HCCI Technology: Operating Principles, Advantages, Challenges, and Future Prospects

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Abstract. In recent years, with the development and research on internal combustion engines, human beings have gained a deeper understanding of the combustion mechanisms and properties of traditional spark ignition (SI) and compression ignition (CI) engines. It has also been discovered that these two distinct types of engines each have their advantages and drawbacks. This is why there has been a growing emphasis on the research and experimental analysis of homogeneous charge compression ignition (HCCI) engines in recent times. This is because achieving high thermal efficiency while maintaining extremely low hydrocarbon (HC) and carbon monoxide (CO) emissions positions it as one of the potential engine technologies to address recent environmental and energy challenges. The article also discusses the difference in emissions when using different fuels for HCCI engines, such as diesel, petrol, and liquefied petroleum gas. Meanwhile, the last part concludes with a description of a stationary application that employs HCCI technology for power generation. This article will introduce the working principles of HCCI engines, the advantages and disadvantages of the HCCI process, and some solutions to its drawbacks. At the end, an application of HCCI technology for power generation and its related information will be presented.

Keywords: Homogeneous charge compression ignition; advantage; challenge; emission.

1. Introduction

From the dawn of the industrial revolution to today's industrialized world, humanity's transportation has largely depended on the internal combustion engine. Acting as the "heart" of vehicles, this engine has empowered people with the ability to journey across distances. Naturally, different types of these engines have various efficiencies and emissions. Two traditional types are SI and CI. Both conventional engines have their advantages and disadvantages. For instance, the advantage of spark ignition is that the timing of ignition initiated by the spark discharge is able to adjust to control the starting of the combustion. Its drawback is that a fixed air/fuel ratio means the load can only be controlled by the amount of air in the combustion chamber, and the throttle valve decreases its efficiency. On the other hand, compression ignition has a much higher compression ratio (12-24) than spark ignition, leading to naturally higher efficiency. However, a deficiency of O_2 in the combustion chamber's fuel area results in significant particulate emissions. Moreover, as the cylinder temperature rises, some of these particulates get oxidized, leading to substantial NOx emissions, which are extremely detrimental to the environment. As a result, there's a rising curiosity in exploring engine types that merge the benefits of both, targeting high thermal efficiency with notably reduced emissions. HCCI stands out as a potential candidate in this regard. [1].

In the late 1970s, a Japanese named Shigeru Onishi, from a clean engine-related institution, introduced a combustion phenomenon named "activity heat atmosphere combustion." Later, Professor Osamu Hirao from the University of Tokyo coined the name “Active Thermo Atmosphere Combustion" for this combustion method. In Europe, it is referred to as "Controlled auto-ignition combustion." Meanwhile, this combustion was incorporated into the "Partnership for Next Generation Vehicle" initiative in 1997 in the U.S., with a dedicated research budget of 3 million American dollars. Besides HCCI combustion, terms like PREDIC, PCCI combustion, ATAC, and AR combustion are also used to describe similar processes [2]. Until now engineers are still on the way to improving or sufficiently using HCCI engines to reach the aim of high thermal efficiency with very low emissions.

2. Homogeneous Charge Compression Ignition

2.1. Principle

The HCCI engine mixes fuel with pre-heated air, and this can be done by injecting the fuel either directly into the cylinder or through a port. This ensures a consistent and even mixture, known as a homogeneous charge. Factors such as heat, pressure, and the prior state of the air/fuel mixture, as well as specific interactions between fuel, air, and remaining gases, greatly influence the ignition timing. As the air/fuel mixture is compressed, it heats up. When it gets close to the highest compression point (TDC), it can ignite on its own. This is important to cause the mixture to self-ignite at various points inside the cylinder [3]. The visual studies showed that the fuel started burning on its own at various spots inside the combustion chamber. Throughout the entire burning process, there was no visible flame moving or spreading. The self-ignition starts due to the warming of the inhaled air or through heat movement from the overheated combusted gases [4].

Furthermore, engineers conducted an in-depth analysis and study of its combustion process using optical techniques. The results showed that auto-ignition occurred at multiple distinct locations within the entire combustion chamber, and throughout the combustion process, no evident flame propagation or flame front was observed, as shown in Fig. 1 [3]. The HCCI process integrates the characteristics of both SI and CI mechanisms, meaning the engine uses pre-mixed air and fuel, and the initiation of combustion relies on auto-ignition due to the temperature rise [1].

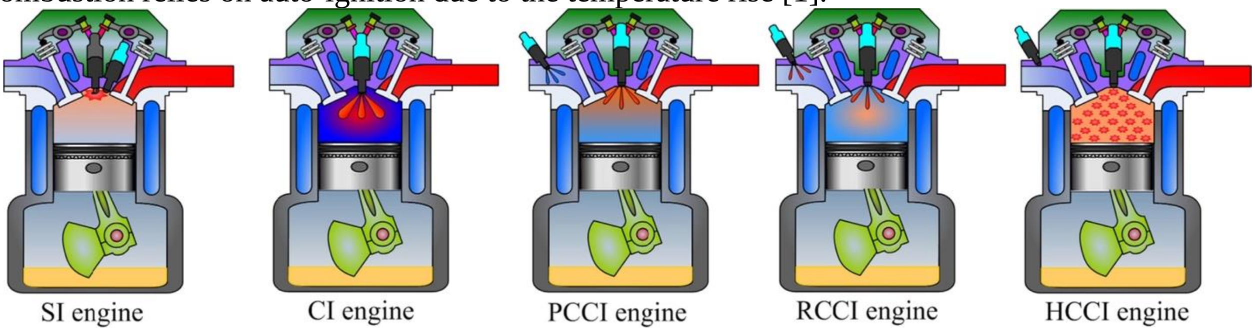

Fig. 1 Different types of IC engines [3]

2.2. Advantages or Benefits of the HCCI Process

2.2.1 Low NOx and PM emissions

The HCCI engine relies on the simultaneous reactivity of the intake within the cylinder, unlike spark ignition engines or compression ignition engines that require the control of spark plugs or injectors to regulate their combustion phase. As long as the temperature meets the conditions for auto-ignition, it can ensure heat release reactions and self-ignition. The absence of spark plugs or injectors does introduce challenges in controlling its combustion phase. However, one undeniable aspect of the HCCI process, as introduced in the previous section, is that combustion in HCCI occurs uniformly at multiple cylinder locations under low-temperature conditions. Furthermore, there isn't a pronounced flame, and the pre-mixed fuel makes soot formation difficult, leading to reduced NOx and PM emissions, making it environmentally friendly [4], as shown in Fig. 2.

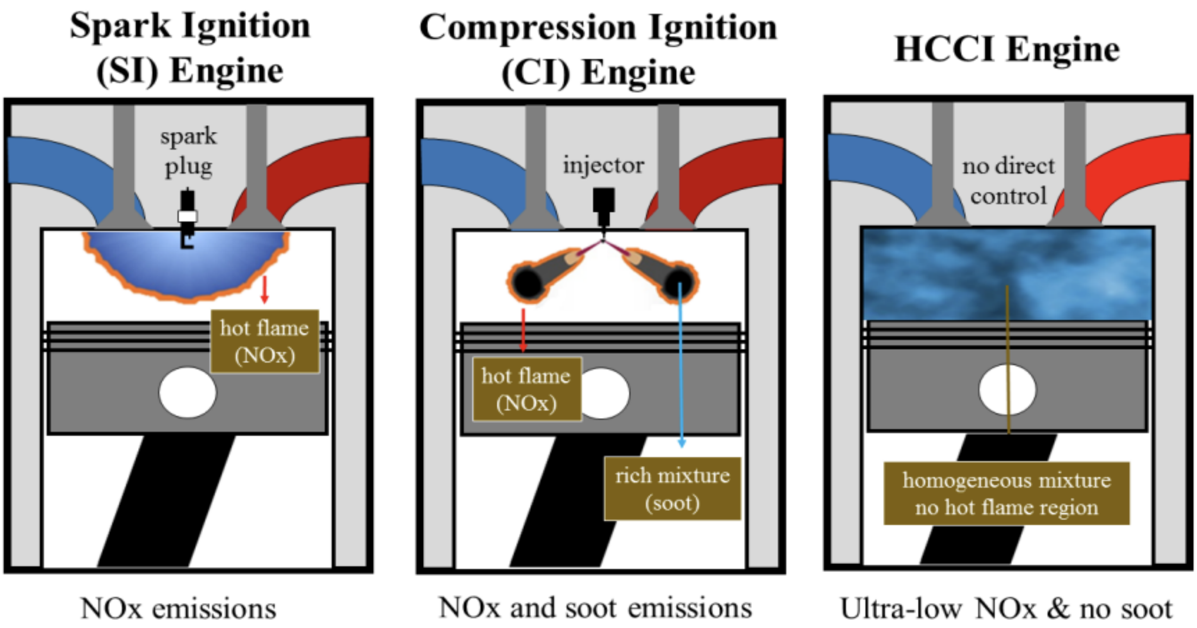

Fig. 2 HCCI engines' emissions compared to SI and CI engines [4]

2.2.2 Thermal efficiency

Some research indicates that many researchers have found the thermal efficiency of HCCI engines to be superior compared to diesel engines. Some engineers compared the thermal efficiency measurements of diesel engines using biogas and HCCI engines, utilizing three different intake temperatures for measurements (Eighty Celsius degree, One hundred Celsius degree, and one hundred and thirty-five Celsius degree). According to the data reports from these individuals, at an intake temperature of 135 °C, the HCCI engine's thermal efficiency was significantly greater than that of conventional diesel engines [5]. Notably, when using hydrogen as fuel, the HCCI engine's thermal efficiency was up to 45 % higher than traditional diesel engines, and that is quite an amazing advantage to such a new technique. Additionally, further studies and experiments have been conducted to dive deeper into the potential thermal efficiency of HCCI engines. Many kinds of fuels and different boost pressures were used in the experiments as measurement variables and parameters. Similar results were observed, with HCCI engines demonstrating greater thermal efficiencies than conventional CI engines. For instance, when biodiesel mixtures are used as fuel and are perfectly gasified, HCCI engines display an enhanced thermal efficiency [5].

2.3. Limitations or Challenges and Strategies of the HCCI Process

2.3.1 Challenges or limitations

Firstly, in HCCI engines, there is no way to dictate when the combustion begins directly. It is actually influenced by the fuel's chemical traits or its reaction speed. Therefore, achieving a homogeneous mixture of fuel is crucial for the combustion process in HCCI engines [1,5,6]. Secondly, another challenge with HCCI engines includes issues with noise and potential growth in Hydrocarbons and Carbon Monoxide emissions. Due to the unique characteristics of HCCI technology, specifically low-temperature combustion, a large portion of the fuel in the combustion chamber may not be fully consumed. When this left fuel re-enters the cylinder, it meets other low-temperature gases, resulting in higher HC and CO emissions. This is quite significant when compared to conventional combustion, such as SI or CI. Specifically, the decreases in combustion efficiency are due to the low temperature (below 1400 K) of the combusted gases, and the oxidation of CO to CO_2 process is completed under low load conditions. However, the effectiveness at higher loads is limited to some extent due to the decline in HCCI combustion efficiency. Simultaneously, a sharp rise in pressure may result in significant engine noise and could even damage the engine [1,6].

The third obstacle involves the formation of the mix between air and fuel. Creating a uniform and efficient blend can effectively prevent interactions with the engine's internal walls. This is vital for attaining peak energy efficiency, minimal emissions, and decreased oil contamination. Moreover, ensuring a consistent blend helps in controlling when the combustion happens in these alternative engine designs. [6]. Another major difficulty is the cold start of HCCI engines. Under this operation, the ignition can result in substantial thermal losses for the compressed air/fuel mixture, and the cylinder remains at a low temperature. A practical and preferred approach is to begin the engine in a standard combustion setting, like SI or CI, and then transition to an alternative combustion mode. The auto-ignition temperature that needs to be reached varies depending on the type of fuel and the engine. This remains a future direction for development in HCCI technology [1,6]. There are also other influencing factors, such as the need for high fuel injection pressures to assist in the mixing of fuel and air, thereby optimizing combustion and spray structure. Additionally, higher variable compression ratios not only help improve thermal efficiency but can also be adjusted to provide higher power outputs. This is an effective parameter for achieving high efficiency and low NOx emissions [6].

2.3.2 Useful strategies

With continuous research into HCCI technology in recent years, engineers have proposed several viable solutions to address its challenges. A technique involves regulating HCCI combustion using the rate of Exhaust Gas Recirculation (EGR), divided into internal and external types. Internal EGR's impact on combustion is twofold: it involves heat processes and chemical interactions, with its effect on HCCI combustion being a blend of these two. The thermal effect relates to temperature; a higher temperature raises the intake air temperature, making ignition easier and reducing ignition delay. Another influence of internal EGR is the chemical component, specifically the types of chemically active species it contains. When certain conditions like intake temperature and the quality and amount of EGR are kept steady, adding hot EGR to the air/fuel mix can make the engine run hotter. By changing the amount of EGR, it can control how efficiently the fuel burns and how long it takes to start burning. On the other hand, using external EGR usually leads to a cooler intake temperature. However, research on external EGR has shown that under specific parameters (engine compression ratio: 18.1, IMEP: 0.5 MPa), varying EGR proportions (Isooctane: 57 %, Ethanol: 62 %, Natural gas: 48 %), and different temperatures (120 °C, 110 °C, 150 °C), HCCI combustion is relatively stable. When using diesel fuel, a higher intake temperature, lower compression ratio, and 50 % EGR are needed to achieve stable combustion at certain loads [7].

Furthermore, certain chemical additives can either decelerate or intensify the heat release rate. For example, DME, due to its unique properties, can enhance heat release efficiency during ignition and stabilize HCCI combustion without increasing UHC and CO emissions. Additionally, the fuel's own physical and chemical characteristics are crucial for how the HCCI combustion works. As inferred from the name HCCI, the mixed fuel needs to be homogeneous, and a higher octane value combined with a lower boiling point is essential. Studies have indicated that fuels like diesel, gasoline, and natural gas can be employed in HCCI combustion and have a direct impact on emissions. For compression ignition, high ignitability is required. If the right kind of fuel could be used for HCCI combustion, controlling the burning process would be much better. So, by evenly mixing fuels that ignite differently, which is obviously a method that can improve HCCI combustion [7]. Of course, this part won't go into detail about the solutions mentioned in the previous section, such as using spark plugs for auxiliary ignition and so on.

2.4. Emissions from HCCI with Different Fuels

2.4.1 Diesel

Singh and Agarwal conducted a study using a twin-cylinder engine, one equipped with HCCI technology and the other being a standard diesel engine. Their focus was on comparing the emissions, combustion, and performance of diesel fuel in both types of engines. Their results showed that HCCI engines produce more HC and CO emissions but fewer NOx emissions than diesel engines. In another observation, Gowthaman and Sathiyagnanam found that NOx and soot emissions from HCCI engines change with different intake temperatures and injection pressures. Expanding on that idea, Singh and Agarwal discovered that integrating volatile materials such as gasoline, kerosene, and alcohol with diesel can enhance the emission profile of alternative combustion methods. Singh and his colleagues also pointed out that tweaking parameters like the "λ" value or the rate of EGR can lead to decreased CO and HC emissions. Finally, Patel and Yadav tested biodiesel and CNG in HCCI engines to understand their performance and emissions. Their research indicates that B15 fuel is effective in reducing HC and CO emissions, while CNG helps in reducing NOx emissions [8]. Details are shown in Table 1.

Table 1. Diesel emissions [8].

Research	NOx	HC	CO	CO_2
[9]	2-4 g/kW h	0.75-3 g/kW h	3-13 g/kW h	--
[10]	10-600 ppm	50-100 ppm	0.05%-0.37%	--
[11]	10-1100 ppm	--	0.4 %	--
[12]	0.15-2 g/kW h	4-20 g/kW h	10-80 g/kW h	--
[13]	0-33 g/kW h	5-30 g/kW h	10-135 g/kW h	--
[14]	10-120 ppm	22-120 ppm	0.01-0.09 %	--
[15]	20-500 ppm	20-140 ppm	0.1%-0.3%	0.5-6.5%

2.4.2 Petrol or Gasoline

Hyvönen and his group researched the operational scope of multi-cylinder alternative combustion engines with an adjustable compression ratio. They altered a 5-cylinder, 1.6 L engine to reach a compression range between 9:1 and 21:1 and contrasted this with the engine's initial compression ratio. With an increase in speed (from 1000 to 5000 rpm), there was an 85 % reduction in CO emissions and a 35 % reduction in HC emissions. Later, they also examined HCCI engines with and without spark ignition, with compression ratios between 10:1 and 30:1. The test results showed that the NOx emission level with spark assistance was slightly higher, by approximately 0.1 g/kg fuel than that of regular HCCI combustion. With throttle provided, there is a decrease in hydrocarbon and carbon monoxide emissions but an increase in NOx emissions. When a catalyst was added, specific emissions of hydrocarbon and carbon monoxide were reduced [8].

2.4.3 LPG

Engineers have analyzed and researched liquefied petroleum gas (LPG) fuel diesel engines using HCCI technology, specifically focusing on the intervention of intake air pre-heating at different loads for LPG-fueled HCCI engines. In contrast with traditional diesel engines under the same load, these engines exhibit elevated hydrocarbon and carbon monoxide emissions but lesser NOx and CO_2 emissions [8]. Details are shown in Table 2.

Table 2. LPG emissions [8].

Research	NOx	HC	CO	CO_2
[16]	5-10 g/kW h	15-135 g/kW h	0.0443-0.4 g/kW h	5-11 g/kW h

3. HCCI Related Application

Linear generators can utilize a variety of green fuels for electricity generation using HCCI technology. They are highly reliable and can adapt to weather changes and flexibly switch fuel supplies. Currently, they have been developed and tested, with a certain level of commercial deployment already in place. Mainspring Energy spent a total of 14 years developing this technology, with its commercialization journey beginning in 2020. These devices have now been installed in dozens of locations, generating 230 to 460 kilowatts [17]. Basic structures are shown below in Fig. 3.

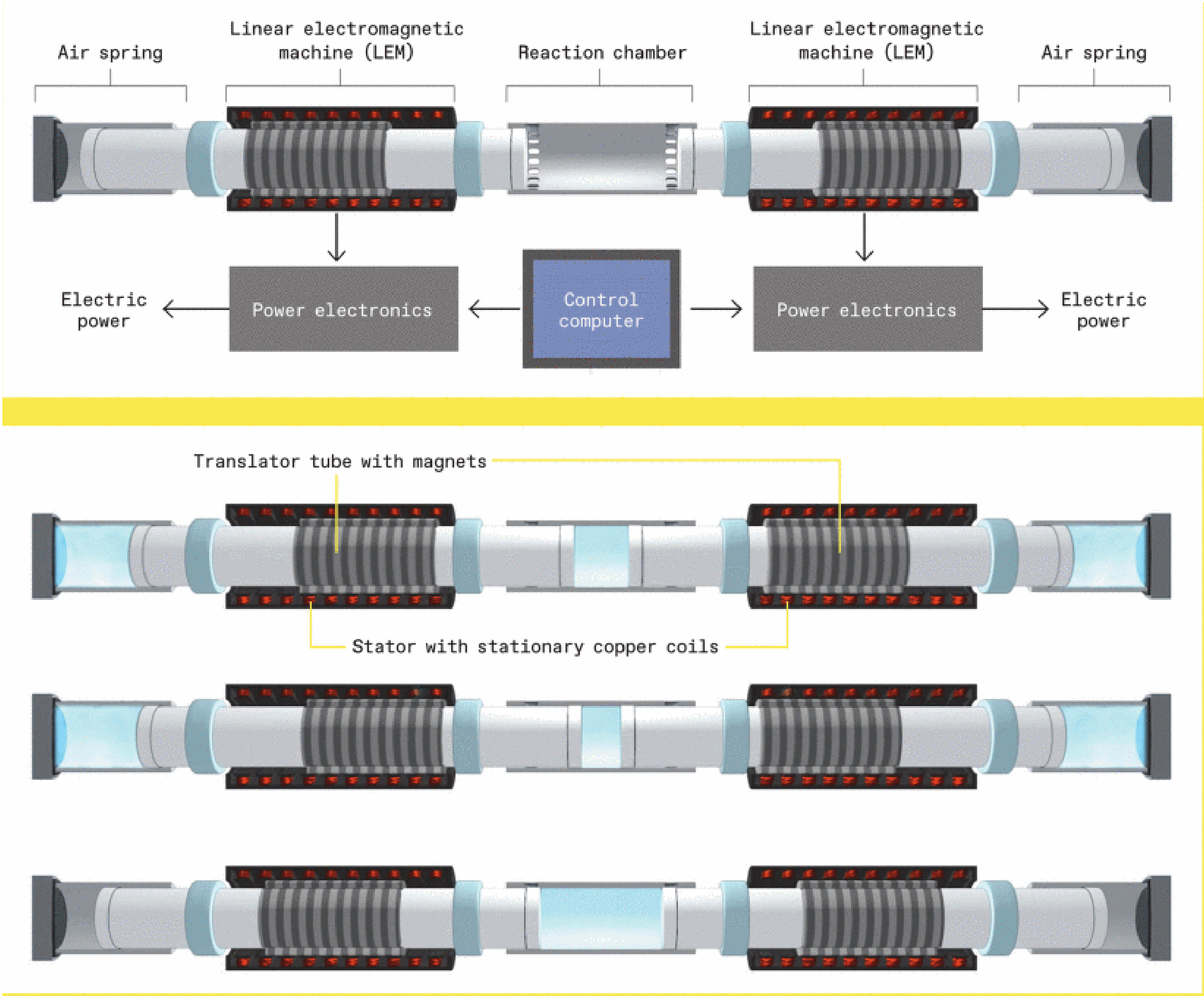

Fig. 3 Structure of mainspring's linear generator [17]

3.1. Basic Background

During the final years of the 1990s and the beginning of the 2000s, West Virginia University pioneered a second iteration of the two-stroke CI FP-LEG test apparatus. Nonetheless, due to design shortcomings and constraints with the starting solenoids, the machinery encountered operational difficulties and opted for kerosene over diesel [18].

In 1998, Sandia National Laboratories introduced a two-stroke DPP FP-LEG, harnessing HCCI combustion to enhance thermal efficiency and examining eight distinct fuel types. Data revealed efficiency levels ranging from 40 % up to 55 %. By 2016, SNL rolled out the ODPP FP-LEG, aiming for inherent engine balance. While they noted encouraging efficiency outcomes, they also grappled with regulating engine specifics [18].

3.2. Principle

The basic working principle of this technology is quite straightforward, involving the compression of an air/fuel mixture to initiate the release of energy, similar to a compression ignition internal combustion engine, as shown in Fig. 4. First, the fuel/air mixture enters a closed chamber with movable end walls. Then, the end walls on both sides move toward each other, compressing the air/fuel mixture inside the central cylinder. The molecules within get squeezed, reducing their available motion space, leading to them colliding at increasing speeds until they split and form new molecules, releasing energy in the process. This energy causes the new molecules to collide more intensely with other molecules and the chamber walls, increasing the pressure inside the chamber. No noticeable spark is produced during the compression stroke. Once the force from the increased pressure surpasses the initial force that pushed the walls inwards, these walls gradually return to their starting position, and the chamber pressure also returns to its initial state. At this point, a fresh batch of fuel/air mixture enters the chamber, and the cycle recommences [17]. Magnets are fixed on the cylindrical bodies on both sides. As these cylindrical bodies move back and forth behind the chamber walls, electromagnetic induction occurs with the spiral coils fixed in the outer shell, generating electricity, as shown in Fig. 4.

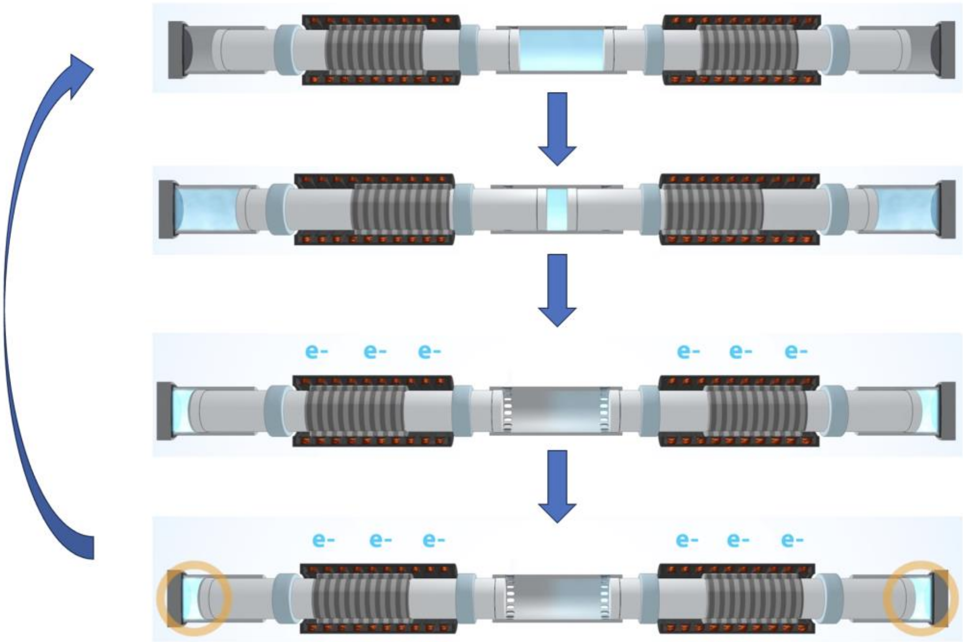

Fig. 4 A complete work cycle of MLG, reproduced from the website: https://www.mainspringenergy.com/technology/

4. Conclusion

In essence, this paper provides an overview of the background of internal combustion engines to highlight the advantages of HCCI technology, outlining the fundamental working principles of HCCI. Furthermore, this technology blends two main advantages: elevated thermal efficiency and significantly reduced NOx and PM emissions, owing to the lack of a specific flame. As such, HCCI has been recognized and widely tested, researched, and analyzed as one of the anticipated "green" engines of recent times. However, challenges like ignition control, cold starts, and preparation of uniform fuel/air mixtures, among other constraints, still prevail. Engineers are actively addressing these issues to enhance its efficiency and stability. Given its stature as a clean engine technology, evaluations are also underway to observe emissions of HC, CO, NOx, and particulate matter from HCCI technology when various fuel mixtures are employed. The article concludes by introducing a stationary application known as Mainspring's Linear Generator (MLG). Beyond transportation, this significant development utilizes piston movement accompanied by electromagnetic induction to generate electricity. The entire power generation process is emission-free, primarily because the combustion chamber lacks open flames. Such generators are now being tested and have seen some commercial deployment. This represents a technological breakthrough, marking a significant stride in the green energy sector's future.

In summary, based on data from various literature, HCCI technology indeed achieves low NOx and particulate emissions, as well as relatively high thermal efficiency. Therefore, given these advantages, not only research labs but also major manufacturers are studying the application and enhancement of HCCI technology to achieve larger-scale production and more cost-effective commercial use. However, attention still needs to be paid to reducing HC and CO emissions, as well as better ignition control. Moreover, we shouldn't limit such technology solely to vehicles. We should also consider how to produce energy in an environmentally friendly manner, thereby reducing even more emissions and pollution.

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