

Homogeneous Charge Compression Ignition Engines for Enhanced Energy Efficiency and Reduced Emissions in Transportation and Power Generation

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Abstract. Rising emissions and pollution from traditional automotive engines, along with the increasing demand for more fuel-efficient and environmentally friendly technologies, have led to the development of "Homogeneous Charge Compression Ignition" (HCCI) engines. Unlike conventional internal combustion engines, HCCI engines do not rely on spark plugs to initiate combustion. Instead, the air-fuel mixture auto-ignites through compression, resulting in a highly efficient thermal process. This technology significantly reduces HC (hydrocarbon) and CO (carbon monoxide) emissions, making it a promising solution for modern environmental and energy challenges. Despite these advantages, the widespread commercialization of HCCI engines has been hindered by several technical challenges. The lack of spark plugs complicates combustion control, particularly in maintaining consistent ignition timing. Additionally, cold starts remain a significant obstacle. This paper will explore the historical development and operating principles of HCCI engines, outline their advantages and limitations, and examine potential solutions to these challenges. Finally, the paper will discuss the application of HCCI technology in power generation, highlighting its future prospects and contributions to sustainable energy.

Keywords: Homogeneous charge compression ignition (HCCI), spark ignition (SI), compression ignition (CI).

1. Introduction

Since the Industrial Revolution, human transportation has been heavily reliant on internal combustion engines, which are often referred to as the "heart" of a vehicle. These engines have enabled long-distance travel and remain essential in modern transportation. Internal combustion engines vary in efficiency and emissions, with the two most common types being spark ignition (SI) and compression ignition (CI) engines.

The main advantage of SI engines lies in their controlled ignition timing, initiated by a spark, allowing for better management of the combustion process. However, a significant drawback is the fixed air/fuel ratio, meaning that engine load can only be adjusted by the amount of air in the combustion chamber. CI engines, on the other hand, offer a higher compression ratio, resulting in greater efficiency. However, insufficient oxygen in the combustion zone increases particulate emissions, and as cylinder temperatures rise, some particles oxidize, leading to high levels of nitrogen oxides (NO_x), which are harmful to the environment.

As emission standards, particularly in the EU, become increasingly stringent, the automotive industry is seeking alternatives to traditional SI and CI engines. HCCI engines have emerged as a potential solution, offering reduced emissions and improved fuel efficiency. HCCI technology has been under investigation since the 1970s when Japanese researcher Onishi introduced a combustion process known as "active thermal atmosphere combustion" [1]. In Europe, this process is referred to as "controlled automatic ignition combustion," and by 1997, it was included in the Next Generation Vehicle Partnership Program in the United States.

HCCI engines combine elements of both SI and CI engines. They utilize a uniform mixture of air, fuel, and exhaust, similar to SI engines, but rely on compression for ignition, much like CI engines. These engines demonstrate excellent volumetric efficiency while producing very low NO_x and soot emissions—98% lower than conventional diesel engines—along with a 10-15% reduction in fuel

consumption. Furthermore, HCCI engines can run on a wide range of fuels, particularly gasoline, making them a viable alternative to diesel engines. Despite these advantages, several challenges remain for the commercial viability of HCCI engines. Although HCCI engines emit significantly less NO_x and soot than traditional engines, they produce higher levels of HC and CO. Additional hurdles include difficulties in controlling the combustion process, ensuring consistent air-fuel mixing, and addressing cold-start issues. This study also explores the application of HCCI technology with exhaust gas recirculation (EGR), providing a detailed chemical dynamics analysis of the F8L413 direct injection diesel engine produced in Algeria [2].

2. Fundamentals of HCCI Engine

2.1. Historical Development

The HCCI engine, initially identified as a potential replacement for the two-stroke engine, gained significant attention over time. In 1979, the combustion process was first termed "active hot atmosphere combustion" and was recognized as a promising alternative to both diesel and spark ignition engines [3]. A key issue with two-stroke engines is their susceptibility to knocking and high emissions. In contrast, HCCI engines rely on the spontaneous combustion of an air-fuel mixture, significantly reducing emissions. The first four-stroke HCCI engine was tested in 1983, with experiments focusing on various fuel mixtures and engine speed ranges. By 1989, further investigations into the HCCI engine configuration had advanced, and in 1994, research demonstrated that methanol could be effectively used as fuel for two-stroke HCCI combustion. In 1997, studies explored the influence of inlet and exhaust throttling on HCCI combustion in production engines. To this day, engineers continue to refine and unlock the potential of HCCI technology to achieve lower emissions and higher thermal efficiency.

2.2. Working Principles

The HCCI process merges elements of both SI and CI engine mechanisms. In HCCI engines, fuel and air are premixed, and combustion is initiated automatically due to the rise in temperature during the compression phase. During the intake stroke, fuel is injected into the combustion chamber through an injector located above the cylinder head. The injected fuel mixes with air, forming a uniform mixture, ensuring a consistent charge. In the subsequent compression stroke, the air-fuel mixture is compressed, causing its temperature to rise. As the piston approaches the top dead center (TDC), the temperature becomes sufficient to trigger spontaneous ignition. No spark is required, as the mixture ignites due to the heat generated by compression. During the expansion stroke, the energy released from combustion drives the piston downward. Notably, combustion in HCCI engines occurs almost simultaneously across the entire mixture, with multiple ignition points observed inside the chamber. Unlike conventional engines, no visible flame propagation is present, resulting in efficient fuel use and lower emissions. Three essential stages influence the effectiveness of the homogeneous combustion process in HCCI engines: (i) Charge homogenization, which aims for a uniform, premixed gaseous charge; (ii) Volumetric ignition, ensuring ignition throughout the chamber; and (iii) Homogeneity in combustion and temperature distribution, with simultaneous heat release across the chamber.

3. Advantages and Challenges

Homogeneous combustion strategies are implemented to lower fuel consumption and exhaust emissions. These strategies come with several advantages and challenges that impact engine performance.

3.1. Advantages

The main advantage of the HCCI engine is its low nitrogen oxide and PM emissions. Unlike SI or CI engines, which rely on spark plugs or injectors to control combustion, HCCI engines rely on simultaneous automatic ignition in the cylinder when temperature conditions are met. At low temperatures, combustion occurs uniformly at multiple points without a clear flame front. This uniform combustion, combined with premixed fuel, makes it difficult for soot to form, thus greatly reducing PM and NO_x emissions and making HCCI engines more environmentally friendly (Figure 1).

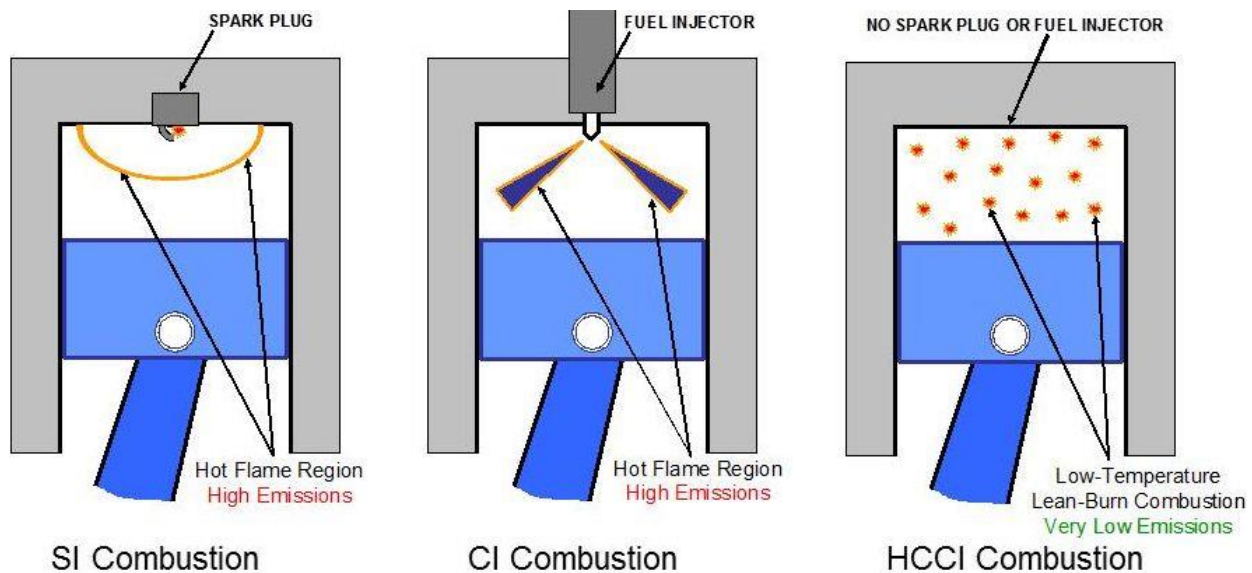


Fig. 1 Combustion differences between the three modes of IC operation [4]

The second advantage of HCCI engines is their superior thermal efficiency. Studies indicate that when the intake temperature is set at 135 °C, the thermal efficiency of HCCI engines is notably higher than that of diesel engines. In particular, when hydrogen is used as a fuel, HCCI engines demonstrate a 45% increase in thermal efficiency compared to conventional diesel engines, highlighting the promise of this emerging technology [5]. Ongoing research continues to validate the potential for HCCI engines to achieve greater thermal efficiency than traditional CI engines. A third advantage of HCCI engines is their ability to operate on a wide range of fuels, including gasoline, diesel, and alternative energy sources. This fuel flexibility broadens the operational capacity of HCCI engines, making them highly adaptable to diverse fuel types, further enhancing their viability in the transition to sustainable energy solutions.

3.2. Challenges

A key challenge with HCCI engines is the inability to directly control the combustion timing. The burn time is influenced by the fuel's chemical properties and reaction rate, making it difficult to achieve precise ignition. This lack of control complicates the optimization of engine performance. Another significant issue is achieving a uniform and efficient air-fuel mixture. Consistency in the mixture is critical for reducing emissions, improving efficiency, and minimizing pollution. Proper air-fuel mixing also aids in controlling combustion timing, which is essential for maximizing engine performance. A third problem is the increased emissions of hydrocarbons (HC) and carbon monoxide (CO), as well as the noise generated by HCCI engines. The low-temperature combustion process in HCCI engines often leads to incomplete fuel combustion, allowing unburned fuel to re-enter the combustion chamber and interact with low-temperature gases, which increases HC and CO emissions [6]. Additionally, the rapid pressure rise during combustion can increase noise levels, potentially damaging the engine over time. Finally, cold starts present a major challenge for HCCI engines. During cold starts, the heat from the compressed air-fuel mixture dissipates quickly, and the cylinder remains at a low temperature, making it difficult to achieve ignition and initiate combustion.

4. Strategies for Improvement of HCCI

In recent years, continuous research into HCCI technology has led engineers to propose various feasible solutions to tackle its challenges.

4.1. Exhaust Gas Recirculation (EGR)

One way to control HCCI combustion is by adjusting the rate of exhaust gas recirculation (EGR). EGR can be split into internal and external exhaust gas recirculation. Internal EGR affects combustion through thermal and chemical processes, and its influence on HCCI combustion is the result of the combined action of these two factors. Thermal shock increases the intake air temperature and promotes ignition [7]. At the same time, the chemical aspect involves the active substances present in EGR. Introducing hot EGR into the air-fuel mixture increases the operating temperature while the intake temperature, EGR mass and quantity remain constant. By adjusting the EGR rate, combustion efficiency and ignition timing can be controlled. In contrast, the external EGR usually results in a lower intake temperature. In addition, certain chemical additives can slow down or accelerate the rate of heat release.

4.2. Enhancing Mixture Homogeneity

Achieving a completely uniform air-fuel mixture is challenging, especially with diesel because of its low volatility. Diesel carburetors equipped with electronic control systems can alleviate this problem. Akhilendra's research shows that using a diesel carburetor can reduce nitrogen oxide emissions by 80 percent and smog by 50 percent. However, HC and CO emissions increased significantly. The integrated starting generator (ISG) can further reduce fuel consumption and emissions of HCCI engines. Another way to improve mixing uniformity is through a high swirl ratio. The premixed charge enters into the combustion chamber. Then its convective heat transfer performance is enhanced by eddy current motion. The high vortex ratio facilitates faster, more uniform mixture preparation, improved fuel-air mixing efficiency and lower emissions.

4.3. Delaying Auto-Ignition

Changing the compression ratio of the engine is an effective way to delay automatic ignition, because reducing the compression ratio further delays the start of ignition. Adjusting the compression ratio allows various fuels to burn in the HCCI engine. Residual gases also play a key role in affecting HCCI combustion timing and engine performance. HCCI combustion is characterized by late injection time, high injection pressure and high EGR rate. Higher EGR levels help delay automatic ignition, while low EGR levels stabilize conventional SI engines and high EGR levels stabilize HCCI engines. Engine speed and EGR significantly affect HC, CO and NO_x emissions. Although EGR improves combustion and emission performance, it has a slight impact on engine power. Diesel-fueled HCCI engines are particularly sensitive to EGR changes, and manipulating EGR scores can control combustion and ignition times [8].

Variable valve mechanism (VV) also helps manage automatic ignition. When the intake temperature is increased, the test engine uses a thinner air-fuel mixture, and the use of the VV mechanism can reduce CO and HC emissions. The internal EGR can be adjusted by adjusting the negative valve overlap with variable valve timing (VVT). However, increasing the internal EGR can cause the engine to knock, while increasing the external EGR can reduce the likelihood of knocking. HCCI combustion is very sensitive to air-fuel mixture temperatures, as increased intake temperatures limit the engine's operating range and increase the risk of knocking and emissions [9]. Therefore, controlling the timing of automatic ignition is essential to ensure that the heat release process occurs at the right point in the engine cycle. Controlling combustion is crucial because it directly affects the efficiency and economy of the engine. The key strategy to control combustion is to improve mixture uniformity and delay spontaneous combustion.

5. Applications

With HCCI technology, linear generators can generate electricity using a variety of green fuels. They are extremely reliable, able to adapt to weather changes, and have the flexibility to switch fuel supplies. These units are now installed in many locations, generating between 230 and 460 kilowatts of electricity. In the late 1990s and early 2000s, West Virginia University conducted the second generation of the two-stroke CI FP-LEG test equipment [10]. However, due to design flaws and the limitations of the starting solenoid, the machine encountered operational difficulties when using diesel [11]. In 1998, Sandia National Laboratories introduced the two-stroke DPP FP-LEG, which utilized HCCI combustion to improve thermal efficiency and tested eight different fuel types [12]. According to the data, efficiency levels range from 40% to 55% [12].

The basic working principle of this technology is to compress the air/fuel mixture to release energy. First, the fuel/air mixture enters a closed chamber with removable end walls. The walls on both sides then move against each other, compressing the air/fuel mixture. As molecules collide at increasing speeds, they split and form new molecules, releasing energy. This energy allows new molecules to collide more strongly with other molecules, creating no noticeable sparks during compression. Once the pressure generated exceeds the initial force pushing the wall inward, the wall returns to its initial position and the chamber pressure returns to its initial state. At this point, a new batch of air/fuel mixture enters the chamber and the cycle repeats. The magnets are attached to cylinders on either side, and when these cylinders move back and forth behind the cavity wall, the spiral coils fixed to the housing generate electromagnetic induction, which generates electricity.

6. Conclusion

This article gives a brief introduction of the background information of the internal combustion engine, and explains its basic working principles. In addition, a brief history of the development of HCCI is discussed, showing how the technology has evolved over time. HCCI combines two key advantages: high thermal efficiency and greatly reduced emissions of nitrogen oxides and particulate matter, mainly because the specific flame is absent during combustion. As a result, HCCI has been widely recognized and analyzed as one of the most promising “green” engine technologies in recent years. However, challenges such as ignition control, cold start and achieving a uniform air/fuel mix remain obstacles. Engineers are actively working to overcome these challenges, focusing on improving its efficiency and stability. Future developments must address issues such as high loads, high-speed performance, ignition control, and mixture preparation to facilitate commercialization of the technology. In addition to the transportation sector, HCCI technology also has great potential in the field of power generation. By utilizing piston motion plus electromagnetic induction, this method generates electricity without discharge, mainly because of the lack of an open flame in the combustion chamber. These generators are currently undergoing testing and have already seen a number of commercial deployments, marking a major step forward in technological breakthroughs and the future of green energy.

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