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Review

A review of internal combustion engines powered by renewable energy based on ethanol fuel and HCCI technology

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Abstract: In general, as compared to conventional combustion engines, the homogeneous charge compression ignition (HCCI) engine offers better fuel efficiency, NOx, and particulate matter emissions. The HCCI engine, on the other hand, is not connected to the spark plugs or the fuel injection system. This implies that the auto-ignition time and following combustion phase of the HCCI engine are not controlled directly. The HCCI engine will be confined to a short working range due to the cold start, high-pressure rate, combustion noise, and even knocking combustion. Biofuel innovation, such as ethanol-powered HCCI engines, has a lot of promise in today's car industry. As a result, efforts must be made to improve the distinctive characteristics of the engine by turning the engine settings to different ethanol mixtures. This study examines the aspects of ethanol-fueled HCCI engines utilizing homogenous charge preparation procedures. In addition, comparing HCCI engines to other advanced combustion engines revealed their increased importance and prospective consequences. Furthermore, the challenges of transitioning from conventional to HCCI engines are examined, along with potential answers for future upgrade approaches and control tactics.

Keywords: HCCI; ethanol blend; premixed charge; low-temperature combustion; combustion phasing

1. Introduction

Today's most crucial energy resource employed in the transportation industry is fossil energy, such as gasoline and diesel. Ethanol is an alternative fuel for internal combustion engines to address these issues. In Vietnam, the development of ethanol fuel is critical since increasing its use may reduce air pollution while also reducing reliance on fossil fuels [1–3]. Ethanol fuel has been known as a promising alternative fuel for internal combustion engines because of its production from agricultural products [4–8]. Accordingly, the results concluded that when employing ethanol-diesel blends, an increase in fuel consumption nearly equal to the decrease in fuel energy content may be anticipated. With ethanol concentrations of 10 percent or below, operators have found no performance changes compared to diesel fuel [4–5]. Yusri IM et al. examined the performance and emissions of compression and spark-ignition engines using alcohol fuels from the first aliphatic alcohol family, including methanol, ethanol, propanol, and butanol, and concluded that alcohol fuels could improve the combustion in the engine [6]. Edwin Geo V et al. focused on the combustion, performance, and emission characteristics of gasoline mixed with ethanol and benzyl alcohol in proportions of 10% and 20% by volume of the total amount [7]. The effect of different gasoline-ethanol blending ratios of E0–E85 fuels on a vehicle's regulated, particle, and unregulated gaseous emission characteristics was studied in [8]. Compared to low-ethanol-content fuels (E0 and E10), the particulate matter reduction performance of blends containing 30–85 percent fuels was superior, owing to the enhancement of the combustion process brought about by an increase in oxygen content and the shift in fuel toward lighter hydrocarbons.

Furthermore, several investigations have been conducted to establish a highly effective and environmentally friendly combustion approach for internal combustion engines (ICEs). Experiments are being conducted to determine the system's use of alternate fuel [9]. Low-Temperature Combustion (LTC) has shown a promising future in complying with environmental emission standards [10]. Researchers have concentrated their efforts on the novel LTC approach, reducing emissions while increasing efficiency over traditional combustion modes. Low-temperature combustion (LTC) is divided into many types such as partially homogeneous charge compression ignition (PHCCI), premixed charge compression ignition (PCCI), etc. It can be divided into three sections to determine the applicability of each LTC derivative for developing a production-grade LTC engine, including PHCCI combustion, PCCI combustion, and mode switching between conventional CI combustion and LTC. The commercialization of LTC technology is facilitated by mode switching, which incorporates dual combustion modes dependent on operational conditions.

By maintaining a low in-cylinder temperature and forming a homogenous charge, the HCCI engine has a lot of potential to satisfy ultra-low NOX and PM emissions. Furthermore, HCCI is a more thermal and fuel-efficient approach [11–14]. Similarly, premixed charge compression ignition (PCCI) and reactivity-regulated compression ignition (RCCI) engines have improved combustion characteristics, but they can't match the HCCI engine's performance and emissions [15]. Various research projects have been carried out worldwide to adopt the HCCI combustion mode for conventional and unconventional fuels in CI engines. However, many elements of alternative biofuel, such as ethanol, were not explored. As a result, the rationale and goal of the present review article are structured to bridge the gap for future advancements.

2. Principal of HCCI engine, advantages, and challenges

2.1. Principal of HCCI engine

As shown in Figure 1, the combustion in a CI engine is heterogeneous, with flames circling the spray plume and fuel auto-ignition initiating combustion. Meanwhile, the S.I. engine uses a spark to start combustion, and the flame spreads in a homogenous mixture. The HCCI engine combines the benefits of both S.I. and CI engines, with auto-ignition initiating homogenous mixture combustion. The combustion period is brief, and the pressure increase rate is significant due to immediate volumetric heat release (PRR). The necessity of a high equivalency ratio advances the ignition timing during high-load operations, resulting in a high heat release rate (HRR), increased NOx emissions, and banging. The HCCI engine employs a recent combustion technique. In theory, there is no spark plug or injector to aid the combustion process, and once the mixture reaches its auto-ignition temperature, combustion begins in various areas. Thus, there are some differences in the combustion process of the HCCI engine compared to diesel and compression ignition (CI) and spark ignition (S.I.) engines, as mentioned in previous studies [16–18].

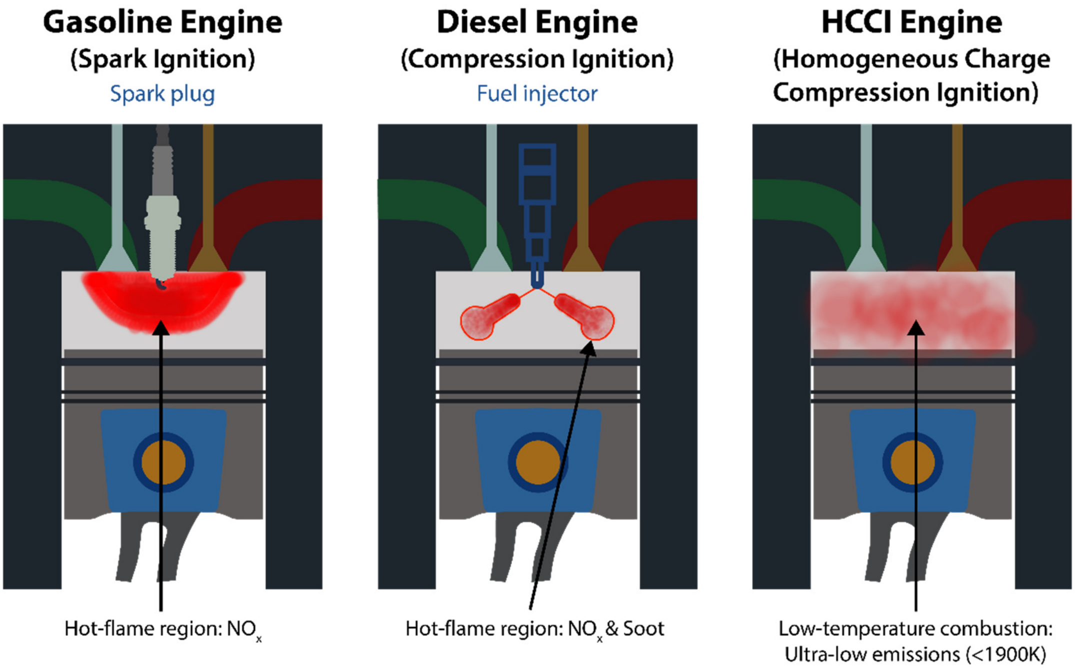

Figure 1. Comparison of HCCI engine with traditional engines.

In the operation of HCCI engines, the fuel and air are combined before combustion [19]. The mixture auto ignites spontaneously at several places across the charge volume owing to the compression stroke's rise in temperature. This combustion mode uses a very lean and dilutes the mixture, resulting in lower bulk and localized combustion temperatures and thus lowering NOx emissions. Moreover, unlike traditional CI combustion, HCCI combustion is well mixed (homogeneous). The lack of fuel-rich areas in the combustion chamber reduces PM formation [20]. Gasoline is delivered directly into each cylinder's combustion chamber using cylinder head injectors on the intake stroke. This is performed independently of the intake plenum. The cylinder's combustion chamber has mixed fuel and air on the intake stroke. The combustion chamber heats up when the piston returns to the top of the compression stroke. The heat from this stroke causes the fuel/air combination to burn spontaneously (no spark required) and forces the piston down for the power stroke. Unlike typical spark engines, the combustion process is lean, low temperature, and flameless. As a result, the same amount of power is produced while consuming considerably less fuel and emitting significantly fewer pollutants. After the power stroke, the piston reverses direction and begins the exhaust stroke, but the exhaust valves shut prematurely, trapping part of the latent combustion heat. Before the next intake stroke, a tiny amount of fuel is delivered into the combustion chamber for pre-charging.

In general, the HCCI combustion displays a two-stage ignition: the initial stage of heat release is referred to as low-temperature heat release (LTHR), in which kinetic processes occur slowly and at temperatures less than 850 K, resulting in a limited heat release of 7–10% in total [15]. The remainder of the fuel energy is released when the charge temperature exceeds 950 K, a process known as high-temperature oxidation or high-temperature heat release (HTHR). A negative temperature coefficient (NTC) zone separates the LTHR and HTHR as mentioned in Figure 2. Even when the total charge temperature increases, the overall response rate exponentially drops throughout the NTC area [22]. Thus, the NTC area determines the combustion phasing since it determines the commencement of the primary heat release rate. Charge reactivity may be managed during the NTC period using a charge pressure-temperature history, EGR, or a low reactivity fuel (LRF) such as gasoline or ethanol in the case of a dual-fuel engine [23].

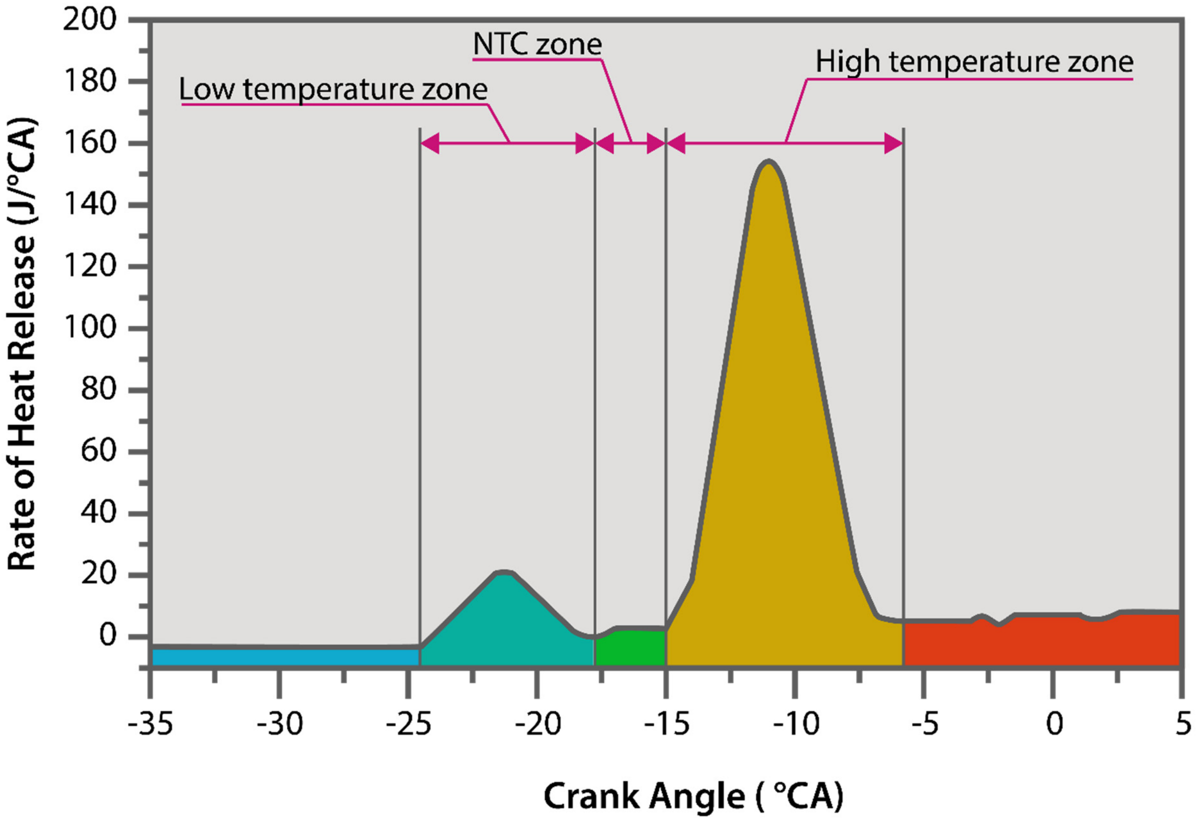

Figure 2. Heat release curve of HCCI combustion with n-Hetane fuel.

2.2. Advantages and challenges of HCCI engines

In summary, the potential advantages of HCCI technology have been concluded in many previous research results of worldwide scientists as follows:

Firstly, HCCI engines are fuel-lean and may run at compression ratios comparable to diesel engines, resulting in better efficiency than typical S.I. gasoline engines [24–26]. Killingsworth NJ et al. presented a simple model of the HCCI combustion process of the test engine with a compression ratio of 16. Mack JH et al. investigated an HCCI engine having a compression ratio of 17 fueled with ethanol in-water mixtures. The compression ratio of the test engine varying from 20:1 to 14.87:1 by changing the thickness of the cylinder head gasket was also conducted in our previous research [27]. Accordingly, The HCCI process was configured on a single-cylinder diesel engine running on n-heptane fuel, albeit owing to the engine knocking at the initial compression ratio of 20:1, the operational range of the HCCI process was restricted to a maximum of 2400 rpm and 30% load. Additionally, the engine speed was improved at 30% load. By decreasing the compression ratio from 20:1 to 14.87:1, the operational range of the HCCI process may be increased to 3200 rpm and 50% load. The optimal compression ratio, in terms of indicated mean pressure, and indicated efficiency, at 2000 rpm and 30% load is 18:1. However, at higher loads, the compression ratio of 15.4:1 improved the stability of the HCCI process, owing to the appropriate start of the combustion and the resulting minimal banging.

Secondly, HCCI can operate on various fuels such as gasoline, compressed natural gas (CNG), and biofuels. Indeed, a greater compression ratio and preheating of the intake air allowed to run of a four-cylinder gasoline engine in HCCI mode within a relatively narrow speed and load range [28]. To build a commercially successful gasoline auto-ignition combustion engine for automotive purposes, the engine must run without external heat, without excessive compression ratios, and without specific fuel mixtures. As stated before, early HCCI research focused on gasoline-powered engines, and this technology is still being studied today. Controlled auto-ignition (CAI) is a new name for gasoline-fueled HCCI. However, the necessity for significant reductions in NOx and PM emissions led to mid-1990s research into the possibilities of diesel-fueled HCCI. Earlier, we discussed research involving dual-fueling. Although this strategy provides excellent control over combustion time, the success in developing HCCI combustion with more readily accessible fuels makes this approach unlikely to be explored shortly.

Natural gas (NG) is a plentiful resource worldwide. Although its principal purpose will be in stationary applications, it is currently utilized as a transportation fuel to some level, especially where local supply makes it desirable. NG has a high-octane rating of 125 and no LTHR, making it resistant to ignition. To create HCCI combustion, high intake temperatures and dilution with EGR or air are required, and even then, it is challenging to prevent excessive heat release rates. The use of onboard reforming to promote NG combustion was investigated in a CFR engine, as mentioned in [29–31]. They discovered that an engine running on NG alone had a very restricted operating range: NOx emissions were high, efficiency was poor, and cycle variability was considerable. While engine design may have a role, attaining HCCI combustion with NG seems quite challenging. The use of Reformer Gas to commence combustion improves performance; some variation on this strategy will probably be required in the future if NG is to be employed as an HCCI fuel. Biofuels, mainly ethanol and biodiesel, are the other alternative fuels currently hitting the market. These may be accessible as standalone fuels if dual-fuel ideas prove practical. Still, they will not be available in significant quantities to replace gasoline and diesel and will most likely be used as blend components. It is thus critical to determine if adding ethanol to petrol or FAME to diesel affects HCCI combustion. An HCCI investigation evaluated ethanol in a diesel engine [32]. Although pure ethanol ignited more easily than iso-octane, it performed less effectively at high engine speeds. Five percent FAME blends in diesel fuel were tested on a four-cylinder engine. The fuels' heat release profiles and ignition characteristics were comparable to those without FAME addition. The addition of FAME seemed to raise PM emissions somewhat, but the impact was negligible compared to the advantages of switching to HCCI combustion. These findings are promising and indicate that incorporating biofuels into gasoline and diesel will not pose substantial challenges for HCCI engines; nevertheless, further research will be required as HCCI engines approach commercialization.

Thirdly, the HCCI technique enables cleaner combustion, with very insignificant exhaust emissions, particularly NOx as mentiond in Figure 3.

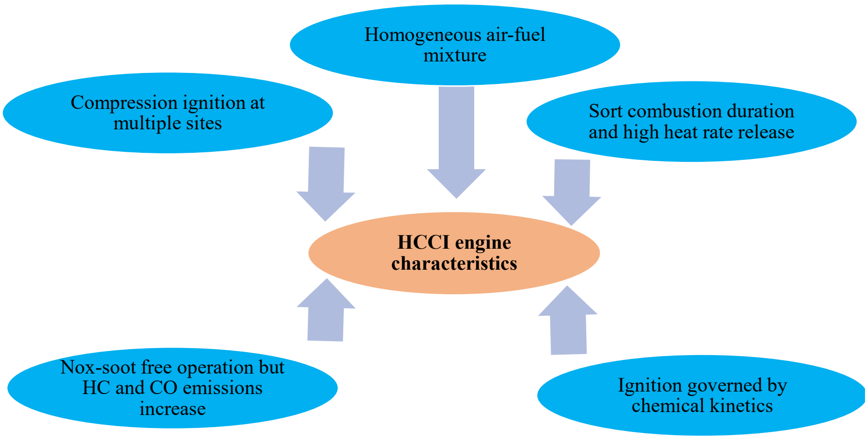

Figure 3. Operating characteristics of HCCI engines.

Gray and Ryan studied particle emissions from HCCI combustion of diesel and hexadecane/heptane blends. As a result, they showed that the HCCI technology reduced pollutants by 27% compared to traditional diesel compression ignition. Furthermore, they found a substantial correlation between intake air temperature and PM emissions [33]. Agarwal AK et al. tested diesel HCCI combustion with varied EGR and air-fuel ratios. They found that increasing the air-fuel ratio (leaner) and EGR enhanced the organic content of particulate matter. In SEM pictures, most particles were agglomerated accumulation mode particles [34]. Kaiser EW et al. measured PM from a gasoline-fueled HCCI engine with an air/fuel ratio of 50 to 230 [35]. Price P et al. found that a gasoline-fueled direct injection HCCI engine had similar particulate emissions to traditional direct injection S.I. combustion. A substantial accumulation mode (80–100 nm) was observed. They found that boosting exhaust gas recirculation reduced accumulation mode particle concentration. A nucleation mechanism with a mean diameter of 10–20 nm was also observed [36]. The homogenous in-cylinder mixture raises temperature and pressure during the compression stroke, causing simultaneous auto-ignition. The lack of a high-temperature flame front reduces NOx production [37,38]. The NOx level was low in biogas-diesel HCCI engines due to a higher homogeneity level between air and fuels [39]. Blarigan V [40] found that a homogenous, lean mixture may reduce NOx generation. The NOx level is low in natural gas HCCI engines, according to Olsson JO et al. [41], and it reduces further with the EGR ratio [42]. Even in non-HCCI mode, NOx emissions are lower than diesel conventional CI engines.. Saravanan N, Nagarajan G found reduced NOx emissions for all load ranges than diesel in traditional mode. They found that temperature influences NOx generation more than oxygen availability [43]. Thus, the HCCI mode produces exceptionally low NOx emissions with no substantial PM [44-45]. However, some challenges have limited the commercialization of the HCCI engine, such as the air-fuel mixture formation, combustion phasing, controlling heat release rate (HRR) and pressure rise rates (PRR), noise, and high emissions of HC and CO.

Indeed, due to the short period and ambient variables within the combustion chamber, it is challenging to produce a homogenous charge preparation in an HCCI engine throughout a wide variety of operating circumstances. Internal or external charge creation may be accomplished by mixing fuel and intake air outside the combustion chamber. External mixture preparation is a straightforward approach for producing a homogenous charge using a volatile fuel. However, it gives limited control over the ignition start under varied operating situations. Otherwise, Internal mixture preparation may be accomplished by injecting fuel directly into the combustion chamber early and late. The term "early fuel injection timing" refers to injection occurring during the early compression stroke.

In contrast, the late injection occurs at the top dead center (TDC) or after the compression stroke. The fuel's characteristics determine the charge generation, injection timing, spray development, evaporation, and diffusion in compressed air [46]. During the compression stroke, the early fuel injection is constrained by the prolonged tip penetration and wall impingement, increasing HC and CO emissions and lubricating oil dilution [47–49]. Split injection and extensive EGR preheating may help enhance air-fuel mixing [50,51]. The combustion phasing is another challenge of HCCI technology requirements in a narrow crank angle window near TDC. CA50, the crank angle point at which 50% of the total heat released appears, is used to describe the combustion phase [51]. The time and amount of fuel injected in CI engines influence the combustion phasing. However, since the fuel in HCCI engines is premixed and lean, the engine's ignition is controlled by the fuel's low-temperature chemistry. The molecular structure of the fuel, its residence duration, its equivalency ratio, and the temperature-pressure history of the intake charge all contribute to the rate of low-temperature oxidation processes. Controlling the combustion time of an HCCI engine is challenging owing to the LTHR's sensitivity to the fuel chemistry and environmental circumstances [52]. Combustion phasing accelerates operating loudness and banging if the primary heat releases prematurely during the compression stroke. On the other hand, delayed ignition combined with a lean charge increases the likelihood of misfiring, resulting in very high HC emissions and lower engine performance.

In addition, in an HCCI engine, volumetric ignition causes fast HRR, which may cause knocking combustion. The high HRR restricts the HCCI engine's brake mean effective pressure (BMEP) [53]. A low-duty CI engine with turbocharging achieves a BMEP of roughly 18 bars. The IMEP of a customarily aspirated HCCI engine is 5 bars at 1000–1500 RPM [52]. High PRR induces acoustic resonance banging and shortens combustion. High load sequential auto-ignition is governed by thermal stratification within bulk gas [54]. Split injection reduces maximum pressure and heat release rate in ethanol-gasoline-powered HCCI-DI engines. Controlling HRR and PRR in HCCI engines requires a dual fuel injection method.

The last one needs to discuss the HC and CO emissions of HCCI engines. In HCCI engines, lower in-cylinder combustion temperatures, spray impingement, and cool cylinder wall temperatures result in higher HC and CO emissions. The HC and CO emissions increase by a longer burn duration, resulting in partial misfire and expansion quenches in the most fabulous zone. The top ring land crevice of the combustion chamber is the primary source of HC production. Unburned HC zones may be seen along the centerline, squish volume, and bowl/central clearance volume. The nozzle area has also been identified as a significant source of unburned HC emissions [55]. CO is not entirely oxidized to carbon dioxide (CO_2) due to lower combustion temperatures, which need temperatures over 1450 K. CO emissions drop as the premixing ratio, load, and fuel-air ratio rise [56]. Increases in input air temperature and compression ratio (C.R.) may reduce HC and CO emissions [57]. A low-temperature oxidation catalyst must be developed to minimize tailpipe emissions in HCCI engines.

3. Thanol fuelled internal combustion engines based on HCCI technology

3.1. Ethanol characteristics

Ethanol is a chemical substance with a hydroxyl group (O.H.) attached to a carbon atom in its molecule. Fermentation of crops such as sugarcane, maize, and manioc, among others, produces ethanol. Sugarcane is used to make most of the ethanol produced globally, mainly in Brazil. Corn is used to make ethanol in the United States. Ethanol is utilized in cars as high-octane fuel. A similar scheme is being implemented in the United States, and the number of ethanol-powered automobiles is growing. Ethanol is a great motor fuel because it has a higher motor octane number than gasoline and lowers vapor pressure, resulting in lesser evaporative emissions. Ethanol has lower flammability in the air than gasoline, reducing the frequency and severity of car fires. Anhydrous ethanol has lower and higher heating values of 21.2 and 23.4 megajoules (M.J.)/liter, compared to 30.1 and 34.9 MJ/liter for gasoline [58–62]. The characteristics of ethanol and gasoline are described in Table 1, including E5. E10, E15, and E20 (e.g., E5 contains 5% ethanol and 95% gasoline in volume).

Table 1. Chemical and physical characteristics of ethanol and gasoline.

Characteristics		Mogas 92	E5	E10	E15	E20
Distillation temperature (ºC)	IBP	38.9	48.05	57.2	66.35	75.5
	t_{10}	53.6	59.45	65.3	71.15	77
	t_{50}	93.6	89.7	85.8	81.9	78
	t_{90}	158.6	138.7	118.8	98.9	79
	EBP	180	165.75	151.5	137.25	123
Octane number		92	92	96	100	104
Latent heat vaporization (kJ/kg)		270	270	412.5	555	697.5
C content (wt%)		85	85	76.8	68.6	60.4
O content (wt%)		0	0	8.675	17.35	26.03
Density (kg/liter)		0.73	0.73	0.747	0.763	0.78
LHV (MJ/kg)		44	44	39.7	35.4	31.1
A/F Ratio (kg)		14.7	14.7	13.27	11.83	10.40

The addition of ethanol to gasoline has several impacts. Ethanol boosts the heat output of unleaded petrol, producing complete combustion and a modest reduction in unburned hydrocarbon emissions [63–65]. The greater the ethanol percentage, the more polar solvent-like qualities the fuel exhibits, influencing fire suppression. However, even at high ethanol percentages, a small quantity of water will separate the ethanol from the gasoline in the mix. The specific gravity of ethanol and petrol is exceptionally comparable. The two dissimilar fuels combine quickly with minimum agitation, but the resulting mixture is more suspension than a real solution. Ethanol has a higher affinity for water than gasoline does. Without agitation, gasoline will float over a layer of ethanol/water solution over time. The resultant ethanol/water solution is still explosive due to the relatively high ethanol concentration. Phase separation may occur in fuel storage systems containing known amounts of water. By combining these fuels, the physical and chemical properties of the original fuels are altered.

However, the changes that ensue may be invisible to emergency responders. One of the most visible distinctions between blended and unblended gasoline is the visual appearance of the smoke and flame. The more ethanol present, the less noticeable the black smoke and orange flame generation are. Other burning substrates may obscure these features, such as automobiles tires. Another apparent difference between ethanol-blended fuels and gasoline is that when foam or water is sprayed over the burning product, the gasoline tends to burn off first, leaving the less volatile ethanol/water mix with no visible flame or smoke.

Ethanol's auto-ignition temperature and flash point are more significant than gasoline's (363 ºC and 14 ºC compared to 250 ºC and –43 ºC, respectively), making it safer to carry and store. Because ethanol's latent heat of evaporation is more than three times that of gasoline, the intake temperature in the manifold is lowered, increasing volumetric efficiency. The blends' calorific value and density have a linear connection, whereas the octane number and vapor pressure have a non-linear relationship. Because ethanol has a lower calorific value than gasoline, more ethanol is needed to provide the same amount of energy. Because ethanol includes oxygen molecules, the air required for complete combustion is less than that necessary for gasoline. Ethanol has a stoichiometric air-fuel ratio (AFR) of roughly 9, while gasoline has an AFR of 14.7.

3.2. The use of ethanol-blended gasoline

Ethanol has the same chemical formula made from starch- or sugar-based feedstocks, such as corn grain, sugar cane, or cellulosic feedstocks. Ethanol has a higher-octane rating than gasoline, making it ideal for mixing. Gasoline octane number regulations avoid engine knocking and assure drivability. Lower-octane gasoline is combined with 10% ethanol to get the usual octane. Ethanol, to variable degrees, has less energy per gallon than gasoline, depending on the volume proportion of ethanol in the mix. Denatured ethanol (98 percent ethanol) has about 30% less energy per gallon than gasoline. The fuel's amount determines the influence of ethanol on fuel efficiency and whether an engine is designed to operate on gasoline or ethanol. In recent decades, ethanol-gasoline mixed fuels have had the potential to improve internal combustion engines' performance significantly. Hsieh et al. investigated the performance and emissions of a S.I. engine running on ethanol-gasoline mixed fuels [66]. Chao HR et al. investigated the impact of a methanol-containing additive on carbonyl compound emissions from a heavy-duty diesel engine [67]. Lu XC et al. investigated the effect of cetane number improver on heat release rate and emissions of a high-speed diesel engine fueled with ethanol-diesel blend fuel [68].

Fuel-ethanol blends that include between zero and twenty percent of their mass fuel content exhibited an increasing degree of leanness at a constant mass fuel rate as the ethanol level increased [69]. Based on the energy content of the fuel mixture, ethanol blends have lower fuel usage than expected. Because ethanol has a favorable influence on combustion efficiency, the drop in net heating value is offset. The leaning effect of the bioethanol addition resulted in considerable reductions in emissions of CO and HC, according to research conducted by Schifter I et al. on the performance and emissions characteristics of port injection engines [70].

3.3. Literature of ethanol fuelled HCCI engine

It is widely believed that HCCI combustion is kinetically controlled [71,72]. In HCCI engines, auto-ignition and combustion rate are primarily controlled by the fuel chemical kinetics, which is highly sensitive to the charge composition and the evolution of pressure and temperature during the compression stroke. The major goal of HCCI combustion is to retain high fuel economy during part load circumstances while reducing soot and NO_x emissions [73,74]. In certain ways, HCCI engines combine the benefits of both compression ignition (CI) and spark ignition (S.I.) engines [74,75]. Both low-temperature and high-temperature heat releases occur during HCCI combustion, according to the findings of the experiment and modeling, and both heat releases occur within certain temperature ranges. One of the most crucial occurrences for HCCI engine functioning is the low-temperature heat release, which is chemically dependent on the fuel type [76,77]. However, there are still a few challenges and issues with its application that need to be addressed. Controlling ignition and combustion, having trouble operating at higher loads, releasing heat more quickly, emitting more CO and HC, especially at low loads, having trouble starting from a cold, emitting more NOX at high loads, and forming a completely homogeneous mixture are some of these issues [78,79]. Many control schemes have been investigated as a result of the absence of a clearly defined ignition timing control. Intake air preheating [80,81], variable valve actuator, variable valve timing, variable compression ratio, and EGR rate are a few of the research that has looked at HCCI combustion control approaches. Additionally, several studies concentrated on the impacts of various fuel physical and chemical features to govern HCCI combustion [82,83]. Since this technology hasn't yet developed to a suitable level, researchers worldwide are creating HCCI engines. They may be used in high compression ratio SI or CI engine setups. Without the use of diesel injectors or spark plugs, HCCI engines are capable of producing high engine efficiencies and little emissions. A prototype automobile with a gasoline HCCI engine was revealed by General Motors Corporation (G.M.), and it was stated that it could reduce fuel consumption by 15% [84]. The engine's ability to eliminate NOx emissions and reduce throttling losses contributes to improved fuel efficiency. The study field has grown significantly in recent years, covering all facets of the combustion process. The image of energy savings and better exhaust emissions has been progressively emerging. Research into alternative fuels is being driven by growing environmental worries about the usage of fossil fuels and global warming. Because of its great fuel adaptability, HCCI may be used with various fuels with various octane/cetane levels. An HCCI engine's combustion mechanism is not too sensitive to fuel properties like lubricity and laminar flame speed. Any Octane or Cetane number fuel may be used; however, various fuels need different operating conditions, affecting efficiency. Theoretically, any liquid hydrocarbon or alcohol fuel might be used in an HCCI engine with variable compression ratio or variable valve timing as long as the fuel is vaporized and combined with air before ignition. In addition to gasoline and diesel fuel, several alternative fuels, including methanol, ethanol, hydrogen, DME, and their mixtures, as well as gasoline and diesel mixtures and various iso-octane with heptane mixtures, have been experimentally demonstrated as potential fuels for HCCI combustion in both two-stroke and four-stroke engines.

To get ultra-low NOx and PM emissions with better performance, the HCCI mode of combustion is a superb option. The depletion of fossil fuels and the massive emissions of conventional engines are the primary reasons for developing biofuel-powered HCCI engines. However, achieving emission standards in all operational phases isn't easy. As a result, current cars' attempts to improve the biofuel-powered HCCI engine are required. Many academics have overlooked a critical and complete approach to the HCCI engine in the previous several years instead of focusing on specific operating parameters and biofuel mixes. The current setting necessitates a deeper understanding of the impact of operational parameters on the performance of HCCI engines fuelled by ethanol before progress can be made. In addition, the scientific community is only aware of a few review publications concentrating on HCCI engines driven by alcohol. As a result, addressing the constraints and nonlinearities of HCCI engines fuelled by this fuel would need integrated insight research. An HCCI engine driven by biofuel might benefit from research like this, which shows the relationship between different operational factors and their effects on performance. There is a need for a complete analysis of HCCI engine characteristics in this study's topic. In addition, the impact of individual and combined factors on ethanol-powered HCCI engine characteristics was critically analyzed. It also discusses the difficulties in making the paradigm transition from a conventional engine to an HCCI engine and the research that went into it.

As the next generation of ICEs, engine experts are exploring the potential of an ethanol-fueled HCCI engine. In the last two decades, supercharging and fuel reforming, valve timing, and forced induction were the primary methods used to develop ethanol-fuelled HCCI engines. Unthrottled operation of the HCCI engine with a shallow mixture resulted in no NOx production in this investigation [85]. The HCCI engine's pressure was increased utilizing a supercharger, as shown by Christensen M et al. Supercharger use was shown to be significantly associated with increasing IMEP for HCCI. While reducing HC emissions, raising the pressure also decreases NOx concentrations. According to the researchers, the critical advantage of HCCI is the reduced NOx emission [86]. Ng CKW and Thomson MJ used a single-zone reactor model and reaction mechanisms to examine how fuel reforming and EGR affect HCCI operation. For reforming, they used hydrogen and CO, which increased the HCCI engine's working temperature range. Because of its broad flammability range, hydrogen may be utilized as an additive. Compared to reforming, EGR was shown to be more successful in extending the engine's operating range. The reforming of HCCI combustion also proved practicable to sustain complete combustion at lower intake temperatures [87].

It has been shown that the acceptable operating range of bioethanol-fuelled HCCI may be improved efficiently by employing forced induction and residual gas trapping, as Yap D et al. has shown [88]. Boost offers the potential to modulate the timing of combustion. A rise in trapped residual gas might reduce the maximum achievable load at a given boost pressure. NOx emission levels may be reduced by using more trapped residual gas and significantly boosting pressure. On the other hand, CO emissions rose as a result of increased pumping losses [89]. Zhang Y et al. used a SI Ricardo engine with a valve timing strategy for their research. HCCI engines running on ethanol were run at various AFRs, speeds, and valve timings to see how the number of trapped residuals changed. Valve timing and lambda significantly affected ignition timing and combustion length, as shown by these experiments. Lambda was determined using an ETAS linear oxygen sensor, and the influence of valve timing was compared to IMEP, residual pressure, and speed in all trials. For HCCI engines, they found that the engine's operating range was restricted to knock and misfire.

Furthermore, the HCCI combustion was accomplished by adjusting the number of trapped residuals by negative valve overlap using a valve timing approach applied to intake and exhaust valves [90]. Combustion-phasing retard has been utilized to minimize HCCI engine knock at high loads. Because autoignition occurs during the expansion stroke, the impact of naturally existing thermal stratification created by heat transmission is intensified, extending the length of the staged autoignition event, and lowering the peak heat release. Knock suppression and emissions reduction may also be achieved using water injection technology. Water has a high specific heat capacity. The high temperature evaporates liquid water into water vapor, absorbing the cylinder's heat and reducing its temperature and pressure. As a result, knocks are less likely to occur. With water injection, it is possible to lower cylinder temperatures and pressures by filling the combustion chamber and diluting the air inside, as well as to enhance the disturbance in the cylinder so that air and fuel mix more uniformly, preventing local oxygen enrichment.

Adding gasoline to ethanol and evaluating the fuel flexibility of this fuel has been the focus of inquiry after the work done to enhance HCCI operation. Mack JH et al. used engine testing and numerical modeling to examine the addition of di-tertiary butyl peroxide to net ethanol and diethyl ether (DEE) as a combustion time advancer [91]. Their study observed that adding DEE-in-ethanol combination had a more advanced impact on combustion than pure ethanol. Diethyl ether (DEE) was also added to pure ethanol. Manente V et al. tested a tiny HCCI engine for a power supply system with varying compression ratios [92]. Due to DEE's strong reactivity, it was discovered that compression energy is the best way to get the combination to self-ignite. The researchers found that quenching issues somewhat influenced DEE fuel and that engine squish distance significantly impacted its performance. Compared to traditional automobile and truck engines, the NOx emissions were equivalent to diesel engines, but the CO and HC emissions were much more significant. Mack JH et al. [93] used isotope tracing and numerical simulations to study the HCCI combustion of ethanol and DEE fuel mixtures. Dehydrogenated ethanol (DEE) is more volatile than ethanol. Fuel mixes containing DEE resulted in combustion, leading to additional completion progress. In addition, there was no substantial increase in intake temperature or decrease in the length of the energy release. They discovered that burning fuel mixtures in HCCI combustion had various properties. This research aims to examine the effects of DEE on the combustion and exhaust emissions of an HCCI-DI engine. A port fuel injection system is used to deliver the premixed gasoline to adjust the DEE concentration. At a constant engine speed of 2200 rpm, the tests were run at a load of 19 Nm. Interest in DME as an alternative to HCCI engines has been growing [80]. Even at greater compression temperatures, the ignition delay of this fuel is unaffected by its negative temperature coefficient zone. Low- and high-temperature reactions (LTR and HTR) contribute to the numerous stages of heat release in the combustion process (HTR).

Xie H et al., ethanol, Methanol, and Gasoline were selected for use in the HCCI engine. The camshaft systems were reworked with low lift valves to maintain stable HCCI engine functioning by trapping residual gas in the intake mixture. According to the findings, HCCI can run efficiently on alcohol fuel and create minimal levels of NOx pollution [94]. They employed a four-stroke, three-cylinder diesel engine and two fuels (ethanol and iso-octane) for their experiment. They investigated the impact of various fuels on the combustion and functioning of HCCI. Adding iso-octane to ethanol retards the onset of combustion, resulting in a drop in the IMEP and thermal efficiency of the combustion process. In addition, they found that increasing the amount of temperature input (T_{in}) accelerated the onset of combustion. This issue has been investigated multiple times to see whether the water in ethanol may help alleviate the HCCI engine's rapid pressure increase at high loads and more tremendous boost pressures. Flowers DL et al. tested an ethanol-water mixture in an HCCI engine using wet ethanol [95]. Water mixing as a means of combustion control was researched by Mack JH et al. [96]. They found that retaining residual gas and forcing induction reduced in-cylinder pressure increase during bioethanol-fueled HCCI combustion when blended with water. It demonstrated the highest lambda attainable with increasing fuel water content. With 10 percent water content, there is a pretty little shift. However, raising the water content to 20% significantly reduces the highest achievable lambda. When ethanol and water are blended, the maximum rates of pressure increase may be lowered. They discovered that the quantity of dilution (trapped gas) decreases when the input valve event for steady combustion is delayed or advanced significantly.

It has been known for at least a century that ethanol fuel performance may be affected by its water concentration [94,95]. However, Limited research has examined the influence of ethanol or alcohol-water concentration on the operating parameters of an HCCI engine directly. Studies on the effects of water as a charge diluent on HCCI engines are discussed in the following text. Fuel flexibility is built into HCCI engines from the ground up. For autoignition, any fuel must be able to vaporize and then be compressed to a temperature of around 1100 K. To put it another way, HCCI's operational limitations are based on its ability to heat fuel, not on its ability to spread a flame over the combustion chamber. A vaporizer heated by exhaust fumes may evaporate fuel outside the engine, eliminating the need for direct injection of liquid fuel into the engine, which would otherwise negatively impact ignition [96]. There have been prior studies on wet ethanol's effect on various I.C. engines, including spray-guided direct injection engines and homogeneous charge compression ignition (HCCI) engines [97,98]. Brake thermal efficiency was increased by 38.7 percent and NOx levels were reduced by 1.6 ppm when hydrous ethanol with 35 percent water content by volume was utilized in an HCCI engine by Martinez-Frias and colleagues [99]. HCCI engine stability was later proved with ethanol comprising up to 40% water by volume in the engine's fuel mix. Olberding J et al. [100] tested the engine's performance on either gasoline or ethanol-water fuel mixes (70 percent ethanol with 30 percent water) using a transit vehicle. When employing wet ethanol, engine thermal efficiency may be greatly boosted while NOx and CO emissions are significantly reduced compared to gasoline.

4. Conclusions

HCCI engines are more efficient because they use less fuel and have compression ratios similar to those seen in diesel engines. Aside from gasoline and compressed natural gas, HCCI can also run-on biofuels. Cleaner combustion is made possible by the HCCI method, which produces very low exhaust emissions, especially in the case of NOx. Fast HRR caused by volumetric ignition in an HCCI engine, on the other hand, may result in knocking combustion. Higher HC and CO emissions are also caused by lower in-cylinder combustion temperatures, spray impingement, and cold wall temperatures in the cylinders. A literature review and some background information were given to emphasize the benefits and limitations of employing ethanol-fueled HCCI by worldwide scientists. Despite these benefits, HCCI engines powered by ethanol blends have drawbacks, including a lack of ignition control, cold starting difficulties, and limited load carrying capacity. Reducing limits and achieving commercial success has been the primary objective of scientists throughout the globe. This article aims to fill the research vacuum and look at different approaches to addressing research questions from prior HCCI operations. HCCI technology has only recently acquired popularity and attracted automakers owing to a lack of supporting electronics and software in its early phases. The execution of the HCCI idea necessitates the development of several elements, including electronics, software, and materials; thus, the development of simply one of these aspects is insufficient. To satisfy HCCI's standards, researchers have made significant modifications to the entities mentioned above.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Conflict of interest

All authors declare no conflict of interest regarding this paper.

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