HCCI Engines: Benefits, Challenges and Future Advancements

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Abstract. Homogeneous charge compression ignition (HCCI) engines represent a significant advancement in internal combustion engine technology. This study examines the main advantages of HCCI engines, such as increased fuel flexibility, decreased pollution from nitrogen oxides (NOx) and particulate matter, and enhanced thermal efficiency. However, HCCI technology also faces challenges, such as controlling the combustion process and achieving stable ignition across diverse operating conditions. With rapid advancements in information technology and scientific methods, the automotive engine industry has made significant strides in recent years. In response to stricter environmental regulations and the growing popularity of electric vehicles, HCCI engines have gained increasing attention. Despite existing challenges, continued technological improvements are expected to enhance the feasibility and performance of HCCI engines. This paper reviews current research and technological developments, emphasizing the potential of HCCI engines to revolutionize the automotive industry while addressing critical issues that need resolution. Vital potential chances regarding this exciting field is highlighted.

1 Introduction

Along with the accommodation of oil becoming less fast, the level of the environment is souring, by the way. Many scientists have tried to find renewable resources of energy to replace conventional engines [1]. Most well-known renewable resources come from nuclear fusion energy source, geothermal energy, ocean energy, and other sources. Nevertheless, there remains a vital problem is that most renewable energies cannot be produced stably because of their availability issues. Take solar resources as an example. Although solar resource is regarded as one of the future main energy resources, they only occupy a small part of global energy requirements, which is only the whole chief energy provision's twentieth, and their low energy transfer efficiency is another insurmountable hinder to today's technology [2].

Additionally, some kinds of batteries are still the best energy storage available , while its capacity is quite restricted. Therefore, dependence on internal combustion engines which based on fossil (ICE) is necessary for many industries. With no ICE provided for transporting, it is impossible to reach such a high living standard today. Traditionally, SI and CI are two

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main categories of internal combustion engines. The former has drawbacks due to high knock, which are low efficiency and low compression ratio.

On the other hand, the latter was exposed to excessive amounts of harmful air pollutants, such as hydrocarbon (HC), carbon dioxide (CO_2), nitrogen monoxide (NO).These pollutants are responsible for some harmful effects like the Greenhouse Effect, etc. Incomplete combustion is one main source of primary matter pollution, as well as sea salt and dust. H_2SO_4, NH_3 and functionalized organic compounds condensed in the atmosphere formate quantities of subordinate primary matter. Human-made airborne particles are an increasing amount compared to that made in nature, PM2.5 and PM10 categorized by aerodynamic diameter size influence visibility and air quality, even making climate worse in the end [3]. One of the chief culprits to these emissions is Internal combustion engines, invisibly affecting human health.

So here comes HCCI engines, which is an unearthly solution to soar engine's efficiency, lower fuel expended and decrease the levels of emission. Compared to traditional CI and SI combustion modes, HCCI mode has a remarkably faster burning rate [4]. Here are the main advantages of HCCI engines. (i) Compared to SI engines, it is probably to reach higher fuel efficiencies, as it is managed in fuel-lean conditions and higher compression ratio. (ii) HCCI engines have remarkable fuel flexibility, and they produce less NOx and PM emissions. Nevertheless, HCCI engines have many challenges as well, including higher emissions in HC and CO emissions.

As future dominating engines instead of CI and SI engines, this paper will summarize previous related articles. This paper will mostly introduce how HCCI engines achieve these advantages, face these challenges and explain how it gains a broad prospect. This document can assist readers comprehend the characteristics of the HCCI mode, and to build the HCCI technology that aspires to produce reduced emissions.

2 Advantages of HCCI engines

2.1 High fuel efficiency

HCCI engines are capable of achieving a better fuel efficiency as compared to conventional engines (such as SI and CI engines). The main reason why HCCI has such high thermal efficiency is that HCCI engines have lean operation conditions and much higher compression ratios, which make it more likely to fit the Otto cycle approximately. According to research by Zhao et al. (2007), HCCI engines are able to reach 20 percent extra thermal efficiency compared to conventional engines, as shown in Table 1 [5]. The key factor is its auto-ignition process, which allows a more uniform, stable, complete combustion, lowering the waste of fuel and maximizing energy extraction.

Table 1. Contrast of thermal efficiency among SI, CI and HCCI

Engine Type	Thermal Efficiency (%)
SI Engine	25-30
CI Engine	35-40
HCCI Engine	45-50

2.2 Low NOx and particulate emissions

The emission of NOx is significantly reduced in HCCI mode mainly achieved by its low combustion temperature, as well as PM emissions. This reduction is indispensable for ensuring emissions lower than governments' regulation standards and improving air quality. Table 2 [6,7] shows that Thring (1989) and Dec (2009) have demonstrated that NOx and PM emissions are significantly lower in HCCI engines when compared to traditional engines. NOx formation is limited because of lower combustion temperature, while the feature of homogeneous charge is useful in reducing soot formation. Research by Syed Yaser Hussaini et al.'s research also revealed that, at 2300 rpm, HCCI engines emit significantly less NOx than SI engines—roughly 10 ppm to 60 ppm, or 13.3% of the former—Fig. 1 [8].

Table 2. Emissions comparison of HCCI, CI, and SI

Emission type	SI engine emissions	CI engine emissions	HCCI engine emissions
NOx	High	Moderate	Low
Particulate matter	Low	High	Low

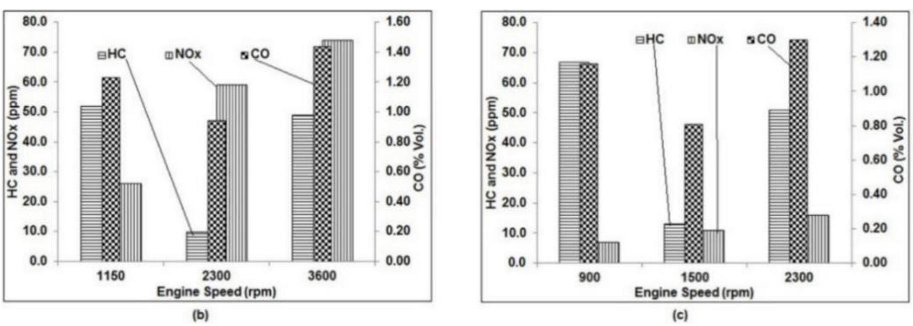

Fig. 1. Comparison of three types of emissions between HCCI and SI engines [8].

2.3 Fuel flexibility

HCCI engines have outstanding fuel flexibility, adaptable in operating various fuels, including gasoline, diesel, and alternative fuels. That is because any fuel type becomes adaptable in HCCI mode, which can be evaporated and blended with air before ignition. This adaptability makes it possible to use different types of fuels like ethanol, methanol, and biofuels in order to develop the sustainability of HCCI technology, as shown in Table 3 [9].

Table 3. Comparison of different fuel types related to their compatibility (Source: Kook et al., 2005)

Fuel Type	Compatibility
Gasoline	High
Diesel	High
Ethanol	Moderate

Methanol	Moderate
Biofuels	High

3 Challenges of HCCI engines

3.1 Combustion control

The first primary challenge of HCCI engines this paper introduced is the precise management of the combustion process. HCCI engines rely on the fuel-air mixture's chemical interactions, which makes it challenging to control the start of combustion and prevent the "knock" phenomena. This might be the biggest difference between SI and CI engines, which is well-defined in the ignition point. Onishi et al. (1979) and Dec (2009) have explored various strategies to improve combustion control in HCCI engines, including variable valve timing and advanced control algorithms, as shown in Table 4 [10,11]. They proved that accurate control over temperature, pressure, and mixture composition is critical for reliable operation.

Table 4. Different control strategies

Control Strategy	**Description**
Variable Valve Timing	Adjusting the timing of valve opening and closing to control the combustion process.
Direct Fuel Injection	delivering fuel straight into the combustion chamber in order to attain exact control.
Advanced Control Algorithms	Using sophisticated software to manage combustion parameters.

3.2 CO emissions

Studies have indicated that HCCI ones emit more CO compared to gasoline engines. This, which is clearly defined in the ignition point, may be the largest distinction between CI and SI engines. As seen in Table 4, Onishi et al. (1979) and Dec (2009) have investigated a number of approaches to enhance combustion control in HCCI engines, including variable valve timing and sophisticated control algorithms [10,11]. They demonstrated that precise regulation of mixture composition, pressure, and temperature is essential for dependable performance.

3.3 HC emissions

HC emissions generally increase when operating in HCCI mode, presenting a significant challenge for widespread adoption in vehicles. Kobayashi et al. investigated the emissions properties of a natural gas-powered HCCI engine that was converted from a gasoline engine. When compared to SI engines, they found much higher HC emissions [12]. A 25cc, four-stroke, air-cooled single-cylinder SI engine was modified by Lemberger et al. to run in HCCI mode using a variety of combustion management methods, and they recorded significant HC emissions [13]. At 3000 rpm and an equivalency ratio of 0.30, the highest HC emission detected was 950 ppm, which is almost 7 times greater than in SI mode. Milovanovic demonstrated that reducing coolant temperature could significantly decrease HC emissions [14].

3.4 Difficulty in high-load operation

HCCI engines are typically operated within a narrow range, usually under low to medium loads. When extended to high-load operations, emissions tend to increase and thermal efficiency decreases. Zhao et al. (2007) highlighted the need for further research to broaden the operational range of HCCI engines. The pressure rise rate can get quite high with high loads, which could harm the engine. Thring et al. demonstrated that the use of a specially designed fuel injector for CI engine applications was ineffective in atomizing diesel properly.

4 Future prospects and technical advancement

4.1 Composite HCCI engines

4.1.1 HCCI Gasoline engine

HCCI gasoline engine The high volatility of gasoline facilitates the formation of a homogenous fuel mixture. Researchers have focused on controlling the combustion rate and modes, allowing for mode switching under high-load conditions. Engines would then be electronically controlled to select the optimal mode for the current situation. This characteristic of modern HCCI combustion applications in gasoline engines provides superior stability during mode switching and precise fuel injection.

4.1.2 Diesel HCCI engine

Diesel features a low ignition point and a difficult time evaporating, it must be heated before it can be utilized as fuel in HCCI ICEs. High pollutant emissions and poor thermal efficiency are the outcomes of a low compression ratio. Heating aids in evaporating and mixing the diesel fuel during late injection and high swirl conditions.

4.1.3 An additional novel hybrid fuel HCCI engine

HCCI engines exhibit excellent adaption in different kinds of fuels due to their ability to accommodate a wide range of octane numbers. Besides gasoline and diesel, alternative fuels such as CH_3OH, CH_3CH_2OH, CH_4,$CH_3OCH_2CH_2OCH_3$, and H_2 have been proven exactly to be suitable for HCCI engines. In particular, using pure hydrogen fuel in HCCI engines offers significant advantages over conventional fuels.

4.2 Advanced control system

Fuel operation plays a key role in regulating the timing of ignition and combustion phases when implementing HCCI technology in engines. This involves manipulating fuel reactivity, adjusting fuel composition, and fine-tuning fuel injection strategies. The first step involved conducting experimental studies on different combinations of high- and low-reactivity fuels and non-reactive fluids to introduce impurities or distribute reactivity within the cylinder. This allowed the researchers and engineers to balance high pressure rise rates and operational range restrictions while controlling auto-ignition timing and maximizing benefit during the combustion phase. Furthermore, widely adopted and tested HCCI engines involve varying fuel compositions and sometimes adding substances to the original fuel. Another less effective method tested on HCCI engines for controlling auto-ignition timing is fuel injection strategy (Fig. 2) [15].

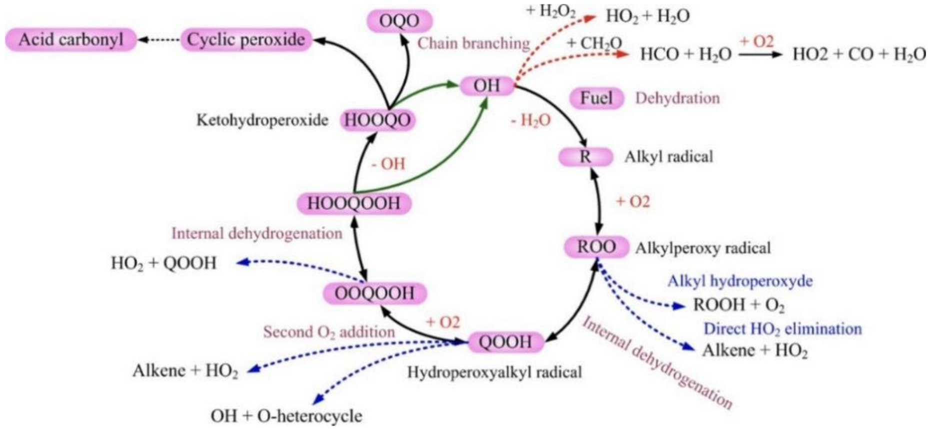

Fig. 2. Formation of different types of products in HCCI engines [15].

5 Conclusions

This article combines the HCCI engine's performance advantages and challenges to look at its prospects comprehensively. HCCI engines are a symbol of promising technology that aims to achieve cleaner and more efficient internal combustion engines. HCCI combustion mode has remarkable potential in emission features and eco-friendly fuel consumption. To cope with various environmental problems, HCCI technology might be the most suitable way for the development of internal combustion engines. HCCI engines offer innovative new ideas as well as options for pollutants and thermal efficiency issues because of their effective efficiency and low-emission characteristics, as HCCI mode has such significant advantages. Plus, HCCI engines operate smoothly and perfectly compared with traditional spark-ignition engines and direct-injection diesel engines, as it is approximately a combination of traditional SI engines and CI engines.

Moreover, HCCI engines are less reliant on scarce fuels such as oil, and their emission control systems may be simpler to manage. However, the obstacles hindering the development of HCCI engines are significant and must be addressed to unlock their full potential. To commercialize HCCI technology, several key challenges need resolution. These include precise control of injection timing, dropping of HC and CO emissions, enhancing capability to begin in cold conditions, overcoming difficulties in high-load operation, achieving homogeneous mixture preparation, and managing intake charge temperature. Given the rapid pace of technological advancements, ongoing research is likely to surmount these challenges, paving the way for practical applications of HCCI engines. Gradually, HCCI engines are expected to become a dominant force in many internal combustion engine manufacturing, offering promising and bright prospects.

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