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Study on characteristics and application of new combustion mode of automobile engines

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Abstract

Improving fuel economy and reducing emissions are currently the two main goals set by the automotive industry. New combustion strategies, with higher thermal efficiency and the ability to reduce both NOx and PM emissions, have been developed over the last 40 years as an alternative to traditional combustion methods for internal combustion engines. However, the new combustion strategy has not yet been widely applied in internal combustion engines and there is a lot of research value and scope for research. This paper summarises and analyses the characteristics of three combustion strategies, namely Homogeneous Charge Compression Ignition (HCCI), Premixed ChargeCompression Ignition (PCCI) and Reactivity Controlled Compression Ignition(RCCI). The results show that HCCI, PCCI and RCCI can effectively improve engine dynamics and significantly reduce NOx and PM emissions compared to traditional DI and SI combustion strategies, and have great potential for development.

Keywords: New Combustion Technology; Carbon Emission; HCCI; PCCI; RCCI

1. Introduction

The internal combustion engine is widely used as the most efficient energy transfer system in industry, transportation and many other applications. As global environmental concerns increase, governments have adopted stricter emission regulations to reduce harmful emissions such as nitrogen oxides (NOx), particulate matter (PM) and greenhouse gases (GHG). [1,2]

Internal combustion engines produce large amounts of NOx and PM during combustion, and reducing emissions of both pollutants simultaneously is extremely challenging [3]. To address this problem, researchers have developed and implemented many solutions, of which the use of alternative fuels [4,5], the use of after-treatment systems [6,7], and the adoption of advanced combustion strategies are a few of the main solutions available [8-10].

Advanced combustion technology (ACT) is a new combustion concept [11] at addressing particulate matter and NOx emissions from internal combustion engines while improving the thermal efficiency of engine combustion. in 1979, Onishi et al [12] introduced the homogeneous charge compression ignition (HCCI) concept in gasoline two-stroke engines. However, these single-fuel ACTs have many obstacles in becoming real-world alternatives to combustion technology because of the difficulty in controlling combustion stages [13], in maintaining combustion stability [14] and in extending the operating range to high-load conditions [15,16]. In addition, they produce large amounts of HC and CO due to incomplete combustion [17,18].

Therefore, researchers have developed the partial premixed compression ignition (PCCI) combustion mode. Compared to the HCCI combustion strategy, the PCCI combustion strategy has a non-complete homogeneous mixture of fuel and air, which allows for better control of combustion. However, NOx and PM emissions are relatively high compared to the HCCI combustion strategy. the PCCI combustion strategy has superior emission characteristics at moderate engine loads, but severe detonation due to excessive pressure rise rates at higher engine loads limits its applicability to production grade engines. It has been suggested that reducing the compression ratio can increase the working load range of PCCI combustion compared to conventional CI combustion, thereby reducing NOx and PM emissions [19-21].

Due to the limitations of the HCCI and PCCI combustion modes, an alternative combustion method, Reactive Controlled Compression Combustion (RCCI), was developed, which allows for more efficient use of different alternative fuels such as alcohols and biodiesel. In RCCI mode of combustion, different combinations of low reactive fuels (LRF) and high reactive fuels (HRF) such as petrol-diesel, petrol (with cetane improver), E85 (85% ethanol + 15% petrol)-diesel and alcohol-diesel can be used to achieve reactive stratification in the engine combustion chamber.RCCI has been shown to achieve lower RCCI has been shown to achieve lower NOx and particulate levels under different engine platforms without the need for after-treatment [22-24].

2Homogeneous Charge Compression Ignition (HCCI)

2.1 HCCI

HCCI, a new combustion method, has attracted extensive attention and research in recent years. It replaces the diffusion combustion of traditional diesel engines with premixed combustion, which can solve the problems of NOx and micro-emissions at the same time and meet the increasingly stringent emission regulations. Since the introduction of the HCCI combustion concept in 1979, a lot of relevant research has been done on it worldwide, but the use of HCCI combustion technology to replace the traditional combustion method throws up a huge challenge.

The HCCI combustion mode is a reliable method that produces ultra-low NOx levels and near-zero particulate emissions and provides equal or higher fuel conversion efficiency than conventional direct injection (DI) diesel combustion. In HCCI mode, the air-fuel mixture is mixed evenly into the cylinders during intake, or fuel is injected into the cylinders during the early stages of compression. In both cases, the mixture is homogeneous before combustion begins. In this respect, the air-fuel mixture is similar to that of a spark plug ignition (SI) engine. Combustion begins with the homogeneous mixture being ignited by compression, similar to a compression ignition (CI) engine. The combustion pattern is shown schematically in Figure 1. The HCCI combustion process rapidly creates a multi-point auto-ignition ignition with no visible flame front, avoiding localised high temperature areas. PM emissions from HCCI engines are reduced to almost zero levels due to the homogeneity and leanness of the air-fuel mixture. The leaner mixture also reduces the maximum in-cylinder temperature and NOx emissions are reduced at the same time as PM emissions. As a result, the in-cylinder temperature reduces the heat loss at the cylinder wall and the thermal efficiency of the engine is improved.

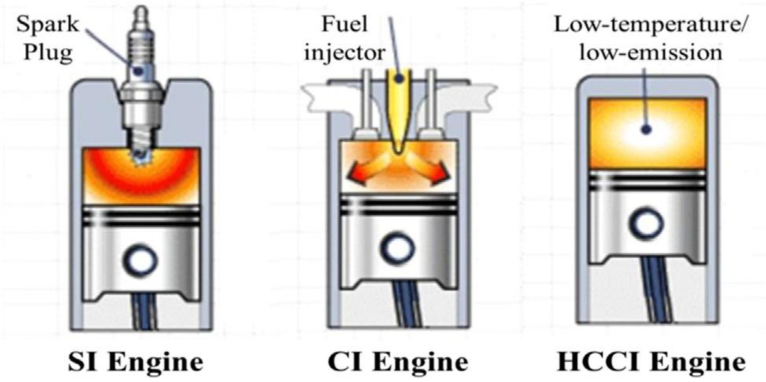

Fig.1 HCCI schematic diagram

2.2 Status of HCCI Research

Currently, the stability, thermal efficiency and cycle variation of HCCI operation of HCCI engines depend mainly on the time of onset of combustion (SOC). Most research has focused on parameters such as fuel type, compression ratio, exhaust gas recirculation and injection timing.

The use of multiple fuels to enhance the combustion process in homogeneous compression-ignition engine cylinders has been developed considerably in the last decades. This technology was established to overcome engine ignition control difficulties and detonation. In addition, there is an urgent need for cleaner and renewable fuels to combat the energy crisis and environmental degradation. Natural gas is one of the best choices of fuel for HCCI engines because of its relatively high proportion of hydrogen and therefore lower CO_2 emissions [25,26]. Currently, the use of compressed natural gas (CNG) innovations in HCCI engines is a preferred strategy for CNG-hydrogen blends (HCNG) [27,28], with higher octane HCNG fuels for HCCI engines making them less prone to detonation at higher compression ratios.

The thermal efficiency of an internal combustion engine is largely dependent on the compression ratio of the engine. Although the burst phenomenon limits the upper limit of compression ratio in SI engines, high compression ratios are beneficial in controlling the SOC of HCCI engines. Hadia et al [29] investigated the effect of compression ratio and injection timing on the performance, combustion and emission characteristics of HCCI engines. The study was carried out numerically by varying the CR between 15 and 20. The results showed that increasing the compression ratio increased combustion duration, in-cylinder temperature and pressure, and that CO emissions were reduced by 40% at a compression ratio of 18. Olsson et al [30] investigated the effect of compression ratio on the maximum load of a natural gas-fired HCCI engine. A comparative study was conducted using compression ratios of 15, 17, 20 and 21. The results showed that the compression ratio had a small effect on the heat release rate and that NOx emissions at high loads could be reduced by varying the compression ratio. kim et al [31] experimentally investigated the effect of reducing the compression ratio and injection angle on HCCI combustion. The researchers reduced the compression ratio from 17.8 to 15 by changing the piston shape in a small direct injection diesel engine, resulting in a reduction in the average indicated pressure from 0.58 to 0.55 Mpa. Machrafi and Cavadiasa [32] experimentally investigated the effects of inlet temperature, equivalence ratio and compression ratio on the auto-ignition process of HCCI. The compression ratios ranged from 6 to 13.5 at inlet temperatures of 25 to 70°C and equivalence ratios of 0.18 to 0.41, and the test fuels were PFR40 and n-heptane. The results show that at the same equivalent ratio, increasing the compression ratio causes an increase in in-cylinder temperature and pressure, and therefore, an increase in the reaction rate and a decrease in ignition delay.

Studying the effect of EGR on HCCI engines is a current research hotspot. EGR dilution technology has been commercialised in SI and CI engines, primarily to reduce high combustion temperatures and lower NOx emissions. The maximum amount of EGR in conventional engines is limited by the dilution limit of the in-cylinder charge, which is determined by the flammability limit. In HCCI internal combustion engines, these limits are much wider. In addition, excess EGR reduces engine durability and performance due to the corrosive and abrasive components it contains, such as sulphur oxides. As combustion duration increases, EGR slows down combustion, resulting in smoother operation. MortezaFathi et al [33] made a single cylinder engine run in HCCI combustion mode and controlled the combustion phase by using different EGR rates. The results showed that the EGR rate had a large effect on the combustion phase, with increasing EGR leading to delayed SOC and longer combustion duration. With the addition of EGR, the heat transfer rate decreases. Under certain conditions, increasing EGR can improve fuel economy and reduce NOx emissions, but increase HC and CO emissions.

2.3 Technical Challenges Facing HCCI

The challenges of HCCI combustion include: (i) control of combustion stages; (ii) control of ignition timing; (iii) extended working load range; (iv) improved cold start capability; and (v) control of HC and CO emissions. Of these, homogeneous gas mixture preparation and combustion stage control play a crucial role in determining efficiency and emissions.

One of the most important parameters affecting HCCI combustion is the air-fuel ratio. Simultaneous self-ignition in all parts of the combustion tank ensures that a lean mixture fire occurs locally, overcoming the misfire problem. However, misfire problems still inevitably occur in overly lean mixtures. In a richer mixture, a large amount of fuel energy is driven into the cylinder and the full heat is released spontaneously at a small crank angle (almost at a fixed volume), increasing the rate of pressure rise. As a result, HCCI engines can burst. In addition, spontaneous ignition of the fuel may not occur in an overly concentrated mixture because there are not sufficient numbers of oxygen molecules in the mixture [34,35].

The cold start problem of HCCI engines is another obstacle in most geographically cold areas. This problem can be solved by starting the engine in conventional mode, then warming it up for a short time and then switching to HCCI mode. Unlike the ignition timing of an ignition engine and the fuel injection timing of a direct injection engine, an HCCI engine lacks a combustion start controlled by auto-ignition. The fuel-air mixture is uniformly premixed before the onset of auto-ignition. Combustion control, is influenced by the following factors [36,37]: fuel chemistry and thermodynamic properties, combustion duration, wall temperature, reactant concentration, exhaust gas residual rate, mixture homogeneity, intake air temperature, compression ratio, EGR volume, speed, engine temperature other engine parameters. Therefore, HCCI combustion control for a wide range of speeds and loads is the greater challenge. Controlled combustion is the most important parameter as it affects the power output and efficiency of the engine. If combustion occurs too early, power will drop and the engine will be severely damaged; if combustion occurs too late, the chances of misfire increase.

3 Premixed charge compression ignition (PCCI)

3.1 PCCI Combustion Strategy

HCCI can significantly reduce NOx and PM emissions, however, it lacks a better means of combustion control, especially at higher engine loads. A great deal of research has been conducted to address this issue, however, in most studies, HCCI mode combustion was not sufficient for practical application in production-grade internal combustion engines [38]. As a result, researchers have developed PCCI mode combustion with advance direct fuel injection to achieve a premixed homogeneous fuel-air mixture. Compared to HCCI mode combustion, PCCI mode combustion allows for better combustion control and better overall engine performance.

In PCCI mode of operation, the fuel air should be pre-mixed before combustion begins. This can be achieved in two ways. Firstly, fuel is injected into the air inlet so that the cylinders can be pre-mixed. Secondly, fuel is injected early in the compression stroke [39]. Ying et al [40] conducted experiments using gaseous fuel to form a premix at the inlet. They supplied a partially homogeneous mixture of DME and air in the cylinder through the intake tract and achieved PCCI combustion by injecting DME directly into the cylinder during the compression stroke using a conventional CI fuel injection configuration.Singh et al [41] carried out an experimental study on a two-cylinder medium-sized direct injection compression ignition production grade engine. The main objective of the experiment was to implement a PCCI combustion strategy on an industrial-grade diesel engine. The researchers installed an open ECU on this engine to enable mode switching between conventional compression-ignition and PCCI combustion modes depending on the engine load, and the results showed that the mode switching technique has great potential for industrial applications of HCCI/PCCI combustion in production grade engines.

3.2 Optimisation study of PCCI combustion strategy

Since the concept of PCCI combustion was introduced, researchers have continued to optimise and improve the PCCI combustion strategy. Up to now, scholars from various countries have mainly optimised the PCCI combustion strategy through injection strategy, EGR rate, combustion chamber shape and selection of suitable fuel.

3.2.1 Optimization by injection strategy

Different from HCCI, the PCCI mode does not have a completely homogeneous mixture of fuel and air, but it can greatly improve the controllability of the combustion phase as well as the combustion rate by controlling the injection timing. The desired ignition delay can be achieved with a lower compression ratio, higher injection pressure and a relatively large EGR rate under the PCCI combustion strategy. Robert Kiplimo et al [42] achieved PCCI combustion with narrow angle injectors, low compression ratio and EGR control. The researchers visualised and analysed the combustion process to obtain the relationship between injection parameters and exhaust gas emissions. The results showed that earlier injection timing and increased EGR extended ignition delay time, reduced NOx emissions and increased HC, PM and CO emissions. Higher injection pressure reduces NOx, PM, HC and CO emissions.

By using a split injection strategy it is possible to increase the operating range of the PCCI combustion strategy, and a PCCI combustion strategy using a split injection strategy has relatively lower NOx and PM emissions with no significant change in the average indicated pressure. Therefore, many researchers have explored split injection strategies using different fuel injection parameters such as fuel injection pressure (FIP), fuel injection timing, etc. Parks et al [43] conducted experiments with conventional CI mode and PCCI combustion strategies. The following conclusions were obtained: the PCCI combustion strategy emitted relatively lower NOx and PM compared to the CI combustion strategy. In another study, the effect of fuel characteristics in the PCCI combustion strategy was investigated and the results showed that the use of dimethyl ether (DME) in the PCCI combustion strategy reduced NOx emissions. Benajes et al [44] also investigated the performance, emissions and combustion noise of a diesel/gasoline hybrid high speed direct injection (HSDI) diesel engine operating in the PCCI mode. The results showed that increasing the proportion of gasoline in the test fuel increased ignition delay and improved combustion conditions due to longer fuel-air mixing. Extensive research has been carried out to extend the high load limits of PCCI and to reduce engine emissions, including the use of the use of multiple fuels [45], multiple injections [46-48] variable valve timing [49] and enhanced fuel-air mixing [50]. the PCCI combustion strategy uses moderately advanced injection, in this case with high levels of EGR and low compression ratios, which ensures adequate air-fuel mixing This ensures sufficient air-fuel mixing time, suppresses NOx formation and improves combustion phasing. As with HCCI, PCCI is prone to high HC and CO emissions and high pressure rise rates, which can lead to high combustion noise or detonation; therefore, the concept is difficult to achieve at high engine loads. Previous studies have shown that engine NOx and PM emissions can be reduced simultaneously by initiating combustion at equivalence ratios below 2 and flame temperatures below 1800K [51].

3.2.2 Optimized by EGR rate

In conventional diesel combustion, EGR has been used to control NOx emissions by diluting the charge and reducing the flame temperature [52,53]. For PCCI engines, tuning the EGR can also improve engine performance and emissions. PCCI combustion uses EGR to reduce flame temperature and oxygen concentration, resulting in a controlled rate of combustion phase and pressure rise. This also results in reduced NOx emissions but increased hydrocarbon and carbon monoxide emissions. Figure 2 shows the effect of EGR on indicated thermal efficiency, average indicated pressure and cycle variation as studied by Robert Kiplimo et al [54] on a single cylinder PCCI engine. At an injection timing of 2-10° BTDC, the indicated thermal efficiency and average indicated pressure were better without EGR than with 40% EGR. This is related to fuel quenching or over-mixing, where the mixture formed is too lean for complete combustion. At an injection timing of 15° BTDC, the indicated thermal efficiency and average indicated pressure reach a maximum and then gradually drop. The introduction of 40% EGR increases the indicated thermal efficiency and average indicated pressure for injection timing located at 15-20° BTDC, meaning that different optimum injection timings exist.

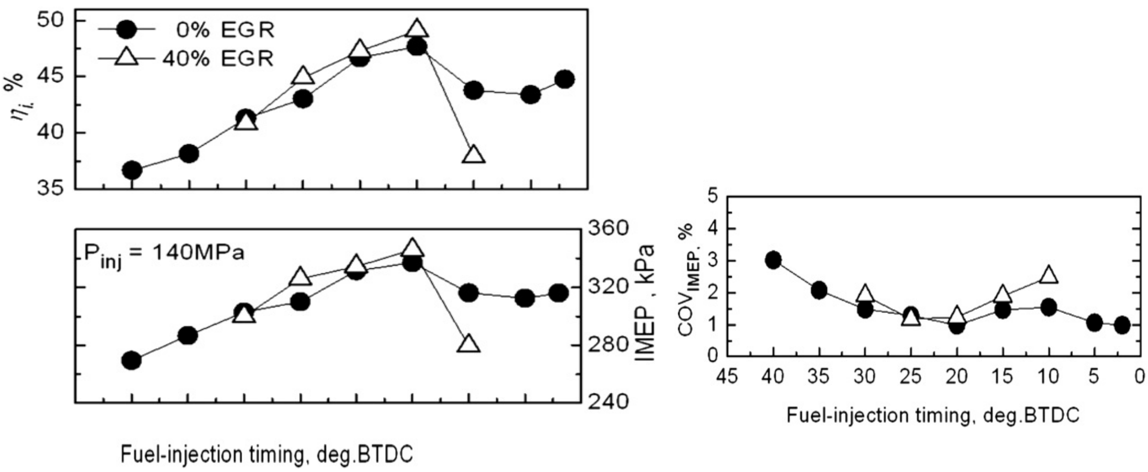

Fig. 2Effect of EGR on indicated thermal efficiency, average indicated pressure and cyclic variation

3.2.3 Optimization by choosing the right fuel

The optimal fuel for PCCI is still being explored by researchers in various countries, and in addition to the traditional single-fuel technology, some researchers have proposed dual-fuel as well as triple-fuel technologies. Euijoon Shim et al [55] compared the effects of PCCI, DF-PCCI (dual-fuel premixed compression ignition) on engine performance under a specified load, using a heavy-duty engine as an example. The results show that both combustion methods reduce NOx and PM emissions, and that DF-PCCI combustion is easier to control the combustion stages than single-fuel combustion by adjusting the natural gas substitution rate (SR) and diesel injection timing. In addition DF-PCCI combustion can achieve an indicated thermal efficiency of 45.3% higher than the original combustion mode, however DF-PCCI combustion produces significant amounts of HC and CO, much higher than the original combustion mode, but still lower than the single-fuel PCCI emission levels. MElkelawy et al [56] proposed a method to optimise the ratio of the three fuels by using a three-fuel operation technique in the new combustion mode The results showed that by changing the fuel ratio, the engine burst combustion or misfire could be improved.

4. Reactivity Controlled Compression Ignition(RCCI)

Due to the limitations of HCCI and PCCI combustion modes, another LTC technology RCCI combustion mode is developed, which can make more effective use of alcohols, biodiesel and other alternative fuels. In RCCI mode combustion, different combinations of low reactivity fuel (LRF) and high reactivity fuel (HRF), such as gasoline diesel, E85 (85% ethanol + 15% gasoline) - diesel and alcohol diesel, can be used to achieve stratified combustion in the engine combustion chamber.

Splitter et al. [60] and Curran et al. [61] studied the effect of fuel reactivity on RCCI mode combustion. They use ethanol, gasoline and E85 as LRF and diesel as HRF, which reflects the superior performance of the engine with higher reactivity gradient in RCCI combustion mode.Hanson et al. [62] studied the effect of injection timing on RCCI mode combustion, and the results showed that the advance of injection timing of mineral diesel would lead to higher NOx emissions. Dempsey and Reitz [[63]] conducted RCCI mode combustion experiments using mineral diesel and methanol as HRF and LRF respectively. The results show that, compared with gasoline, due to the higher vaporization latent heat and octane number of methanol, the RCCI mode with higher methanol premix ratio delays the start time of combustion. Jia and denbratt [64] studied the combustion characteristics of RCCI mode combustion under higher engine load.They conducted experiments on diesel methanol fuel and obtained ultra-low PM and NOx emissions compared with traditional CI mode combustion. Han et al. [65] compared the combustion modes of PCCI, HCCI and RCCI using n-butanol and mineral diesel as Test fuels. The results show that, compared with the standard CI mode, the NOx and soot emissions of PCCI and HCCI combustion modes are significantly reduced. However, compared with other LTC technologies, RCCI combustion mode shows relatively higher efficiency and superior combustion controllability.

In RCCI engine, ignition timing and combustion rate can be controlled by adjusting the ratio of low reactivity fuel to high reactivity fuel and injection timing of high reactivity fuel. It can be found from previous studies that when RCCI engine is fueled with different fuels, the combustion and emission characteristics are quite different. Park et al. [66] studied the effect of Premixed Gasoline and biogas on RCCI performance of single cylinder engine. The results show that increasing the premixed ratio of gasoline or biogas can increase the indicated mean effective pressure, reduce NOx and PM emissions, and reduce HC and CO emissions. In high compression ratio diesel engines, Gao et al. [67] used ethanol and butanol as premixed fuels of RCCI respectively. The results show that butanol at low load to medium load and ethanol at high load are the best strategies to achieve good fuel efficiency and exhaust emissions.

In addition to obtaining the optimal operating parameters of RCCI with different fuels, in order to obtain better operating performance, the optimization of multiple operating parameters has been widely studied. Splitter et al. [68] carried out an optimization study to optimize the in cylinder fuel stratification by using two kinds of fuels with different reactivity without cooling the piston, and achieved a thermal efficiency of nearly 60% by using RCCI strategy. In addition, splitter et al. [69] studied the effects of direct injection fuel characteristics on total thermal efficiency, which are related to fuel reactivity, CA50 and load. The results show that the fuel reactivity difference affects the engine efficiency, not the loss trend mechanism. Li et al. [28] carried out multidimensional simulation combined with fast non dominated sorting genetic algorithm (NSGA), and obtained the optimal operation parameters of RCCI engine to meet the performance requirements. However, few studies focus on improving the operation efficiency of high load RCCI, which is of great significance to realize the efficient operation of this combustion mode under high load conditions. As we all know, compared with EGR dilution, air dilution can obtain higher thermal efficiency, which is mainly due to the higher air dilution level, the greater the specific heat ratio. Therefore, the main purpose of this study is to explore the potential of improving the thermal efficiency of gasoline / pod circulating cooling water (RCCI) operation through air dilution and EGR dilution under high load conditions (about 1.35 MPa IMEP), because the unique performance of pod can effectively inhibit PPR and reduce NOx and soot emissions under high load conditions.

5. Conclusion

Compared with the traditional combustion strategy, the new combustion technology has better power performance and less NOx and PM emissions. However, in order to control the deflagration problem of internal combustion engine under high load, a higher EGR rate is introduced, which makes the engine cylinder temperature lower and produces a lot of HC and CO emissions. At present, each combustion strategy has some technical problems. For HCCI and PCCI, accurate control of combustion, expansion of working load range and cold start are still the key points to be overcome. Although it can be optimized by changing the injection pressure, injection timing, EGR rate, geometry of combustion chamber and piston, and intake air temperature, it is still far from being able to completely replace the traditional combustion mode. Although RCCI combustion mode performs better than the first two combustion modes, its fuel requirements are more stringent than other combustion modes. Whether it can be widely used in commercial vehicles remains to be considered.

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