Exploring Fuel Characteristics and Performance in HCCI Engines with Alternative Fuels

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Abstract. In recent years, as automobiles have become essential in daily life, the demand for enhanced engine performance and environmental protection has increased rapidly. Traditional diesel and gasoline engines are known to produce excessive Nitrogen Oxide (NOx) and Particulate Matter (PM) emissions, coupled with low fuel utilization and combustion efficiency. This paper provides a concise overview of the current characteristics of Homogeneous Charge Compression Ignition (HCCI) engines and explores methods to enhance their performance and thermal efficiency using alternative fuels that surpass traditional options in various aspects. Biodiesel emerges as a viable substitute for diesel due to its environmental benefits and agricultural potential. Hydrogen, gaining popularity among engineers and automotive manufacturers, is also explored for its promise of clean energy. Additionally, natural gas, methanol, and ethanol are highlighted for their suitability under different thermal conditions. The paper further introduces a dual fuel mode in H_2/air-fueled HCCI engines, using a compound of H_2O_2 and H_2, and discusses the effectiveness of fuels mixed with nano additives like Al_2O_3 and $FeCl_3$. Through these alternatives, this study aims to present a pathway to improved engine performance and reduced environmental impact, paving the way for future advancements in HCCI engine technology.

Keywords: HCCI engine, fuels, combustion characteristics.

1. Introduction

The concept of HCCI was introduced by engineers in the 1990s as the popularity of automobiles and the demand for their performance grew rapidly. Homogeneous Charge refers to a homogeneous mixture of oil and gas, which is the way oil and gas are mixed in a conventional intake-injection gasoline engine [1-5]. Compression Ignition refers to compression ignition, which is the way combustion occurs in a conventional diesel engine. Literally speaking, HCCI is a combination of the characteristics of both gasoline and diesel engines [6-8]. Similar to traditional gasoline engines, HCCI engines add a precisely measured air-fuel mixture into the cylinder.

A conventional gasoline engine generates energy by igniting the air-fuel mixture through a spark plug. However, HCCI engines are different in that the ignition process is similar to that of a diesel engine [9, 10]. In other words, the piston compresses the mixture and causes it to combust on its own when the temperature rises to a particular degree. It is a novel combustion mode based upon reciprocating gasoline engines, which is merely a compression ignition proposal for gasoline engines. The advantages of HCCI engines over conventional gasoline engines lie in high thermal efficiency, low fuel consumption, and low NO_x emissions. The advantages of the HCCI engine lie in less NO_x and PM emissions and greater thermal efficiency. However, it is still facing a sort of technical tasks such as the limited operating range and inefficient conventional fuels which still need innovation. For conventional fuels like diesel and gasoline, which turn out to emit too many harmful and intractable emissions, engineers are looking for new energy as fuels for engine combustion like biodiesel, hydrogen, natural gas, ethanol and methanol. Also, further novel proposals are introduced by giving a dual fuel strategy or adding additives to improve the combustion characteristics and performance to some extent.

As for the practical applications of the HCCI engine, the appearance of the SKYACTIV-X engine from Mazda nearly represents the highest level of engine technology worldwide introduced by large displacement but low fuel consumption.

2. Advantages and disadvantages of HCCI engine

2.1. Advantages

When the compression stroke of the gasoline engine is almost finished, the gasoline is injected into the cylinder through the direct injection nozzles. HCCI’s compression ratio is higher, so the tiny oil droplets released have enough time to distribute evenly throughout the cylinder when the compression stroke is over. In comparison, the HCCI mode has an advantage over both RCCI and dual fuel modes in gross thermal efficiency. The specialty of HCCI combustion at high loads is due to its capacity to form a homogeneous fuel-air mixture during ignition [1]. The low combustion temperature of the HCCI engine results in deeply low heat transferring to the walls of the combustor, which reduces radiant heat transference and NO_x emissions.

2.2. Problems of Combustion Mode

Although the primary appealing superiority of the HCCI engine is reducing exhaust gas emissions by retaining preferable thermal efficiency, however, there are a couple of disadvantages to operating an HCCI engine, mainly introduced by the instability of combustion and restricted range of operation due to high inlet pressure [2].

Firstly, in detail, by controlling the combustion moment, the HCCI engine has high demands on temperature and pressure for self-ignition. The ECU management program should also be strengthened according to the density of oil and gas and the high demand for the precision of pressure and temperature.

Secondly, because of the concurrent compression ignition and heat release of HCCI, the transient cylinder and piston will be subjected to high pressure, and the phenomenon of detonation may occur, so it is crucial to enhance the mixture of air-fuel ratio, which requires HCCI to work in a dilute combustion condition, and the temperature of the effluent gas is comparatively low, making it difficult to use the turbocharging. For the descriptions mentioned above, HCCI's maximum loads may be significantly lower than those of conventional diesel engines. Furthermore, redox reactions require higher temperatures to begin. Low outlet temperatures are particularly problematic for catalytic converters.

Thirdly, because the maximum loads that may be reached by the HCCI engines mentioned are rather lower than those of conventional spark-ignition and directly injected diesel engines, HCCI engines must depend on the conventional spark-plug ignition system at great loads and high rpm as well, which indirectly requires the engine to have a variable compression ratio and changes back to a low compression ratio during the conventional ignition mode. So, the valve timing system and numerous pressure sensors are also necessary.

So as far as the present limitations are concerned, the HCCI gasoline engine is not yet capable of carrying out a full compression-ignition rarefied ignition mode, which intervenes only at low and medium revolutions to improve efficiency and reduce fuel consumption.

2.3. Problems with Fuels

Traditional fuels like diesel are not recommended because of the lower speed, larger mass, manufacturing and maintenance costs, noise and startup difficulties. Because of the long driving distance of diesel vehicles, the temperature and pressure of the engine become very high, and the cylinder produces more soot and carbon. The engine oil is also easy to oxidize and produces gum, so the diesel engine oil is required to have better high-temperature cleanliness. As for gasoline engines, they are confirmed to have higher fuel consumption rates, poorer economy and low exhaust purification indicators. This category of traditional fuels no longer meets the needs of the population.

3. Alternative Fuels Used in HCCI Engine

3.1. Biodiesel Use

Biodiesel used for HCCI engines turns out to not only improve ignition characteristics and engine performance but also decrease harmful emissions. HCCI engine occurs as a novel proposal to reduce emissions, while simultaneously keeping the advantage of diesel engines over gasoline engines with greater engine performance and economic benefits [3].

In addition, biodiesel is beneficial in reducing the risk of the greenhouse effect. CO_2 is released into the atmosphere with the use of biodiesel, but the plants used for producing biodiesel take away CO_2 from the air. Also, the feedstocks of production have multiple selections. Producers acquire feedstocks at extremely low prices, thus decreasing the fluctuating price of biodiesel on the market [4].

3.2. Hydrogen Use

Hydrogen contains no carbon and produces no CO_2 when burned. It is abundant and can be produced in a variety of ways. For example, it can be extracted from natural gas and can also be produced by electrolysis of water.

Its theoretical cycle is close to the Otto cycle. Hydrogen engine combines the high thermal efficiency of diesel engines and the high speed of gasoline engines in one system, which is an ideal system. Hydrogen engines can regulate power output by the concentration of the air-fuel mixing ratio, eliminating the need for a throttle. It improves the overall efficiency of the engine because there is no loss of flow in the fuel pump, and the higher efficiency of the thin fuel also plays an important role.

3.3. Natural Gas, Ethanol and Methanol Use

Fuels with a better auto-ignition specification are proper for low-load situations, while in the condition of high loads, fuels that have greater octane numbers have superiority. According to the present research, three fuels, natural gas, ethanol and methanol, which have distinct octane numbers, are experimented with in a single-cylinder engine to investigate an appropriate working range. Results concluded that natural gas is proper for higher inlet temperatures. On the contrary, ethanol and methanol are appropriate for lower inlet temperatures and lean mixtures [5].

4. Dual Fuel Mode

Consequently, another novel proposal to add H_2O_2 into the H_2/air-fueled HCCI engine is pointed out, which changes the combustion performance of H_2. H_2O_2 decomposes directly into oxygen and water and liberates a large quantity of energy when the temperature reaches 80°C, which will not produce air pollution [2]. According to the research, H_2O_2 effectively improves the engine performance compared to an HCCI engine fueled with H_2 singly.

Fig. 1 presents the impact of engine speed on temperature at the inlet valve close and indicated mean effective pressure (IMEP) at three different phi: 0.15, 0.20, and 0.25. The addition of H_2O_2 contributes to decreasing inlet temperature and increasing IMEP in each case. However, when the H_2O_2 volume fraction is invariant, a higher speed produces a higher inlet temperature in the same condition. Consequently, as the speed increases from 1800 to 3000 rpm, the temperature rises from 12 to 14K, and it shows a mere change in IMEP [2].

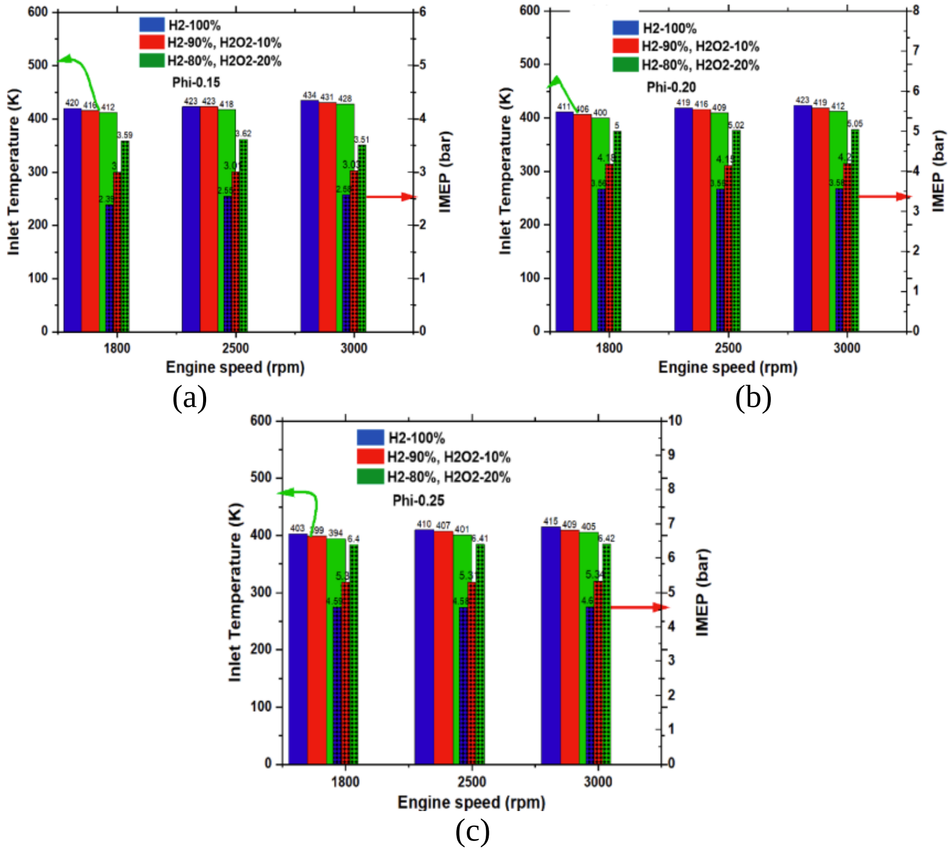

Figure 1. Impact of engine speeds on the inlet temperature and IMEP at different effective equivalence ratios (Phi) with various volume fractions of H_2O_2 [2]

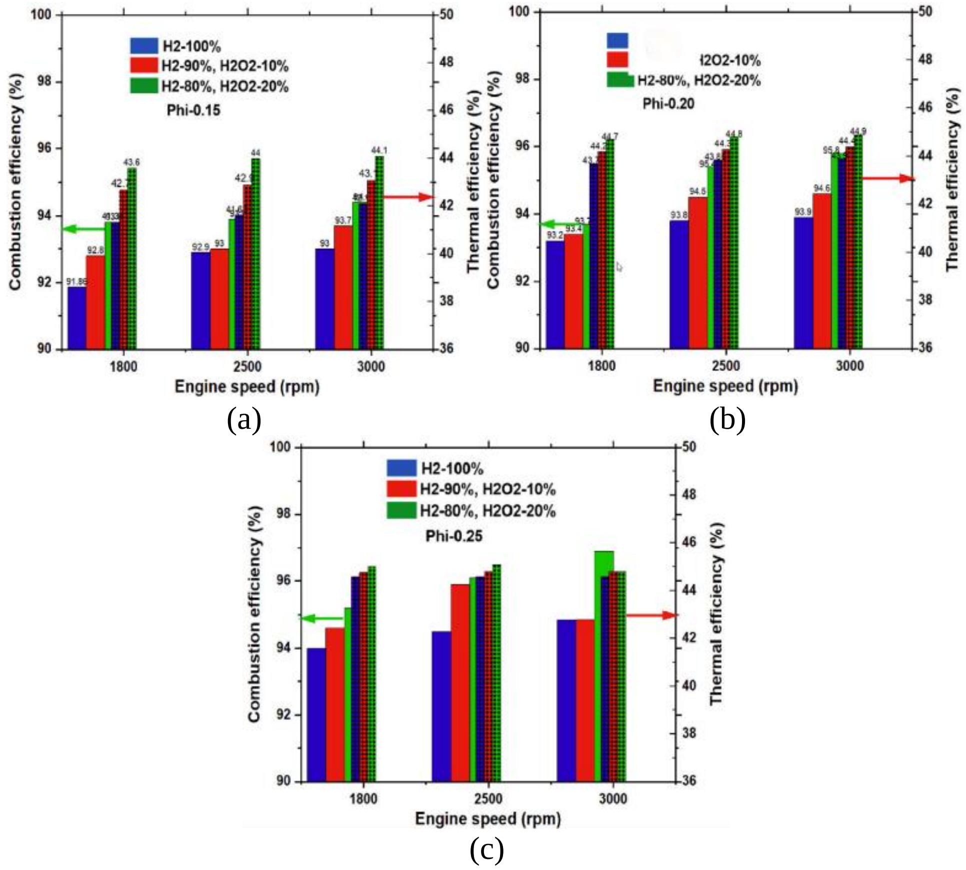

Figure 2. Impact of engine speeds on combustion efficiency and thermal efficiency at different effective equivalence ratios with various volume fractions of H_2O_2 [2]

Furthermore, Fig. 2 describes the characteristics of the HCCI engine at distinct engine speeds, adding H_2O_2 at different Phi. With the rise of the content of H_2O_2, the combustion and thermal efficiency increase at all three speeds. In the condition of a constant volume fraction of H_2O_2, the engine performance develops. Thereby, the combustion efficiency at maximum reached 97% at the speed of 3000 rpm in the condition of 20% H_2O_2, as the thermal efficiency reached 45% in the same condition [2].

Conclusively, the addition of H_2O_2 mixed with H_2 enhances the engine performance and thermal efficiency of HCCI engines in most conditions.

5. Additives Used in HCCI

5.1. WCOB with Al_2O_3 and $FeCl_3$

There is new research for exploring the condition and emissions of HCCI engines fueled by waste cooking oil biodiesel (WCOB) mixed with Al_2O_3 and $FeCl_3$ nano additives and pre-blended with gasoline. The results showed that the addition of WCOB largely reduced the emissions of HC, CO and smoke by 54.17%, 50%, and 22.69%, with the increase of NO_x emission instead. In contrast to diesel engines, adding Al_2O_3 and $FeCl_3$ showed a significant result in the improvement of BTE and the decline in HC, CO and smoke emissions [6].

5.2. DME, DEE, and n-heptane

Another proposal for adding three different additives (DME, DEE, and n-heptane) by oxidizing methane has been proven to be effectively reactive in high-pressure and temperature environments. Although the three additives turn out to have a nearly similar impact on the ignition operation, the research found that DEE is said to be the best choice among these three according to the engine requirement, while for the operating range, DME is better [7].

6. Conclusion

In conclusion, this paper provides a brief overview of the background of the HCCI engine and introduces its advantages over traditional engines along with the challenges being faced. The advantages lie in its combustion mode by mixing fuel with air in the inlet system of the HCCI engine to produce a homogeneous mixture of air and fuel, which is then compressed in the cylinder. Additionally, it benefits from using compression ignition in a much higher compression ratio thus igniting automatically. Nevertheless, because the recent technology cannot provide a complete compression ignition mode, the usage of fuels is considered an alternative to enhance the engine performance and combustion characteristics by another means. For single fuel mode, choosing hydrogen, biodiesel, natural gas, methanol and ethanol as the ignition fuel has proved successful by certain research to improve the combustion performance and reduce the emissions to a certain extent. In regard to dual fuel mode fueled with the mixture of H_2 and H_2O_2, the combustion also shows a considerable improvement. Additives such as Al_2O_3 $FeCl_3$ nano-additives, DME, DEE, and n-heptane can activate the fuel and influence the ignition temperature.

All in all, HCCI is a relatively new combustion mode based upon reciprocating gasoline engines, which has been now commonly used in the automotive industry but requires more technical support to improve its combustion mode and fuel selection. In the future, HCCI is expected to be much more competitive in the automobile market by improving its energy, thermal efficiency and stability.

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