



# Introduction of HCCI for Hydrogen Fuel Engines

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## **Authors' contributions**

*This work was carried out in collaboration between both authors. Author CZ designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors CZ and YL managed the analyses of the study. Author CZ managed the literature searches. Both authors read and approved the final manuscript.*

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## **ABSTRACT**

This paper is a brief review of the homogeneous charge compression ignition (HCCI) model for hydrogen-fueled internal combustion engines based on an analysis of the advantages and disadvantages of hydrogen internal combustion engines and HCCI combustion. It found that HCCI can be realized in a hydrogen-fueled internal combustion engine, meanwhile the HCCI can effectively reduce the emission of hydrogen internal combustion engine.

**Keywords:** *Hydrogen; internal combustion engine; homogeneous charge compression ignition (HCCI).*

## **1. INTRODUCTION**

As the global environment continues to deteriorate and energy depletion becomes more and more serious [1], the traditional internal combustion engine can no longer meet the

needs of sustainable development [2,3], and hydrogen has become an ideal alternative energy source with its renewable and clean combustion products. HCCI, as a new type of combustion method, can effectively improve the thermal efficiency of internal combustion engines

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and reduce NO<sub>x</sub> emissions. When HCCI is combined with hydrogen internal combustion engines, it not only alleviates the energy crisis, but also reduces pollutant emissions.

## 2. HYDROGEN INTERNAL COMBUSTION ENGINE

The hydrogen internal combustion engine is the use of hydrogen as an alternative energy source to conventional energy sources in an internal combustion engine. The combination of hydrogen and internal combustion engine has multiple benefits [4-6]:

- (1) Hydrogen is one of the cleanest energy sources because it does not contain carbon element and the only theoretical combustion product is water. Therefore, the emissions of hydrogen internal combustion engine will be greatly reduced compared with the traditional internal combustion engine;
- (2) Hydrogen has a strong diffusion capacity, its diffusion rate can reach 0.61 cm<sup>2</sup>/s. The strong diffusion can make the hydrogen better mixed with air or other fuels, so that the mixture in the cylinder is more uniform, furthermore, the combustion is more complete, thus improving the efficiency of internal combustion engine;
- (3) Hydrogen flame propagation speed is fast, faster than the traditional internal combustion engine fuels. The flame propagation speed enables the hydrogen fuel to burn rapidly in the cylinder, which makes the cycle of the internal combustion engine closer to the theoretical cycle and improves the efficiency of the internal combustion engine;
- (4) The ignition range of hydrogen gas is wide, which can be used in various combustion modes such as equivalent combustion, lean burn combustion, etc.

However, there are some shortcomings of the hydrogen internal combustion engine. Such as: the auto ignition temperature is higher, and it needs to reach 858°K. Hydrogen internal combustion engines may have abnormal combustion such as pre-ignition and backfire etc, which affects the normal operation of the engine, and some NO<sub>x</sub> is the main emission pollutant emitted during combustion. The Table 1 shows a hydrogen and other fuel properties.

Overall, hydrogen energy has advantages when compared to conventional energy sources. the hydrogen internal combustion engine has the most potential to be the new drive of the future from an automotive perspective.

## 3. HCCI COMBUSTION

Homogeneous charge compression ignition (HCCI) is a new combustion method for internal combustion engines that has been developed in recent years. It is different from both spark ignition and compression ignition. The difference between HCCI and spark ignition engine is in the ignition method, one is compression ignition, the other is spark plug ignition combustion. The difference between HCCI and compression-ignition internal combustion engine is whether the fuel is evenly mixed, whether there are multiple points of ignition or a single point of ignition in the cylinder, and whether there is a distinct flame front. The main cores are homogeneity, low temperature, and rapid heat release. Eight properties of HCCI are listed as follow:

- (1) HCCI can be applied to a variety of fuel types [7,8]. Theoretically, HCCI can be used as an ignition method for fuels that are suitable for compression to reach their auto-ignition temperature. It is also possible to combine different fuel choices and HCCI methods to compensate for their respective shortcomings and achieve a more effective ignition.
- (2) Uniform pre-mixing of fuel [9]: HCCI can mix the fuel with air outside the cylinder in advance, and after entering the cylinder, there is no need to rely on the gas flow or direct injection to mix the fuel inside the cylinder, so as to achieve the better uniform mixing effect inside the cylinder. The evenly mixed fuel can be burned quickly and fully in the cylinder, which improves the fuel utilization rate and the efficiency of the internal combustion engine. At the same time, it avoids excessive emissions due to incomplete combustion caused by the uneven fuel.
- (3) Low-temperature combustion [10-12]. Low-temperature combustion is one of the main methods of new combustion. The low temperature effectively avoids the temperature needed for NO<sub>x</sub> generation, which results in a reduction of NO<sub>x</sub> emissions.
- (4) High thermal efficiency [13-15]. This is mainly reflected in the three aspects. First,

because of the low temperature in the cylinder to reduce the heat transfer loss of the cylinder wall, thus improving the thermal efficiency. Secondly, the cylinder ignites at multiple points, making the combustion process more rapid and promoting the improvement of thermal efficiency. The third aspect is no throttling losses and a higher compression ratio. In terms of combustion and losses, all three aspects contribute to the thermal efficiency of the HCCI engine.

- (5) High levels of HC and CO emissions [16]. The peak temperature of the combustion gas is too low (below 1400K or 1500K) to oxidize CO to CO<sub>2</sub> at low load, resulting in a certain amount of CO and HC.
- (6) The HCCI combustion mode cannot operate all load conditions [17]. When operating under low load conditions, it is prone to engine misfires, while under high load conditions, the combustion process is abnormally fast and can lead to detonation, excessive noise, and other damage.
- (7) HCCI combustion control is difficult [18]. HCCI uses compression ignition and the fuel mixture at the beginning of combustion is multipoint ignition, and its combustion is directly controlled by chemical kinetics, rather than controlling the onset of combustion by the timing of ignition as in spark-ignition engines.
- (8) HCCI cold start difficulties. Ignition in HCCI mode is very sensitive to the inlet gas temperature, and small changes can significantly change the combustion phase. In addition, the initial temperature required to achieve self-ignition varies with fuel characteristics and operating conditions, so there are certain fuel requirements. Under cold start and idling conditions, the compressed gas temperature will drop because the fuel is not initially preheated from the inlet manifold and is rapidly cooled by the heat transferred to the cold combustion chamber walls. Without some sort of compensation mechanism, the lower compressed gas temperature may prevent the HCCI engine from igniting, making ignition starting difficult.

The above eight points illustrate the advantages and disadvantages of the HCCI model, many of which cannot be replaced by traditional combustion methods, but there are still some limitations to its operation, so one needs to find a

better way to solve these problems and bring out the advantages of this new combustion method.

## **4. HYDROGEN-FUELED INTERNAL COMBUSTION ENGINES WITH HCCI**

### **4.1 HCCI Engine with Hydrogen Fuel**

When HCCI mode is applied to pure hydrogen internal combustion engine, because of the low temperature combustion characteristics of HCCI mode, the temperature inside the cylinder can be controlled in a certain range (below 1400°K or 1500°K), which cannot produce NO<sub>x</sub>. So, it can effectively reduce the emission of NO<sub>x</sub> in the hydrogen internal combustion engine, thus further improving the emission performance of the hydrogen internal combustion engine, making the hydrogen internal combustion engine more clean. However, the combination of the two, because of the higher spontaneous combustion temperature of hydrogen, when the internal combustion engine in the case of compression ignition for cold start, there will be some difficulties. It is necessary to achieve a certain inlet temperature to ensure that the hydrogen can be compressed and ignited to achieve a normal start. The following solutions can be used: (1) preheating the gas mixture in advance to increase the inlet gas temperature; (2) using EGR technology to increase the temperature of the inlet gas; (3) changing the internal combustion engine structure to adopt a larger compression ratio; (4) using spark plugs to assist ignition start. These technical measures can effectively solve the problems of cold start and compression ignition difficulty, so that the HCCI mode of hydrogen internal combustion engine can be guaranteed in multiple operating conditions. Many researchers have studied the HCCI mode of hydrogen engine. Antunes et al. [19] conducted an experimental study on the F1L511 compression ignition (CI) engine using hydrogen fuel in HCCI mode. It is found that hydrogen is a viable fuel for CI engine operation in HCCI mode, meanwhile it has a very high heat release rate. Ibrahim et al. [20] improved the performance of a hydrogen fueled homogeneous compression ignition (HCCI) engine by regulating the filling temperature and adding carbon dioxide to extend its load range to control the phase of combustion by regulating the filling temperature and adding carbon dioxide. Priybrat et al. [21] developed a stochastic multi-region chemical kinetics model to perform an equivalent ratio, inlet temperature and charge quality analysis on a hydrogen HCCI engine. Maurya et al. [22] used

**Table1. Hydrogen, methane, octane properties at 330K and 1 atm**

Property	Hydrogen	Methane	Iso-Octane
Molecular weight (g/mol)	2.016	16.043	114.236
Density (Kg/m <sup>3</sup> )	0.08	0.65	692
Mass diffusivity in air (cm <sup>2</sup> /s)	0.61	0.16	~0.07
Lower heating value (MJ/Kg)	120	50	44.3
Flame velocity (ms <sup>-1</sup> )	1.85	0.38	0.37-0.43
Auto-ignition temperature in air(K)	858	723	550

a chemical reaction model to simulate a hydrogen HCCI engine and to simulate the parameters of the HCCI engine under various speed and load conditions. Much research has been done on the HCCI mode for pure hydrogen-fueled engines, and numerous previous studies have shown that the hydrogen-fueled HCCI mode can be implemented and can be effective in reducing NO<sub>x</sub> emissions, but the higher auto-ignition temperature when hydrogen is used as the fuel makes compression ignition, which requires a higher compression ratio, difficult to achieve and has a narrower operating range.

#### 4.2 HCCI engine with Hydrogen Blended Fuel

When hydrogen is burned as part of the fuel, the problem of hydrogen being difficult to compress in HCCI mode can be solved by adding a fuel with a lower auto-ignition point to ignite the hydrogen, or add hydrogen as fuel to reduce engine emissions. Either way, the combination of hydrogen and HCCI can reduce emissions and increase combustion speed. Kozlov et al. [23] carried out a numerical study of emission characteristics of HCCI engines in a fuel mixture containing hydrogen, using hydrogen as an additive, on the basis of different equivalent ratios ( $\phi=0.4$  and  $0.2$ ). The results show that the higher the hydrogen content in the mixture fuel, the more effective the reduction of CO, unburned hydrocarbons, and organic matter emissions. The addition of hydrogen also delayed ignition and shortened combustion time. Yoon and Park [24] studied and discussed the combustion behavior in HCCI engine by varying parameters including compression ratio, excess air ratio, and hydrogen content. The results showed that as the hydrogen content increased, the combustion rate increased and the combustion time was reduced by 10-90%. Hairuddin et al. [25] showed that when hydrogen and diesel are combined in a dual-fuel mode, an internal combustion engine can achieve lower levels of NO<sub>x</sub>, CO, and PM emissions and a 13-16% increase in engine efficiency in the HCCI mode through numerical

simulation. Elkelawy et al. [26] studied the performance of HCCI engines using natural gas as the main fuel, dimethyl ether and hydrogen as added fuels, and found that engine performance could be improved by incorporating a 10% hydrogen volume fraction into the natural gas/dimethyl ether fuel mixture.

Many studies have shown that hydrogen as an additive in HCCI internal combustion engine can get lower emission result, expand the performance of the internal combustion engine at a certain amount of hydrogen adding, and promote the combustion speed in HCCI mode.

#### 5. CONCLUSION

It is possible to use HCCI combustion mode in hydrogen fueled engines. Hydrogen fuel is a clean and renewable new energy. The combustion of hydrogen fueled internal combustion engines produce few polluting emissions., only a small amount of NO<sub>x</sub> and HC emissions, and HCCI mode can effectively reduce the emission of NO<sub>x</sub>. However, some issues, such as control difficulties and cold start difficulties, have yet to be addressed. The combination of hydrogen fueled engines and HCCI combustion mode can effectively reduce engine emissions and environmental stress while reducing the consumption of conventional primary energy. It facilitates to solve today's environmental problems and energy crisis problems.

#### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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