Combustion Process and Performance of HCCI Engines under Different Fuels

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Abstract. In the wake of industrial advancement, environmental protection has garnered significant attention, particularly concerning engine-generated pollution. The Homogeneous Charge Compression Ignition (HCCI) engine emerges as a promising solution, offering enhanced combustion efficiency with diverse fuels. This research delves into the combustion characteristics of HCCI engines, employing various fuels under assorted conditions. For natural gas HCCI engines, an elevation in the hydrogen ratio bolsters the combustion reaction and augments thermal efficiency. A heightened compression ratio diminishes CO and HC emissions, albeit with a surge in NOx emissions. The n-butanol HCCI engine, utilizing a gasoline and n-butanol fuel mixture, reveals enhanced reactivity and thermal efficiency with an increased mixture ratio. Optimal power is achieved at an excess air coefficient (α) of 0.88, diverging from conventional aviation engines. The coal-based naphtha HCCI engine exhibits amplified thermal efficiency with escalating mixture ratios and temperatures. This comprehensive study underscores the pivotal role of fuel type and operational conditions in optimizing HCCI engine performance, contributing to the reduction of environmental impact while ensuring efficient energy utilization.

Keywords: Different fuel; HCCI engine; thermal efficiency; environmental protection.

1. Introduction

With the continuous development of industrial production in today's society, people pay more attention to scientific and technological innovation and have developed generation after generation of scientific and technological products. However, at the same time as rapid social development, the environment has also been seriously polluted [1]. People through the industrial emission of various nitrogen oxides, carbon monoxide and other pollution gases, resulting in global warming, the destruction of the ozone layer and other phenomena. Among them, the pollution generated by the engine in the industry accounts for a large part, and the traditional Spark Ignition Engine (SI) and Compress Ignition Engine (CI) are more serious for exhaust gas emissions, so how to make the engine more environmentally friendly and efficient has become a major challenge. At this time, the emergence of the Homogeneous Charge Compression Ignition engine (HCCI) effectively solved this challenge.

The concept of the HCCI engine was first applied in the research of Onishi et al., who used the HCCI engine as a two-stroke engine and as the concept of ATAC. A very important reason why the HCCI engine is widely concerned is that it produces high efficiency, low nitrogen oxide emissions, and low particulate matter content when it is burned. First of all, let's clarify the relevant knowledge of the HCCI engine. HCCI engine is different from SI and CI engines; it belongs to the complete mixture of fuel and air, and the mixture used in combustion is thin gas, which makes the temperature used in combustion relatively lower than SI engine. The SI engine is the kind of engine that needs to ignite to produce a heat source in order to promote the remaining gas combustion. In the combustion process of an SI engine, due to its combustion nature, more heat sources are needed to assist the combustion, and in some special cases, the heat transfer process will be lost. Hence, the combustion is incomplete in the process of converting carbon monoxide into carbon dioxide and eventually produces a certain amount of air pollution and waste emissions. Different from the SI engine, the HCCI engine is the engine that can burn itself because the mixture in it is relatively thin, and the temperature requirement is not so high as the SI engine, so at a certain temperature, the HCCI ignition will quickly react in the cylinder and complete the combustion.

For HCCI engines, the use of different fuels will affect the combustion process to a certain extent, and several common HCCI engines are Natural gas HCCI engines, n-butanol HCCI engines and coal-based naphtha HCCI engines. These fuel engines are different from the traditional diesel HCCI engine. These engines are more inclined to cleaner energy. Of course, in these engines, there is also a more important fuel ratio problem, which is called the doping ratio. Different fuels doping other different substances in nature will affect the combustion reaction process; this article will also be around this direction to launch an in-depth discussion.

2. Combustion Performance and Influencing Factors of Natural Gas HCCI Engine

2.1. Fuel Requirements for HCCI Engines

The main component of natural gas is methane. While using natural gas as a clean energy fuel, it can be clearly seen that the combustion products generated are more environmentally friendly than traditional diesel engines because the development of natural gas at this stage is not so high, but the potential for increasing production is still very huge.

Ayat conducted studies to investigate the load range of the HCCI engine when using natural gas as fuel. He did this using a modified single-cylinder VCR(variable compression ratio) diesel engine. Studies have shown that natural gas is the optimum fuel option for HCCI engines under concentrated mixture (high load) conditions and high intake temperatures. However, at all comparable ratios and intake temperatures, its CO emissions are substantial and exceed the emission limits of Euro VI rules.

The ZS195 direct injection diesel engine served as a prototype by Iklavo of Huazhong University of Science and Technology in China to set up a test bench and create a chemical dynamics model for conducting simulation and experiment studies on the characteristics of combustion and emission variation rules of HCCI engines doped with the gas from natural gas. The findings demonstrate that hydrogen addition might speed up combustion, advance the combustion phase, and boost indicated thermal efficiency. The stable thin burn limit of natural gas may be efficiently extended by adding hydrogen, which helps to realize thin burn in a natural gas HCCI engine and lower pollution emissions. The in-cylinder reaction process can be sped up by hydrogen mixing, and the ratio of hydrogen to air can control the combustion phase and increase engine load. Hydrogen mixing can also speed up the formation rate of H2O2 and OH free radicals. Many experiments have shown that hydrogen blending ratio and compression ratio will have a certain impact on the reaction of natural gas HCCI engines. This chapter will focus on these two directions.

2.2. Effect of Hydrogen Blending Ratio on HCCI Engine

The single-zone model is appropriate for the engine and has been extensively researched in the numerical simulation of hydrogen-doped natural gas HCCI engines. More precise predictions can be made about the combustion process. As hydrogen has combustion-supporting properties, it can be seen from Fig. 1 that the natural gas HCCI engine has a certain improvement in the ignition stage after mixing hydrogen. At this time, combined with the principle of the HCCI engine, the HCCI engine is fired after a full mixing of thin gases, while the natural gas HCCI engine has improved the ignition efficiency on the original basis. After adding hydrogen, it is equivalent to using a catalyst, which improves the thermal efficiency of the whole reaction.

The combustion heat release of 1 kmol of mixture per unit of time or unit of crankshaft angle is the definition of heat release rate. In simulated operating conditions, the hydrogen-doped ratio of 0% to 40%, Fig. 1 depicts the variation curve of the heat release rate of a natural gas HCCI engine. As can be seen from Fig. 1, compared with the heat release rate of pure methane combustion, the peak heat release rate of the engine combustion process decreased slightly after adding 10% hydrogen, while the peak heat release rate increased when the hydrogen content ratio was increased. It can be seen that the changing trend of the heat release rate with the increase of the hydrogen content ratio was the same as that of the temperature in the cylinder, and the heat release rate was not affected by the hydrogen content ratio.

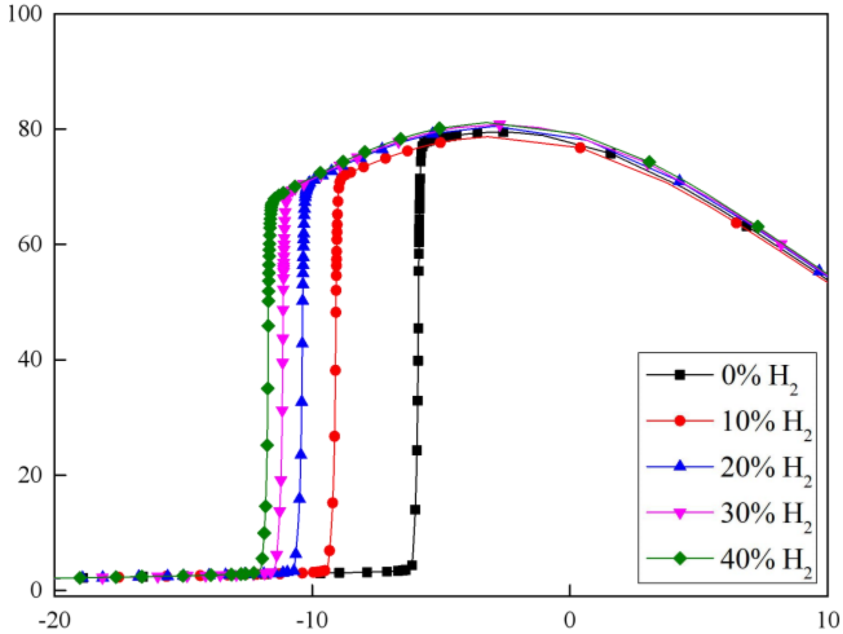

Fig. 1 Thermal efficiency under different hydrogen mixing ratios [1]

2.3. Effect of Compression Ratio on Natural Gas HCCI Engine

It can be clearly seen from the experiments of Li Yi et al. that the performance and emissions of engines co-operated by methanol and gasoline have great differences under the action of different compression ratios. The increase in compression ratio decreases the emissions of CO HC. However, the NOx increases, while the HCCI engine with a high compression ratio is economically beneficial [1].

Similarly, in Feng Renhua's research, it can be seen that because a high compression ratio is conducive to combustion, it can be found that increasing the compression ratio will reduce fuel consumption. At the same time, when the load is in the middle and high stage, it is the best position for the whole engine to respond. In the end, the experiment also proposed that the whole engine has the best performance when the compression ratio is 13 [2].

2.4. Summary

As for the influencing factors of the natural gas HCCI engine, it can be clearly seen that both the hydrogen mixing ratio and the compression ratio are conducive to the combustion to a certain extent, but on the contrary, if the engine reaction stage does not have sufficient compression ratio support, the exhaust gas emissions generated by the reaction will increase.

3. Combustion Performance and Influencing Factors of N-Butanol HCCI Engine

For n-butanol HCCI engines, a mixture of n-butanol and fuel oil is used. For n-butanol, it belongs to the second generation of biofuels. Compared with the first generation of biofuels, n-butanol in nature has good knock resistance and high density, which means it can provide relatively more energy in the reaction to promote the reaction in a more efficient direction. Secondly, the n-butanol HCCI engine and natural gas HCCI engine mentioned above have the advantages of reducing NOx and soot emissions.

3.1. Effect of Blend Ratio on Gasoline/N-Butanol HCCI Engine

It can clearly be seen from Fig. 2 that when a small amount of gasoline is added to n-butanol, the heat of the fuel can be increased to a certain extent. For the essence of n-butanol and gasoline, the N-butanol reaction is mainly related to the OH element, and the n-butanol reaction is more active than gasoline at low temperatures, which results in a situation. When the n-butanol reaction produces OH in the reaction, it will oxidize the gasoline in the mixed fuel, which will cause the result of the reaction to be lost [3].

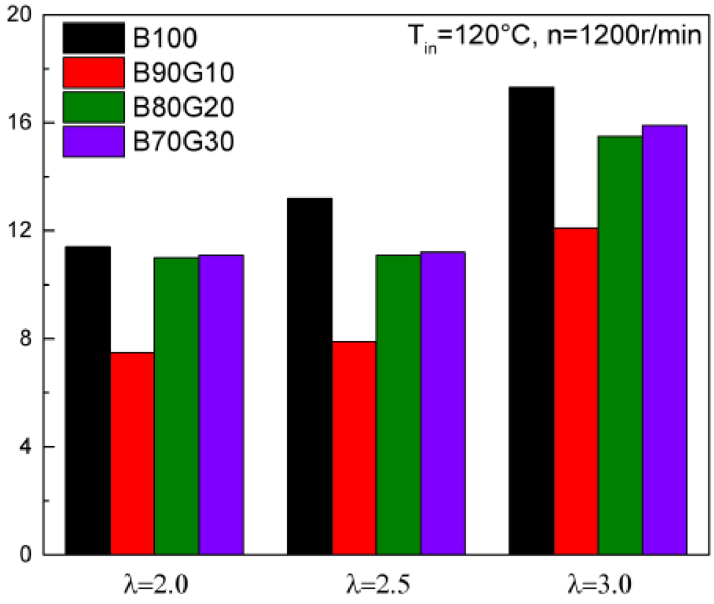

Fig. 2 Effect of mixing ratio on combustion duration BD [3]

As for the change of the temperature in the cylinder, adding a small amount of gasoline to n-butanol will increase the atomization degree of the fuel. The HCCI engine is fully mixed in the ignition stage, and the n-butanol fuel mixed with gasoline is more completely mixed in the ignition stage, and the ignition point is relatively low, which will promote the whole reaction to have a higher combustion efficiency.

3.2. Effect of Excess Air Coefficient on N-Butanol HCCI Engine

For the excess air coefficient, when $\alpha < 1$, the fuel is not fully burned, and when $\alpha > 1$, the fuel is thinly mixed. So, how to locate the best excess air coefficient to make the best reaction through experience when $\alpha = 0.88$, the maximum engine power? As can be seen from Fig. 3, for the n-butanol HCCI engine, the reduction of excess air coefficient will increase the temperature in the cylinder, making the fuel mix more fully and the heat release increase.

It is evident that the four fuels' increased NOx emissions have resulted from their reduction in NOx emissions. This is due to the mixture's concentration changing as a function of the slow increase in temperature caused by the cylinder's falling temperature is advantageous for NOx creation and boosts NOx emissions [4]. Because the in-cylinder temperature of blended fuel B90G10 was higher than the critical temperature of NOx generation at 1800 K, which causes an increase in NOx emissions, the NOx emissions of blended fuel B90G10 were significantly greater than those of the other three fuels when $\lambda=2.0$.

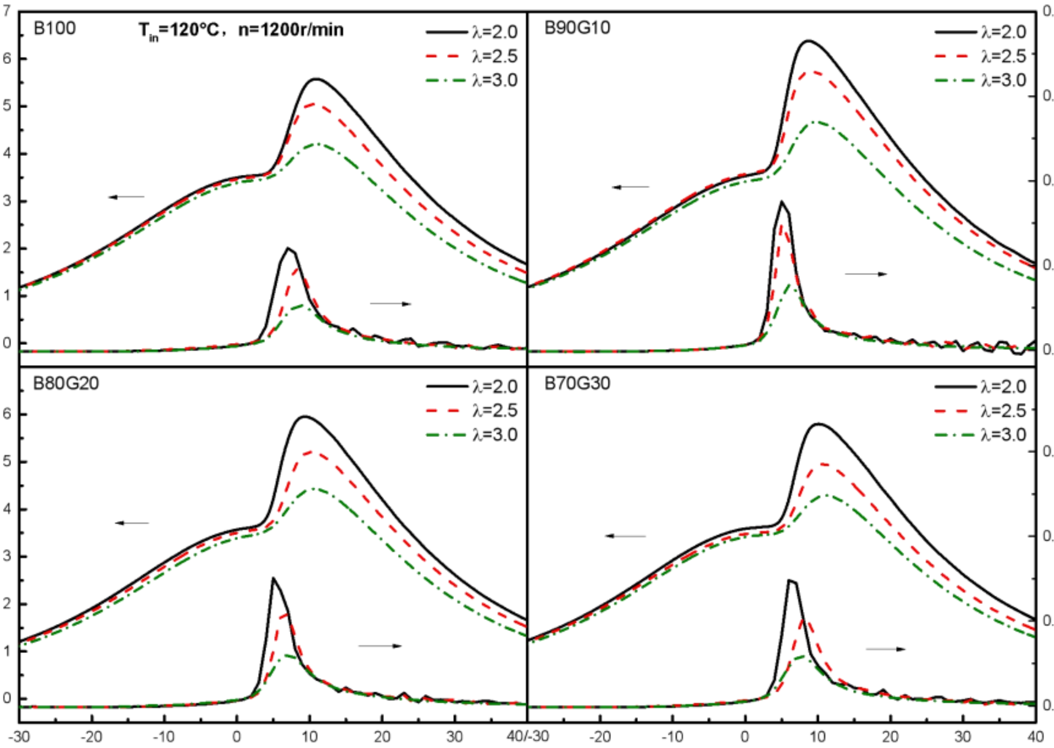

Fig. 3 Influence of excess air coefficient on cylinder pressure [3]

4. Coal-Based Naphtha HCCI Engine

The kinetics of fuel chemical reactions limit the HCCI combustion process, causing the fuel to self-ignite once it reaches the ignition temperature after being compressed by the piston close to the top dead center. The combination in the cylinder burns quickly and releases heat concentratedly. The physical and chemical characteristics of the fuel, specifically its octane number and cetane number, dominate the HCCI combustion process when all other boundary conditions of the engine stay constant. While naphtha's ignition characteristics fall between those of gasoline and diesel, its average carbon chain length is slightly lower than that of gasoline. It can achieve compression self-ignition while assuring adequate premixing of the mixture, and its atomization properties are comparable to those of gasoline. For HCCI engines, it is the perfect fuel [5].

4.1. Effect of Blending Ratio on Coal-Based Naphtha/Ethanol HCCI Engine

When compared to diesel, coal-based naphtha has better volatility, a shorter carbon chain, and better ignition properties. During the intake stroke, it may swiftly create a homogenous mixture; during the early phases of the compression stroke, it can absorb heat and build up heat; and frequently, before the top dead center of compression, it can initiate combustion. A homogenous mixture can easily generate a detonation when it burns before the top dead center of compression because it can ignite at several compression sites [6]. Additionally, both the octane number and the latent heat of ethanol vaporization are high. On one hand, the inclusion of ethanol enhances the blended fuel's explosiveness and combustion stability. However, coal-based naphtha clearly exhibits two-stage exothermic properties. The intermediate product H2O2 is produced during the low-temperature reaction stage, and it quickly breaks down into two active free radicals, OH. The severity of the ensuing reaction depends on the quantity of free radicals that are present [7].

4.2. The Temperature of Air Entered from Outside

First of all, the active free radical molecules in the reaction will be affected by the intake temperature. When the intake temperature is high, the molecular activity will be activated, making the combustion time in advance, the heat is more concentrated, and the whole reaction speed in the cylinder is faster. Secondly, ethanol will be vaporized to a certain extent in the reaction, and the increase in the intake temperature will offset part of the effect of vaporization, which is why it is necessary to control the intake temperature accurately [8-10].

5. Conclusion

The thermal efficiency of HCCI engines varies with different fuels under different conditions, and HCCI engines have higher thermal efficiency at low loads and emit fewer nitrogen oxides than SI engines. Compared with the SI engine, the HCCI engine is more stable than the SI engine. It fires evenly, which is why it burns more completely. The different conditions discussed in this paper also have certain constraints. For the natural gas HCCI engine, the hydrogen blending ratio actually has a low impact on the thermal efficiency. Secondly, for the entire HCCI engine system, the efficiency of HCCI is actually lower than that of the SI engine at high load. The reason why HCCI has not yet replaced the traditional SI engine is that more research and exploration are needed for HCCI engines, such as how to combine the characteristics of HCCI and SI engines in high loads. After the addition of hydrogen, it will promote the OH oxidation to generate more CO2, and if the compression ratio is adjusted in hydrogen, the chain reaction will be accelerated to a certain extent so as to promote the consumption reaction of free radicals to fuel.

For the n-butanol HCCI engine, the optimum reaction time of mixing ratio is not explored in this paper. Secondly, when adjusting the mixing ratio, it is not convenient to study the optimal mixing ratio, so it needs to be improved in this aspect.For the study of various HCCI engines, the paper only stays in the study of a single condition; if each condition is mixed together, then the model constructed will be more complex and abstract.

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