The research and analysis of Homogeneous Charge Compression Ignition Engine

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Abstract—HCCI represents homogeneous charge compression ignition. It is a cleaner, higher thermal efficiency, and higher fuel efficiency alternative combustion technology. This engine combines the advantages of diesel and gasoline engines so that the compression ratio of diesel engines can be achieved even when gasoline is used as fuel, and there is basically no NOx and soot emissions. However, the HCCI still has some problems such as ignition timing unstable, bad load and speed variation, and cold start capacity. Today, due to the above shortcomings, HCCI is still mainly researched and developed in the laboratory without mass production. The purpose of this paper is discussing the advantage and disadvantage of HCCI technique and analyse the operating principle to provide possible solution that will improve the quality of HCCI engine before the mass production of HCCI.

1. Introduction
With the development of internal combustion engines, major vehicles in the world today, such as automobiles and motorcycles, use internal combustion engines, which makes a large amount of fuel consumed with a large number of harmful gases generated by the internal combustion engine to be discharged into the air. These exhaust gases have caused environmental problems such as global warming. Due to the increasingly serious environmental situation, the government has a public policy to limit the emission of automobiles. It promotes the development of clean and high-efficiency combustion engines. Homogeneous Charge Combustion Ignition (HCCI) engine is an immature technology that is supposed to provide high thermal efficiency and fuel efficiency to catch the demands of the market and government.

The HCCI engine was first proposed and demonstrated in the 1990s. It is still in the research and development stage, so it has not been widely commercialized. It usually uses the compression ignition method, but it can also use the spark plug ignition method. At the time when it was first proposed, its application was delayed due to the limitation of electronic control technology. With the development of related industries, the HCCI engine has gradually entered the public view and been applied. It combines
some of the advantages of conventional gasoline and diesel engines, such as higher compression ratio and efficiency compared to gasoline engines, and less polluting gas emissions compared to diesel engines. However, HCCI still needs to solve some problems such as combustion instability before mass production. Besides, the emission problems of carbon monoxide(CO) and Hydrocarbon(HC) due to inadequate combustion also need to be improved to follow the demand for environmental protection. This paper will specifically analyse and research the working mechanism, advantages and disadvantages, status quo, and prospects of the HCCI engine.

2. Working Mechanism of HCCI engine

2.1. Working Process
In this article, we will examine the four-stroke HCCI engine. Similar to other four-stroke engines, the HCCI engine's four strokes include intake, compression, combustion, and exhaust. While different from other four-stroke engines, it draws air and fuel mixture and its ignition mode:

Intake: The piston moves from the TDC to the BDC while the intake valve opens and the mixture of air and fuel is drawn into the engine due to the low pressure in the chamber created by the piston movement.

Compression: At this stage, the piston moves from BDC to TDC while both the intake and outlet valves are closed, air and fuel are compressed to produce high temperatures and pressures so that the mixture of fuel and air is ignited. One of the biggest challenges of this process is how to control the combustion timing.

Combustion: The piston moves from TDC to BDC due to the high temperature and pressure generated by the combustion.

Exhaust: The exhaust valve opens, the piston moves from BDC to TDC, and the combustion exhaust gas is discharged.

2.2. Calculation Methodology
To demonstrate the HCCI engine internal structure, Fig. 1 is used. B represents for crank arm radius, S represents piston diameter, L represents stroke length, a represents crank arm radius, Vc is the clearance volume, Vd is the displacement volume (Vc + Vd is the cylinder volume), θ represents for crank angle and l is the rod length.
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Based on the Fig. 1 model and simple geometry relationship. Some parameters can be calculated:

### Tab.1 Related parameter calculation formula

| Parameter     | Formula                                                                 |
|---------------|-------------------------------------------------------------------------|
| S(θ)          | a cos θ + (l^2 - a^2 sin^2 θ)^1/2                                      |
| Vd(θ)         | (πB^2/4)[(l + a) - s(θ)]                                               |
| Vd(θ)_{max}   | πB^2L/4                                                                |
| CR_{(Compression Ratio)} | (V_d + V_c) / V_c                                                             |

Then some basic thermal parameters can also be calculated:

### Tab.2 Thermal parameter calculation formula

| Parameter     | Formula                                                                 |
|---------------|-------------------------------------------------------------------------|
| dQ/dθ {ROHR} | [k/(k-1)]P(dV/dθ) + [1/(k-1)]V(dP/dθ) + (dQ_{heat}/dθ)               |
| η {Thermal Efficiency} | W_{net} / mQ                                                          |
| W_{net}       | fpdV                                                                   |
| IMEP {Indicated Mean Effective Pressure} | W_{net}/V_c + V_d                                                             |

Here, ROHR means the rate of heat release, k refers to the ratio of specific heat value [5].

In some related experiments, heat loss is used as an important indicator to express the efficiency of the HCCI heat engine. The heat loss is mainly determined by the following equation:

\[ Q_{loss} = hA(T_{cylinder} - T_{wall}) \]  

(1)

where Gloss is the heat loss, Tcylinder is the mean cylinder temperature. In the experiments, the air is approximated as an ideal gas. Therefore, the average cylinder temperature is calculated using the ideal gas equation of state. In the experiments, the air is approximated as an ideal gas. Therefore, the mean cylinder temperature is calculated using the ideal gas equation. Twill is the cylinder wall temperature.
In the experiments, all the wall temperature is assumed to be 400K. A is the total surface area of the cylinder, which is also a constant in the experiment. \( h \) is the heat transfer coefficient [6]:

\[
h_c = 130P^{0.8}T_{\text{cylinder}}^{-0.4}V^{-0.06}(v_p + 1.4)^{0.8}
\]

(2)

In Eq.(2), \( P \) is the in-cylinder pressure. \( V \) is the volume of the cylinder and \( v_p \) is the mean piston speed. The air-fuel equivalent ratio(\( \phi \)) will be calculated by the following equation:

\[
\phi = \frac{\left( \frac{m_{\text{fuel}}}{m_{\text{oxidant}}} \right)_{\text{stoichiometric}}}{\left( \frac{n_{\text{fuel}}}{n_{\text{oxidant}}} \right)_{\text{stoichiometric}}}
\]

(3)

2.3. Fuel

HCCI engines can be fed with different fuels [7]. For example, gasoline, diesel, methanol, and Methane [8]. HCCI engines have low requirements for combustion conditions. Any alcohol and hydrocarbon liquid fuel mixed with air that can be vaporized before combustion can be used as HCCI engine fuel. Gasoline is now a preferable fuel option for HCCI engine for gasoline is lively and easy to evaporate, easy to generate combustible mixture these characteristic helps to shorten the combustion process [9].

3. Advantages

3.1. Higher efficiency compared to the gasoline engine

3.1.1. Factors Affecting the Efficiency--Compression Ratio

The existing research shows that the increase of compression ratio is beneficial to the improvement of engine thermal efficiency [5]. By increasing the compression ratio, the maximum pressure and the maximum temperature of the engine are increased, while the mixture fuel is fully burned, and the efficiency and power of the engine are improved. Compared to a gas engine that uses spark ignition, an HCCI engine can have a higher compression ratio and the combustion is more complete.

3.1.2. Thermal efficiency of HCCI engine

In this section, the influence of primary reference fuel(PRF) number and compression ratio on HCCI engine will be discussed according to a series of experiments which are conducted by Yang et al [6]. In all experiments, to ensure the same intake temperature range which is the requirement to achieve HCCI combustion at each compression ratio the primary reference fuel PRF number has been changed in different ranges of different compression ratios. In the experiments, the equivalent ratio of all fuels is 0.3 and each experiment needs to achieve the crank angle when the combustion heat release reaches 50% of total heat release(CA50) of 5 degrees after the top dead center [3]. In Fig.2, It is shown that the range of the intake temperature is from 310K to 400K. The primary reference fuel is a mixture of n-heptane and isoctane in a specific ratio.

The PRF number is used to express the octane number. the octane number of n-heptane is 0 and the octane number of isoctane is 100. Therefore, fuels with different octane numbers can be obtained by mixing them in different proportions.
It is shown from Figure 3 that when the PRF number of the fuel increases, to achieve the same crank angle (CA50), the intake air temperature needs to increase. After increasing the compression ratio, the PRF value of the fuel also needs to be increased, and the intake air temperature and PRF still maintain the same tendency. In addition, when the compression ratio of the engine is between 11 and 13, only two sets of data can be collected. This may be due to the engine being unstable under these compression ratios which require a high intake air temperature to make combustion occur.

3.2. Low NOx and soot emissions

Due to the combustion characteristics of the HCCI engine (homogeneous fuel, spontaneous combustion), it can achieve high efficiency with low NOx and soot emissions. NOx is a general term for a large class of nitrogen oxides. During engine operation, high temperatures will cause nitrogen in the air to be oxidized into nitrogen oxides. Nitrogen oxides are a type of air pollutants that are very harmful to the environment. Nitrogen monoxide and nitrogen dioxide are relatively stable among nitrogen oxides, so most of the exhaust gas is nitrogen monoxide and nitrogen dioxide. Compared to traditional diesel engines, HCCI engines have less nitrogen oxide emissions and no soot emissions. The formation of soot and nitrogen oxides will be illustrated in Fig.5.
Fig. 5 Equivalence ratio versus temperature [10]

The abscissa of this figure is the combustion temperature, and the ordinate is the fuel-air equivalence ratio($\phi$). The fuel-air equivalence ratio is the ratio of the mass ratio of the fuel to the oxidant and the stoichiometric ratio between them when the fuel is oxidized. The formation of NO$_x$ is mainly related to the combustion temperature. It can be seen from the figure that when the temperature is greater than 2200k, nitrogen oxides begin to form. The main combustion temperature of the HCCI engine is lower than 2200k, so nitrogen oxides emission is very low. Soot formation occurs in high equivalent ratio fuels area with moderate temperature. Since the fuels of the HCCI engines needed is very lean. Therefore, The HCCI engines have no soot emission.

4. Disadvantages

Although the HCCI has higher thermal efficiency and cleaner emission, the HCCI still has some difficulties that need to be solved before mass production. The emission of NO$_x$ for the HCCI is much lower than the regular engine, but the cost is the increase of CO and HC emission. The technology and tools to clean the CO and HC are cheaper and easier than the NO$_x$, but it is still harmful pollution.

Fig. 6 $\phi$ ratio VS temperature [11]

Fig. 6 above shows the working temperature of the HCCI engine, and the low combustion temperature makes the HCCI engine doesn't approach the requirement of producing NO$_x$. However, the low temperature will increase the emission of CO and HC.
Fig. 7 Intake temperature vs Emission [12]

Fig. 7 above shows the relationship between intake temperature and the Emission of CO, NOx, and HC. From the chart, the CO and HC have the same trend, but NOx has a different trend. The emission of CO and HO will decrease as the intake temperature increases. The emission of NOx will increase as the intake temperature increases. Therefore, the low combustion temperature of HCCI engines increases the emission of HCCI.

Exhaust Gas Recirculation is a technology that can decrease the emission of HC and CO without increasing the risk of NOx emission.

Fig. 8 Exhaust Gas recirculation [13]

Fig. 8 above simply shows how EGR works in Engine. There is an EGR valve that can control the movement of exhaust gas. When the valve opens, part of the exhaust gas will move back to the cylinder and engage the combustion again. It can increase fuel efficiency and decrease waste. The indicator usually used for EGR is the EGR rate.

HCCI compresses well-mixed fuel and oxidizer to the point of auto-ignition instead of using a spark plug to control the ignition timing like traditional combustion engines. This ignition method provides HCCI with high thermal efficiency and cleaner emission, but it is hard to control. Unlike regular combustion engines that have spark plugs to control the ignition time, the HCCI engine tries to use the pressure and temperature inside the cylinder to cause automatic ignition.
Fig. 9 Working situation of HCCI

Fig. 9 above shows the HCCI engine working situation under different loads. From the figure, the possibility of failure in low loads and high loads is about fifty percent, which is an unaffordable failure rate. Besides, the working situation is also unstable for HCCI engines. From the figure, the fire successful rate of the mid load is higher than the low load and high load. In addition, the HCCI engine will need to face different challenges for high load and low load.

Misfires usually happen during the low load, start-up, and middle of engine idling. It is caused by the combustion reaction doesn't work correctly. For example, the ignition happening both earlier and later will cause the misfire.[16] The misfire will make the engine stop working for a while. Besides, it will cause speed loss. Because the misfire always happens during low load which means the automobile moves slowly, it will not cause a large accident. However, it will put extra pressure on the multiple parts of the engine and damage the engine. In addition, even in low-load situations, small accidents will also cause property loss.

EGR is one possible solution for the misfire during low load. The risk of misfire is high for an HCCI engine because it doesn’t have a mechanism ignition system, which causes the ignition time to be hard to control. The EGR rate can be used to control the ignition time.

Fig. 10 EGR VS Ignition advance angle [14]

Fig. 10 above shows the relationship between the EGR rate and the ignition advanced angle under different load situations. The low load part should be 2000 rpm to 300 rpm. The ignition advance angle is an indicator of ignition timing. From the figure, increasing the EGR rate could increase the ignition advance angle, which will change the ignition timing. Therefore, controlling the ignition timing by changing the EGR rate is a possible solution.
The working principle of HCCI is very similar to the knocking. For the diesel engine, the knocking will happen with an uncontrollable burn process. The fuel auto ignites when the spark starts the ignition. Because the HCCI doesn't have a spark, the risk of knocking largely increases during high load. The result of figure 10 shows that the range that knocking happens is almost the same as the range of perfect fire. When knocking happens, the pressure and temperature rapidly increase. It will damage the piston and cylinder. The pressure wave will shock the oil film. It will decrease the heat preservation capacity, which will negatively affect the thermal efficiency. The most dangerous situation of knocking will cause the cylinder to burst. A new engine will be needed when the cylinder burst happens.

5. The status quo and prospects of HCCI engine

5.1. Status quo of HCCI technology
Research on HCCI has been going on since 1979 when Onishi found that the HCCI engine had significant improvements in operating stability, fuel economy, and exhaust emissions at low loads (1000r/min–4000r/min) [18]. Subsequent studies have been carried out around these three characteristics.

Nowadays HCCI still exists mainly in laboratories. Gasoline compression combustion is not good at cold start, and HCCI almost makes the mixture burn at the same time. This way is not ideal in the conditions of large load and small load. The power output is not high in the state of large load, and the requirements for temperature and pressure are higher, which are not easy to solve. At the same time, Knocking is one of the main reasons limiting its commercialization. Because the heat release of HCCI combustion mode is very concentrated, the Knocking tendency is particularly large near the compression top dead center. Knocking greatly affects the upper-temperature limit in the cylinder [19].

5.2. Industry leader Mazda HCCI engine status
Today, Mazda is at the forefront of HCCI technology, the Mazda SPCCI engine is the closest thing to an HCCI available in production.

When they tried to make a pure HCCI engine, they ran into the same problems as other carmakers. Without a timed spark or fuel injection, it is difficult to control the timing of homogeneous combustion (which can be precisely timed with a spark plug in a traditional engine), requiring compression combustion by tightly controlling the air, fuel, pressure, and temperature in the cylinder. So HCCI cannot tolerate higher engine speeds and extremely sensitive changes in atmospheric pressure. As a result, vehicles may not adapt well to altitude changes and seasonal rotation. Even assuming that the operating conditions are mild, that is, ideal, and the HCCI burns uniformly in theory, engineers still need to solve the problem of the HCCI engine's narrow operating conditions (that is, it can only operate under low and light loads).

In the end, Mazda had to control the whole process by using sparks, which incidentally solved most of the problems, and extended the operation range of compression ignition to higher engine speeds and even moderate loads, such as acceleration.

6. Conclusion
HCCI internal combustion engine has obvious technical advantages compared with other type of engine. It has higher efficiency; lower NOx and other PM emission; The mixture dilution degree is much higher than the direct injection diesel engine and other HCCI internal combustion engines through the piston movement to achieve the cylinder temperature rise, automatic instantaneous combustion, for which the compression combustion diesel engine cannot reach the technical level.

The HCCI engine still has many problems, there are four main problems to be solved:

1) Cold start of the engine is difficult. Various cold-start solutions have been proposed and investigated, such as using preheaters, using different fuels or fuel additives, increasing compression ratios, using variable compression ratios, or variable valve timing techniques. There is evidence that lighting is a viable option.
(2) The range of HCCI operating conditions is limited. HCCI combustion is almost simultaneous, too fast a combustion speed under a large load will cause Knocking combustion of the engine. Too slow combustion at a low load can cause flame propagation interruption. The results show that stratified combustion can effectively broaden the range of HCCI operating conditions, and the use of two kinds of fuel with different characteristics is also an important way to broaden the range of HCCI operating conditions and control the ignition time.

(3) Exhaust gas control systems should be further developed. Engines using HCCI technology produce low and particulate emissions but high UHC and CO emissions due to low combustion temperatures and uniform mixing of the mixture. Off-machine purifiers to reduce UHC and CO emissions are mature, but exhaust gas recirculation is preferred [20]. It is generally believed that recirculation of exhaust gases has such functions as heating, dilution, stratification, and chemical properties.

(4) Ignition time and combustion rate should be precisely controlled. The ignition process of HCCI is mainly controlled by chemical reaction kinetics, and the ignition time is determined by the composition, temperature, and pressure of the mixture. The ignition time and combustion process can only be controlled indirectly. The current solution is through EGR, VCR, and VVT.

Shortly, it can be predicted that the application of HCCI is limited by science and technology and will mainly be used for low load operations, such as highway cruises. After solving the above problems, we believe that HCCI will become a new generation of environmental protection heat engines.

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