Proceedings of the 3rd International Conference on Computing Innovation and Applied Physics
DOI: 10.54254/2753-8818/25/20240949

# Revolutionizing engine technology: The emergence and potential of novel engine materials

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**Abstract.** Concerns from both society and the government about the pollutants from automobile exhaust is becoming more and more noticeable in recent years. Compared with the engines mostly used currently, which are gasoline engines and diesel engines, the HCCI engine has ameliorated not only the problem of pollutant emissions but also efficiency to a large extent. This paper provides an in-depth analysis of Homogeneous Charge Compression Ignition (HCCI) engines. It first introduces the fundamental processes governing HCCI combustion and illustrates its working mechanism. While HCCI engines promise heightened efficiency, reduced emissions, and fuel versatility, they also present challenges such as combustion timing and related emissions. Commercial implementations by Nissan and Honda are discussed, shedding light on real-world applicability. Furthermore, the potential amalgamation of biodiesel with HCCI is explored, signaling a promising future for renewable fuels in advanced combustion engines. Despite the rise of hybrid vehicles, the unique benefits of HCCI position it as a significant player in future transportation. This paper emphasizes the necessity of ongoing research to overcome HCCI's challenges, ensuring it remains at the forefront of green automotive solutions.

**Keywords:** HCCI engine technology, Application of HCCI, Prospects of HCCI technology

## 1. Introduction

HCCI is a relatively new technology that has not been used widely or commercially worldwide compared with commonly used engines [1]. HCCI engine uses compression ignition or spark ignition engine configurations, assigning priority to higher engine efficiency and lower emissions. Due to the possibility for the HCCI engine to use a great range of fuels, it produces much lower emissions than conventional engines, which enables it to be applied to the hybrid engine configuration. In this way, it can reduce fuel consumption to a large extent.

For years, scientists and automobile companies have been struggling with engines to make them more efficient, energy-saving, and, at the same time, more environmental-friendly. It is widely recognized that the utilization of hydrogen as an energy carrier, facilitating energy extraction through fuel cells or adapted internal combustion engines, holds the potential to mitigate apprehensions associated with diminishing oil reserves, escalating fuel costs, and, notably, the environmental repercussions stemming from the combustion of hydrocarbon-based fuels [2]. Even though hydrogen is always considered the future of the fuel, the transition from the current era of fossil fuel to a desired hydrogen-fuelled world is still challengeable, scientifically and technologically, which is said to require a few decades' strive of the scientific community. The biggest problems for the energy carrier, the

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hydrogen, are believed to be the storage, transportation, and distribution [3].

It is critically imperative to explore the mechanisms underlying the superior performance of the HCCI engine relative to conventional engines such as gasoline or diesel engines, in addition to analyzing its constraints to pave the way for imminent advancements. In this paper, the examination of the HCCI engine is conducted in conjunction with a comparative analysis of gasoline and diesel engines, which allows for a more nuanced and intuitive elucidation of the merits of the HCCI engines.

## 2. The Working Principle of HCCI

The HCCI procedure commences with the introduction of a pre-mixed fuel-air mixture into the cylinder, configured to achieve specific equivalence ratios. Following compression of the mixture within the cylinder, it attains the requisite ignition temperature. Subsequently, ignition takes place simultaneously at multiple locations around the cylinder, facilitating an exceptionally rapid combustion process and the efficient dissipation of heat from the cylinder within an abbreviated temporal interval [2].

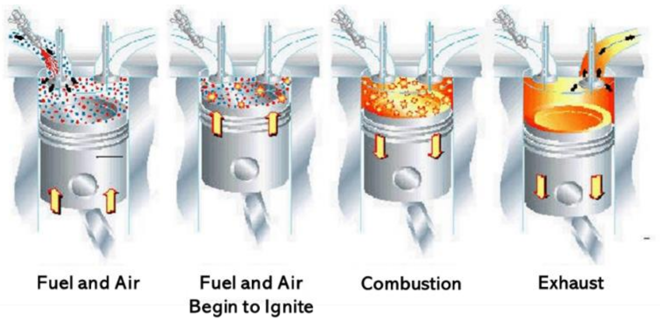


**Figure 1.** Scheme of HCCI Process [4]

For the basic working process of the HCCI engine, separate steps could be classified as shown in Figure 1: i.) Exhaust Gas Recirculation (EGR) is applied to regulate both the combustion process and the rate at which heat is dissipated. Concurrently, it is utilized to formulate an air mixture. ii.) Once the temperature within the cylinder reaches the auto-ignition threshold towards the culmination of the compression stroke, ignition transpires spontaneously at multiple distinct sites within the engine simultaneously. iii.) The balance between exhaust emissions and combustion efficiency could be achieved through accurate control of heat removal.

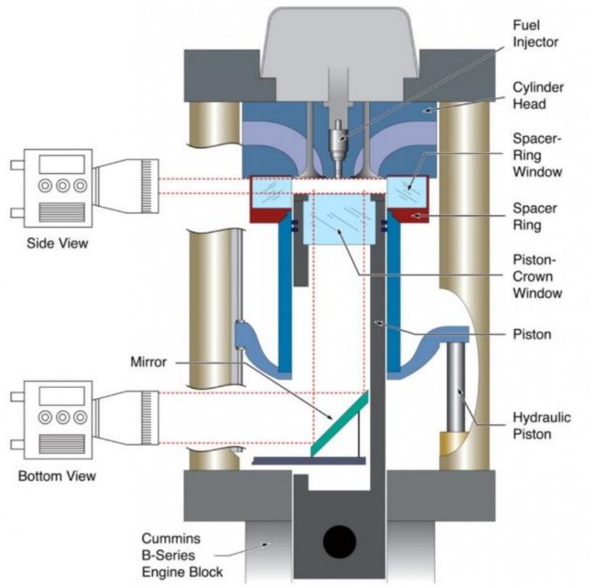


**Figure 2.** Schematic of the optically accessible HCCI research engine [5]

Despite its designation as a homogeneous charge, practical considerations arise out of heat transfer during the compression stroke and convective transport, resulting in thermal inhomogeneities even in a well-mixed fuel-air mixture. The thermal stratification leads to sequential combustion as different sections of the charge reach their autoignition temperatures at distinct points during compression by the pistons. This lowers the combustion rate, enabling significantly higher fueling rates without encountering knock, a scenario not achievable with a completely homogeneous charge (Figure 2).

## 3. Advantages and Demerits of HCCI

### *3.1. Advantages*

An advantage associated with the HCCI operational mode is the eradication of regions within the cylinder characterized by fuel-rich and elevated temperatures. This absence of such zones subsequently mitigates the generation of exhaust emissions, including nitrogen oxides and particulate matter.The HCCI mechanism could attain elevated temperature at the culmination of the compression stroke, fostering spontaneous ignition of the charge, attributed to its substantial compression ratio, which experimentally ranged from 18:1 to 25:1 [2]. HCCI also owns a much shorter combustion duration compared to conventional engines [6], which also reduces the amount of pollutants whilst having a higher thermal efficiency.

Another big advantage of HCCI is the fuel flexibility [6], which enables the usage of a range of renewable fuels, for instance, alcohols like ethanol, butanol methanol etc., which shows that the HCCI could be a good alternative for fossil fuel. Moreover, it is found by Telli et al. (2020) that there is no need to completely abandon the conventional SI engines and CI engines for the use of the HCCI engine. Instead, it is possible to convert those conventional engines into HCCI mode, which is the best solution.

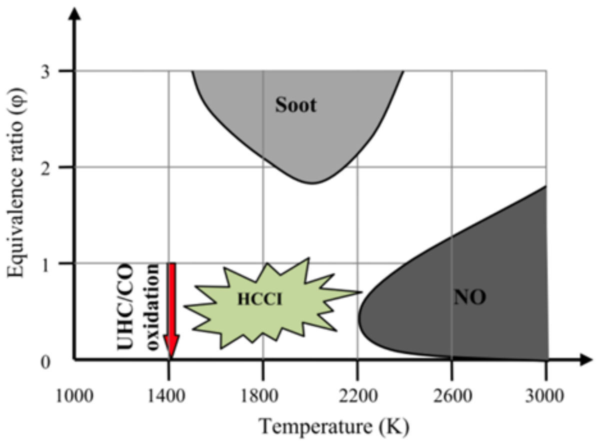


**Figure 3.** Nitrogen Oxides and soot formation with respect to equivalence ratio and temperature [6]

With respect to environmental protection, figure 3 shows the region of soot and nitrogen oxides regarding to different equivalence ratios and temperature. Soot formation depends on a high equivalence ratio, while nitrogen oxides rely on high temperature. However, it is obvious that the HCCI is out of both regions since the HCCI process runs at low temperatures and requires a low equivalence ratio.

### *3.2. Demerits and Solving Solutions*

As mentioned in the last part, the HCCI process has a shorter combustion duration in comparison to SI engines and CI engines. However, it is quite hard to control when exactly the combustion occurs. One of the most challenging tasks for HCCI combustion is the controlling of the combustion phasing. In contrast to spark-ignition or traditional diesel engines, where the initiating stage of combustion is directly controlled, the HCCI system operates differently. It does not rely on direct control mechanisms for commencing combustion. Instead, combustion is initiated through the auto-ignition of the air-fuel

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mixture. The auto-ignition process in a fuel-air mixture is influenced by both the composition of the fuel-air mixture and the temperature prevailing within the cylinder. Stanglmaier and Roberts (1999) conducted an investigation into the variables that impact the combustion process within the HCCI engine [7]. They identified several factors as influential, encompassing aspects such as the fuel's auto-ignition characteristics, concentration, residual rate, reactivity, homogeneity of the mixture, compression ratio, and various temperature-related parameters, including but not limited to intake temperature, the latent heat of fuel vaporization, and overall engine temperature. Furthermore, they underscored the significance of heat transfer to the engine and various engine-specific parameters in this context. They emphasized that improper combustion timing, resulting from an increased equivalence ratio, can lead to reduced efficiency and power output [8]. There have been a few methods attempted to control the combustion phase, but a basic distinction can be made between the methods.

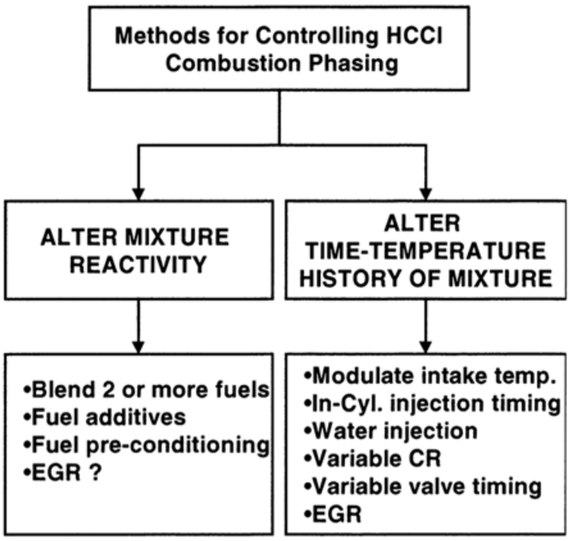


**Figure 4.** Methods for controlling HCCI combustion phasing [8]

Figure 4 illustrates various approaches employed to regulate the combustion phase, encompassing strategies such as in-cylinder injection timing, water injection, modulation of intake air temperature, adjustment of compression ratio, and manipulation of valve timing. Empirically, the method most frequently employed to govern the commencement of the combustion reaction involves the modulation of intake air temperature. Elevating the intake temperatures induces an earlier initiation of combustion, whereas conversely, lower intake temperatures delay the onset of combustion. More than this, the method is generally deemed impractical for mobile applications. The utilization of this approach for regulating the combustion phase has been demonstrated to be inefficient due to the substantial influence of the fuel vaporization process on the temporal-temperature profile of the mixture. Another method that has been explored in an effort to postpone the commencement of the reaction is the injection of water. However, this approach was similarly deemed unsuitable [7].

Despite the reduced emissions of pollutants in the HCCI process, it is noteworthy that the process still generates hydrocarbon and carbon monoxide emissions. These emissions can occur due to incomplete combustion, and their persistence can lead to a decline in in-cylinder temperature, consequently resulting in excessively delayed combustion timing. The in-cylinder temperature plays a pivotal role in determining the characteristics of hydrocarbon which is unburned, and carbon monoxide emissions [8] as the HCCI process runs at low temperatures, which would lead to higher emissions of unburned hydrocarbon and carbon monoxide. Figure 5 and 6 illustrates the amount of hydrocarbon and carbon monoxide produced versus the length of combustion timing. The data indicates that reduced equivalence ratios and extended combustion timing are associated with heightened levels of both hydrocarbon and carbon monoxide emissions.

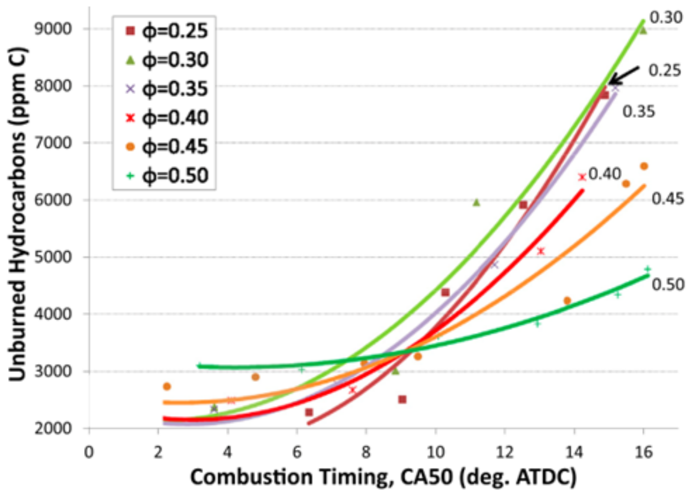


**Figure 5.** Experimental results of unburned hydrocarbon emissions for different equivalence ratios and combustion timings at pin = 1.8 bar and 1800 RPM [8]

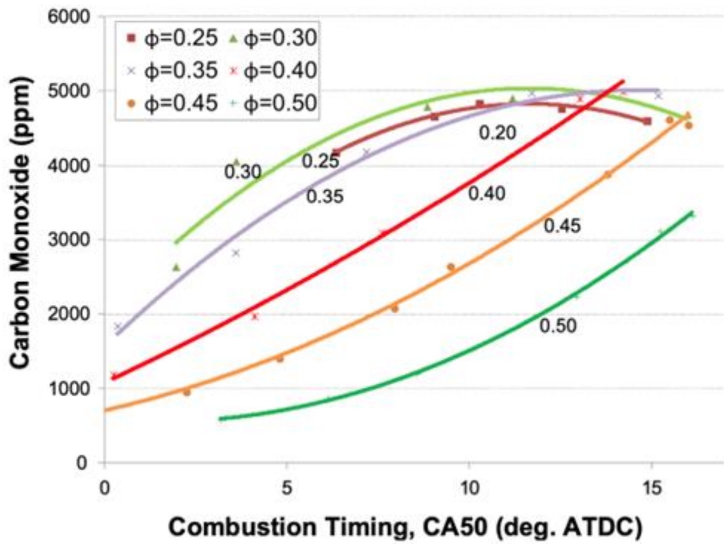


**Figure 6.** Experimental results of carbon monoxide emissions for different equivalence ratios and combustion timings at 1.8 bar and 1800 RPM [8]

Summarizing the hydrocarbon and carbon monoxide results from Figures 5 and 6, and it is obvious that in-cylinder temperature has a detectable impact on the emissions. At around 1000 K, the unburned hydrocarbon emissions are extremely high, but little carbon monoxide is produced since only a small part of the oxidation of hydrocarbon into carbon monoxide occurs. At temperatures 1000 K to 1500 K, hydrocarbon is oxidized more effectively, but carbon monoxide emissions are high. Above 1500 K, both are oxidized faster, which causes low emissions of both products.

## 4. Application of HCCI

The main point that differentiates HCCI engines from conventional engines is the mixing phenomenon in the combustion chamber before ignition. The HCCI is reported to be sharing similarities with both SI engines and CI engines. It requires the premixed charge like the SI engines do, and meanwhile, a high auto-ignition temperature is also needed to be the initiation, which is also an essential step for CI engines [4].

In 2003, there were two commercially available engines worldwide operating in HCCI mode [5]. The first was introduced by Nissan, which featured an innovative combustion technology known as the MK Combustion System. The second engine was developed by Honda and named the AR Combustion System. Nissan's engine, as depicted in Figure 7, was referred to as the 'Modulated Kinetics' and was integrated into a conventional Compression Ignition Direct Injection (CIDI) engine utilizing diesel fuel.

Under light loads, the duration required to attain nearly complete homogenization of the fuel-air mixture is shorter than the time necessary for spontaneous fuel autoignition. Consequently, this condition leads to nearly uniform combustion with a low equivalence ratio, resulting in notably diminished emissions of particulate matter (PM) and nitrogen oxides. On the other hand, Honda introduced a conceptual HCCI combustion system for a production two-stroke engine, demonstrating its feasibility by participating in the Granada-Dakar desert race [5]. The AR Active Radical engine also functions as a dual-mode engine, transitioning to spark ignition mode at higher loads. Notably, the AR engine has exhibited substantial improvements in fuel economy, boasting a 27% enhancement compared to a conventional two-stroke engine.

## 5. Challenges and Prospects of HCCI

It is believed that the combination of biodiesel and HCCI engines can play an important role in renewable fuel and advanced combustion engines among the most available biofuels and modern engine systems. Experimentally, biodiesel has been proven to be a promising biofuel that effectively reduces harmful emissions. However, this kind of fuel has not been used widely on new types of engine combustion systems such as HCCI, indicating a long way to go.

Moreover, the greatest challenge for the HCCI engine is its worldwide usage and commercial production, including temperature control during ignition and combustion phasing, as it produces high carbon monoxide and hydrocarbon emissions. To solve all the problems above, the focus is to ensure that automatic fuel ignition occurs at the proper time to lower the emissions and enhance fuel efficiency. Another issue is that there will be carbon monoxide emissions during the process as at the combustion phase temperature, which is relatively low, the conversion of carbon monoxide into carbon dioxide may not succeed. In this case, engine noise, which comes from knocking, will occur due to large pressure rises from combustion. It is quite a effective way to solve the problem with the use of biodiesel.

At the current stage, even though hybrid cars are becoming more popular, the technology still lacks maturity due to the problem of low battery density. As a result of this, internal combustion engines such as HCCI still occupy a large market share in coming years [9]. As a novel, environment-friendly, energy-saving engine, HCCI is believed to become the mainstream of internal combustion engines [10].

## 6. Conclusion

The HCCI engine represents a significant leap in internal combustion engine technology, drawing the best elements from both SI engines and CI engines. Its potential to offer improved efficiency, reduced emissions, and adaptability to various fuels underscores its relevance in the transition toward greener transportation. Commercial strides have been made by giants like Nissan and Honda, highlighting its applicability and promise. However, the challenges facing HCCI, such as combustion phasing, emissions of hydrocarbons and carbon monoxide, and ignition temperature control, must be judiciously addressed for its broader acceptance and application. The synergy between biodiesel and HCCI engines presents a promising pathway for renewable fuels and advanced combustion engine technology. Though hybrid cars are seeing an upswing, HCCI's distinct advantages ensure its place in the future of automotive technology. Continued research and innovation are paramount to refining this technology, making it a viable and efficient choice for the next generation of vehicles.

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