mixes with the residual waste gas. The simultaneous intake of EGR and fresh charge is when the piston reaches BDC in the expansion stroke, the exhaust valve is opened and all exhaust gas is discharged from the cylinder. When the piston passes TDC in the intake stroke, the intake valve and exhaust valve open at the same time, and fresh charge and exhaust gas are drawn into the cylinder at the same time. When the piston passes BDC, the intake and exhaust valves close at the same time, and the fresh charge in the cylinder mixes with the inhaled exhaust gas and enters the compression stroke. The use of variable valve timing enables low specific fuel consumption in lean mixture conditions while reducing pollution emissions.

3.4. High Boost Pressure

Supercharging or turbocharging is used to increase the indicated mean effective pressure of the engine and to extend the air-fuel ratio range of HCCI combustion. Under different compression ratios and inlet pressure conditions, the test results of different fuels show that under the condition of maintaining the inlet temperature constant, the pressurization increases the indicated average pressure and expands the range of air fuel ratio in engine operation. However, too high inlet pressure will cause a significant increase in the pressure in the cylinder, which is also not conducive to the stable operation of the engine.

3.5. Heavy Oil Injection

When using inlet injection, non-volatile fuels, such as diesel, often cause high HC and CO emissions and high fuel consumption due to inadequate atomization process and wall adhesion effect in the combustion chamber. Therefore, researchers have conducted a lot of research on in-cylinder direct injection HCCI. In general, there are two types of in-cylinder direct injection, early in-cylinder direct injection and late in-cylinder direct injection. Early in-cylinder fuel injection is the injection of fuel into the cylinder before the TDC. In this case, the injection advance Angle of the engine is much larger than that of conventional diesel engines, allowing the diesel and air to be fully mixed before ignition. Fuel

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injection can be used as an ordinary diesel injector, but also through a special injection valve to achieve. Late in-cylinder fuel injection is a process in which diesel fuel is injected into the cylinder near or after the TDC of compression, and the ignition delay is achieved by increasing pre-cooled exhaust gas recirculation (EGR), enhancing the eddy current and reducing the compression ratio, and finally, make sure the ignition happens right after the fuel injection is over. Although the mixture formed in the cylinder by the late in-cylinder direct injection is not as homogeneity as that of the inlet injection and the early in-cylinder direct injection, the NOx and soot emission is still lower than that of the traditional diesel engine.

3.6. Spark Plug to Assist Ignition

The spark plug assisted ignition can effectively avoid the HCCI knock combustion at the high load and obtain more output power. Besides, the spark plug assisted ignition before the spontaneous combustion of the homogenous combustible mixture can enhance the combustion stability and greatly reduce the occurrence of misfire. The spark plug assisted ignition can achieve two-stage exothermic combustion of combustible mixture, which has become a hot direction of HCCI combustion.

In general, achieving stable HCCI combustion within the full load range of the engine is very difficult. However, the optimization and integration of the above mentioned methods are expected to achieve further control of HCCI combustion under partial load. To achieve successful commercial applications, problems such as controlling the ignition time and combustion rate within the full load range of the engine must also be addressed.

4. Results and expectation

Energy conservation and environmental protection has always been one of the driving forces to promote the research progress of internal combustion engine combustion technology. As a hot research topic in the field of global internal combustion engine, homogeneous compression ignition still has many obstacles, such as narrow operating range, excessive HC and CO emissions, excessive cyclic fluctuations, etc. The research work on HCCI combustion technology can draw the following conclusions.

The advanced mixture control strategy is more important than the simple homogeneous mixture in the HCCI combustion process control. The control of the thermal stratification, concentration and composition of the mixture throughout the combustion process is the key to realize the efficient and clean combustion of internal combustion engine.

Indirect control of HCCI combustion process is an effective method due to HCCI combustion being almost synchronous. Methods for indirect control of HCCI combustion are divided into two categories: one is to change the air/fuel mixture characteristics, such as intake temperature, air fuel ratio, EGR and fuel properties. The other is to change the operating and design parameters of the engine, such as variable compression ratio, variable valve timing, supercharge and the use of different fuel injection methods.

The research of effective methods to control the combustion process of HCCI in the full load range of the engine still has a wide space. The control of HCCI combustion process has become a hot topic in the research of HCCI combustion mode. To achieve widespread use of HCCI combustion, problems such as controlling the ignition time and combustion rate within the full operating load range of the engine must also be addressed.

The study of turbulent mixing and chemical kinetic coupling as well as their effects on the formation of harmful products and thermal efficiency is also important in homogeneous compression combustion and low temperature combustion processes. From the microscopic point of view, however, the non-uniform components in the homogeneous mixture have spatial and temporal differences and changes in the overall combustion. In the application research to expand the combustion range of HCCI, the use of technologies, such as direct injection in cylinder, multi-stage injection, and large EGR rate, makes the engine have uniform characteristics. In the long term, a unified engine that mixes fuel in real time or with a dedicated fuel is the ultimate solution for future engines.

In addition, multi-mode composite engine with interval HCCI combustion mode, in the short and medium term, is the development trend of HCCI engine in the near future according to the current research and development status of HCCI. Explore the influence factors of composite HCCI

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combustion and emission is very complicated. Therefore, it is necessary to explain the conclusions drawn from the test from the theoretical and microscopic perspectives, and the establishment and research of numerical simulation model should be further carried out. At the same time, the influence of some control parameters, such as the effects of secondary injection of direct injection fuel and its injection phase on combustion and emission and engine performance and the effects of intake pressurization and exhaust gas recirculation on composite HCCI and the expansion of its operating range, also needs to be further studied.

According to the operation characteristics of HCCI, starting from the application level of the whole vehicle, the rational optimization of power system parameters to match the combustion zone of HCCI with the operation zone of the whole vehicle is a new breakthrough to realize the product application of the four-stroke HCCI composite engine. With the increasing attention to the environment in various countries, HCCI combustion technology will be put into use.

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