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A Comprehensive Review on Homogeneous Charge Compression Ignition Engine

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***Abstract*— Research on engines using different combustion principles has been spurred up by widespread worries about dangerous pollutants, stringent emission restrictions, and global warming. Low Temperature Combustion (LTC) is a cutting-edge idea for internal combustion engines that will be able to replace the standard modes of combustion and have the benefit of using both conventional and renewable fuels. In this sense, LTC has garnered interest on a worldwide scale recently, particularly the Homogeneous Charge Compression Ignition (HCCI) mode. The absence of flame propagation or diffusive flame distinguishes this combustion mechanism from spark ignition and compression ignition. On the contrary, chemical kinetics controls HCCI combustion. When the mixture approaches chemical activation in HCCI engines, which employ much diluted homogenous charge, auto ignition occurs simultaneously in several locations. In comparison to diesel engines, HCCI technology enables high efficiency operating with little nitrogen oxide, soot, and particulate matter emissions. The primary obstacles to be addressed are, however, the regulation of ignition timing, the impossibility of the high load operation, as well as increasing emissions of carbon monoxide and unburned hydrocarbons. The past and current work across the globe has revealed that engine working on HCCI module can be fuelled with different fuels with little emissions and high efficiencies. All the past work has been mentioned and explained in this current work.**

***Index Terms*— Low Temperature Combustion, Homogeneous Charge Compression Ignition, Spark Ignition, Compression Ignition, Carbon Monoxide, Nitrogen oxide.**

I. INTRODUCTION

In recent years, conventional diesel fuel has been widely used in the transportation sector and in power generation. The usage of energy has become inevitable in every human life, with the increase in industrialization and globe population, alternative fuels are chosen instead of fossil fuels [1]. Petroleum fuels are currently the dominant global source of CO_2 emissions, and their combustion is posing a stronger threat to clean environment [2]. Furthermore, more focus is given on biodiesels (methyl esters) as alternate fuel for transportation sector to overcome the accelerated increase in the price of fuel and rapid depleting of fuel reserves. Most of the developed and developing countries have promoted the production of non conventional fuels with the financial support of the government. This made us draw our attention to biofuels i.e vegetable oils as an alternative fuel in IC Engine, they are biodegradable, renewable and clean and can be produced very easily in the rural places [3]. From the different possible options of liquid fuel, different vegetable oils have been taken into picture as a promising alternate fuel because of its wide fuel properties. As per the records many practices have been made by several researchers of using vegetable oils such as pongamia, rubberseed, sunflower, peanut, soybean etc as an alternate fuel. As

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vegetable oils are edible in nature, using them continuously would cause a shortage of food supply. As per the studies done it is shown that vegetable oils show good performance and short-term operation for emission [2].
The viscosity of vegetable oils is having higher viscosity then the diesel fuel, Because of this it develops gumming, injector deposits, ring sticking etc [1]. Reducing the viscosity of vegetables oils is very important for making a suitable diesel engine; many methods are there for this purpose i.e. blending or dilution, preheating and transesterifiaction. Testing by preheating, blending with diesel and blending with preheating improves the performance and reduces the emission compared with neat vegetable oil. It also ensures the reduction of the filter clogging and smooth flow of oil. From the above reasons, it is clear that identification and testing of nonedible vegetable oils on the present conventional diesel engine with modification is required [2]. A non-edible oil derived from Jatropha, sea mango, rubber seed, and candlenut are not suitable for human consumption because it contains toxic substances in the oil [4-6]. Thus, oil extracted from the non-edible crops can be utilized for the production of biodiesel in order to overcome food versus fuel obstacles by tapping into non-edible oils for manufacturing biodiesel. Though biodiesel is the environment-friendly, prominent alternative to conventional fuel, the usage of 100%biodiesel is not endorsed in the diesel engine; consequently, biodiesel and diesel are mixed at certain ratios [7]. Blending non-edible oil with diesel fuel is the simplest way to utilize non-edible oil as a fuel, as it does not require any chemical process. The purpose of blending non-edible oil is to minimize the viscosity and enhance the volatility since the poor volatility and high viscosity are the main obstacle to using nonedible oil as a fuel [8].
The present paper mainly focuses on the usage of nonedible vegetable oils, their biodiesels and blends in diesel engines and Homogenous Charge Compression Ignition (HCCI) engines. The present Compression Ignition (CI) Engine shown first-class superiority on thermal efficiency, fuel economy and Carbon Dioxide (CO_2) emission, also in addition it gave elevated particulate and Nitrogen Oxide (NO) emission as reduced gas mixture homogeneity emerges. A new mode of combustion, HCCI engine combines the advantages of burning for gasoline and diesel engine, which has aroused from extensive concern of many researchers [9,10]. Taking HCCI engine mode into consideration provides the opportunity to accomplish low-temperature combustion and homogeneous mixture combustion, in this manner improving the emission performance [11]. This study reviews the fundamental concepts of HCCI engine, the development, benefits, and the future scope. This paper mainly focuses on a comprehensive review of the research made by many researchers on HCCI engine, and an attempt is made to prevail over some challenges.

II. HCCI COMBUSTION FUNDAMENTALS

The Petrol and Diesel engine development is attained to peak stage from the ages even it has the substantial advantages in the efficiency and exhaust emission, further there is a need for the advance research in near future is required. Diesel has a fuel efficiency advantage over petrol due to its high thermal efficiency and for low pumping loss. Looking at the exhaust emission the petrol has a benefit over diesel. The work of many researchers revealed that the new concept i.e. HCCI is promising technology that combines elements of engine principles. HCCI engine operation allows for thermal efficiency improvement and significant reduction in oxides of nitrogen emission [12].
HCCI is recognized by the fact that the fuel and air are mixed before combustion starts and the mixture auto-ignites because of the temperature increase in the compression stroke. Thus, HCCI is like SI in the sense that both engines use premixed charge and like CI as both rely on auto-ignition to initiate combustion [13, 14]. The process of combustion in HCCI engine is totally managed by chemical kinetics and there is not any flame propagation due to volumetric combustion throughout the combustion chamber [15, 16]. The combustion in HCCI engine is different when compared to petrol engine and diesel engine which have turbulent and diffusive flame propagation respectively. The HCCI engine considerably augments the thermal efficiency and reduces the emissions significantly. The main causes for the elevated thermal efficiency are: HCCI engine abolishes the throttling process and thus ending the pumping losses, with HCCI engine it is possible to use higher compression ratios, HCCI engine has shorter combustion duration resulting in lower thermal losses [17, 18]. In this review, the below Table 1 shows the comparison of SI, CI and HCCI engines [17, 19, 20].
The combustion in HCCI has an excellent potential for reduction of Oxides of Nitrogen (NOx) and Particulate Matters (PM) [21]. On the contrary, HCCI engine produces higher Carbon Monoxides (CO) and Hydrocarbon (HC) emissions compared to conventional combustion. This is due to air-fuel mixture entering the gaps through the compression stroke and gets away at some point through the expansion stroke without combustion because of low temperature inside the cylinder [17, 22-24]. Fig. 1 depicts the area of HCCI combustion above the HC and CO limit and dodges from the formation of both NOx and Soot [19]. The HCCI combustion is one of the best combustion methods to be adopted widely in the coming days, as it offers wide range of fuel flexibility [25-27]

with low emissions and higher thermal efficiency. Fuel flexibility is also considered as a potential benefit [28]. The lean homogeneous mixture preparation and low temperature combustion are adopted in HCCI engine to suppress the soot emissions and NOx from the engine [29].

TABLE I. COMPARISON OF SI, CI AND HCCI ENGINES.

Sl.No.	Parameters	SI	CI	HCCI
1	Fuel	Gasoline	Diesel	Flexible fuel
2	Ignition	Spark	Auto Ignition	Auto Ignition
3	Air-fuel ratio	λ=1(ideal)	λ= 1.2 - 2.2(lean)	λ= 2 - 8(lean)
	Throttle process	Present	Absent	Absent
4	Flame propagation	Turbulent	Diffusion	No flame propagation, homogenous oxidation
5	Combustion type	Premixed	Premixed and diffusion	Premixed volumetrically, Dominated by chemical kinetics
6	Thermal efficiency	upto 30%	upto 40%	Greater than 40%
7	Emission	Very low and higher CO_2	NO_x and soot are high	Low soot and NO_x with high HC and CO
8	Fuel economy	Good	Superior	Superior

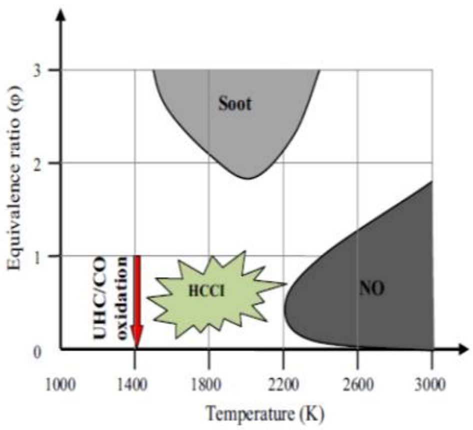

Figure1. HCCI combustion showing reduction of NO_x and soot

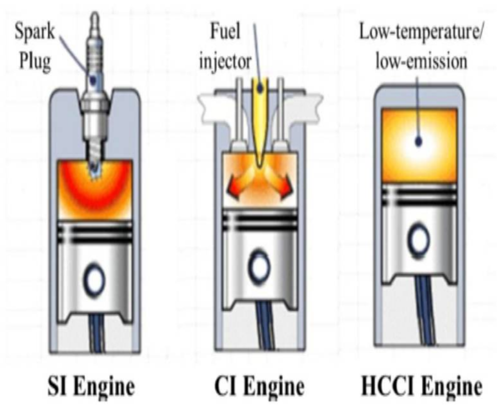

Figure 2: Schematics illustrating conventional engine with modification [30]

Fig. 2 represents the comparison between petrol engine (SI engine), diesel engine (CI engine) and HCCI engines. A lean homogeneous mixture is prepared before the initiation of ignition and due to higher temperature in the compression stroke it is auto ignited. The oxides of nitrogen are mainly formed due to oxidation of atmospheric nitrogen. The reactions, which result in the formation of NOx, are availability of oxygen and higher temperatures [31]. The use of HCCI engine has an advantage of having lower cylinder temperature as compared to diesel engine.

III. MAJOR ADVANTAGES AND DISADVANTAGES OF HCCI ENGINE

The key advantages and disadvantages pertaining to various engine types are summarized in the Table. II

TABLE II: COMPARATIVE ANALYSIS OF VARIOUS ENGINE TYPES

Engine type	Advantages	Disadvantages
SI engine	➢ The compression ratio varies from 4:1 to 8:1. ➢ The air-fuel ratio is from 10: 1to 20:1. ➢ Brake thermal efficiency varies from 25%-35.	➢ SI engines have high NOx and PM emissions
CI engine	➢ The compression ratio varies from 12 to 22. ➢ The air-fuel ratio is from 18:1 to 80:1. ➢ Brake thermal efficiency varies from up to 36%	➢ Higher particulate and nitrogen oxide (NO_x) emissions as compared to SI engine.
HCCI engine	➢ fuel flexibility. ➢ Uses higher compression ratio. ➢ Replacement of conventional SI and CI engines ➢ Low NOx and soot emissions ➢ Thermal efficiency up to 46% [32]	➢ It has a shorter combustion duration, compared to SI and CI engines. ➢ The UHC and CO emissions are more due to poor combustion efficiency.

IV. A HISTORICAL PERSPECTIVE ON EVOLUTION OF HCCI ENGINE TECHNOLOGY

The combustion of the HCCI engine was first suggested by Onishi as an alternative combustion technique for a 2-stroke petrol engine in the year 1979 [33]. This technology showed Active Thermo-Atmosphere Combustion (ATAC), which is different from conventional engines like SI and CI. The negative aspect of a 2-stroke engine is the elevated degree of residuals at low loads, and it tends to carry on the combustion even though the engine is stopped. Onishi and his associates transformed these lags into qualities by developing the ignition mode (ATAC), which depended on both the high level of internal residuals and the high initial charge temperature. Because of the instantaneous ignition inside the cylinder charge, there is a significant reduction in UHC emissions and an improvement in fuel economy. This concept of ATAC in a 2-stroke SI engine can be easily familiarized for stable operation, and it can also be seen that there is no misfiring in the engine when operating at a wide range of part-throttle operation. For the SI engine, with a compression ratio of 7.5:1 and an engine speed range of 1000–4000 rpm, stable HCCI engine operation can be attained.

Noguchi [34], made an investigation on reversed crank case scavenging 2 stroke cycle engines, utilizing the particular self ignited combustion process to identify the temperature pressure range that is happening in the combustion chamber and this self ignited combustion is termed as Toyota Soken Combustion (TS). This phenomenon of self ignited combustion suggests itself under relative low cylinder temperature and pressure that compared with the conventional diesel engine combustion. Ignition process that took place at different place with identifiable flame propagation in the cylinder during combustion was seen through the ocular investigation. Before the initiation of auto ignition process high levels of Formaldehyde (CH2O), Hydroperoxy (HO2) and Oxygen (O) radicals were found in the cylinder and were measured by spectroscopic method. The radicals mentioned above are caused by the low temperature auto ignition chemistry of large paraffinic hydrocarbon fuels. Following that, Najt and Foster conducted extensive research on the 4-stroke engine in order to better understand the fundamental physics of the HCCI engine [35]. They concluded that HCCI auto-ignition is controlled by low temperature (below 1000 K) chemistry and the bulk energy release is controlled by high temperature (above 1000 K) chemistry dominated by CO oxidation. They created a correlation for the energy release rate based only on chemical kinetics that clarified the HCCI's observed response to modifications in compression ratio, equivalence ratio, dilution level, engine speed, and fuel type.

These findings, together with those of Onishi [33] and Noguchi [34], lead researchers to the conclusion that HCCI is a chemical kinetic combustion process that is governed by the temperature, pressure, and composition of the in-cylinder charge. Contrary to diesel combustion, which is primarily reliant on fuel-air mixing, classical SI combustion relies on the spread of the flame According to Najt and Foster [35], HCCI has a constrained working range and poor control over the ignition process. Onishi and Naguchi both discovered the same issues in the two-stroke HCCI engines. Furthermore, there was little chance that active radicals would be recycled into the cylinder and cause auto-ignition because external Exhaust Gas Recirculation (EGR) was utilised to dilute the mixture. Their research found that while radicals might be important in two-stroke HCCI engines, they are not necessary for HCCI auto-ignition. Ryan and Callahan continued their research and found that diesel fuel requires a low compression ratio otherwise auto-ignition happens too early during the compression stroke [36]. Later, Thring [37] expanded the tests to investigate the impact of external EGR and air-fuel ratio on the engine's performance. The term HCCI, which has since been used by many other researchers to characterize this kind of combustion process in both gasoline and diesel engines, was first used by Thring in his paper. He and his team once again noticed the limitations of HCCI operations. The working regime is limited to part load, and timing control for the auto-ignition is difficult to manage. It was proposed in his paper that HCCI could be integrated into an engine operating strategy, with the engine running on HCCI under part loads and switching to SI flame propagation during higher engine loads.

Stockinger [38] used a regular 1.6-liter VW engine that had been modified to operate with preheated intake air in order to test HCCI for the first time on an actual production engine. The efficiency of the part load increased from 14 to 34%. By using a greater compression ratio and pre-heating the intake air, showed that a four-cylinder gasoline engine could be operated in HCCI mode within a highly constrained speed and load range. However, it is a requirement that engines function without providing external heat to the external charge, without subjecting them to extremely high compression ratios, and without using special fuel blends in order to develop a production-viable gasoline auto-ignition combustion engine for automotive applications. The adaptation of Controlled Auto-Ignition (CAI) to 4-stroke gasoline engines made the greatest strides, according to Zhao [39], in Europe around the year 2000. Three separate experiments [40-42] demonstrated the ability of 4-stroke gasoline engines to run in CAI combustion mode over a range of speed and load by using early exhaust valve closure or negative valve overlap. Since that time, HCCI combustion has attracted attention and grown to be a popular research area on a global scale.

Aoyama [43] conducted an intriguing study on HCCI. They compared the operation of HCCI, diesel, and Gasoline Direct Injection (GDI). At its ideal values A/F ratio, HCCI showed the lowest fuel use and much lower NOX emissions, but greater HC emissions. Supercharging was also employed to boost the engine's output. However, in this study the boost pressure was fairly low, no inferences could be drawn about the likelihood of achieving an engine torque similar to that in SI operation. Many of the early investments made in HCCI targeted gasoline-fueled engines, and this technology is still actively being developed today. To define gasoline fueled HCCI, a new word called CAI was developed. However, studies into the possibility of diesel fueled HCCI started in the mid-1990s due to the requirement for significant reductions in both NOx and PM emissions. Overall, it is concluded that earlier research on HCCI has demonstrated that it may be applied to both two-stroke and four-stroke engines. However, the actual working circumstances are constrained, because of the need for combustion rate. This necessitates a high residual gas concentration in two-stroke engines, which is present at part load. Four-stroke engines, which typically have substantially less residual gas, need the usage of ultra-lean mixes or significant levels of EGR. NOX emission has been said to be extremely low, typically only a few Parts Per million (ppm).

V. Investigations And Possible Solutions

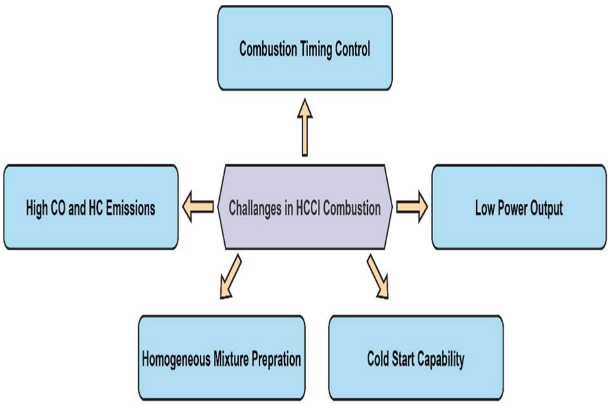

Figure 3: Challenges in HCCI combustion [44]

As was already noted, HCCI combustion has several benefits, but there are technical challenges that need to be addressed for wider adoption in various industries. The main challenges in developing HCCI engines include difficulties in achieving reliable ignition, controlling combustion phasing, managing combustion stability, and ensuring low emissions [17,19,21,22,45 and 46]. These challenges are depicted in Fig. 3 and require further discussion.

A. Ignition timing and control

The beginning of combustion in HCCI engines is constrained by chemical kinetics, which is regulated by the chemical and physical characteristics of the fuels as well as the temperature and pressure of the air-fuel combination, all of which may be influenced by a wide range of variables. However, according to Haraldsson [47], four variables—initial charge composition, initial charge temperature, rate and amount of compression work, and rate and distribution of heat transfer from the engine—governed the ignition timing, combustion characteristics, engine load, and efficiency. There are a few combustion phasing control methods, and they may be categorized into two classes based on the variables they affect: the charge's temperature and the mixture's reactivity [17].

The Utilizing heaters or recovery heat exchangers, Variable Compression Ratio (VCR) [20, 48- 51], Variable Valve Timing (VVT), residual/exhaust gas trapping [52–58], variable EGR [59–62], in-cylinder injection timing control, and water injection [63, 64], as well as residual/exhaust gas trapping and VVT, can all modulate the temperature of the charge. These techniques can adjust the intake temperature of the charge and regulate the ignition time. The use of two or more fuels [65-68], fuel additives [69], variable EGR, ozone injection to advance the combustion phasing [70-75], and water injection to retard the combustion phasing are strategies to change the reactivity of the mixture. Every combustion timing control has advantages and disadvantages of its own. Although, in accordance with Agarwal [17], the development of new methods to control the fuel and air system by a close loop control, using cost-effective feedback sensors instead of pressure sensors, which are expensive for commercial applications, is also required for the HCCI combustion control.

B. Low power output

The power output in IC engines is governed by the load and engine speed, and it is often calculated using the Indicated Mean Effective Pressure (IMEP) or Brake Mean Effective Pressure (BMEP), as these parameters enable comparisons between various engines. In automotive applications, typical BMEP values for 4-stroke SI engines range from 10.5 to 12.5 bar for naturally aspirated engines and 18 to 24 bar for turbocharged engines, while BMEP values for CI engines range from 8 to 9 bar for naturally aspirated engines and 18 to 24 bar for turbocharged engines [76].

According to Saxena [21], in spark ignition and compression ignition engines, respectively, the IMEP is typically approximately 5 bar operating at 1000–1500 rpm for naturally aspirated HCCI engines, and this represents roughly 40% and 30% of the available load. Additionally, the maximum load operation range is extremely constrained, leading to a small working window for HCCI. To slow down the chemical kinetics of the air-fuel combination, new research and approaches must be created. By decreasing the high-pressure peaks and extending the time the combustion can continue under high loads, it will minimize excessive noise and structural damage.

Increasing the intake air is one of the best ways to expand the HCCI engine's operating range [20, 50, and 77]. Olsson [78] used dual fuel and turbo charging in early investigations to obtain large loads, up to 16 bar BMEP at 1800 rpm, and extremely low NOX emissions. At 1000 rpm, Christensen and Johansson [79] were able to reach 16 bar of IMEP by using 50% of the EGR rate and 1.5 bar of boost pressure. An HCCI engine with 20 bar of BMEP operating at 1200, 1500, and 1800 rpm, 8:1 compression ratio, and boost pressure of 3 bars was described by author [80].

Dual-mode operation is yet another method for overcoming low power output and achieving large loads. To put it another way, it means running the engine in SI-HCCI or CI-HCCI mode. In the academic and automotive industry communities, Spark-Assisted HCCI (SA-HCCI) or Spark-Assisted Compression Ignition (SACI), which are the same, has received a lot of attention [81-83]. According to Saxena [21], SA-HCCI has been a highly effective strategy to close the gap between HCCI and SI engines since it allows for operating over the HCCI ringing limit end and below the SI engine misfire limit. Additionally, SA-HCCI can address the drawbacks of pure HCCI engines, including combustion timing management, an extension of the stability of low loads, and better emissions [21].

C. High CO and HC emissions

Studying HCCI combustion is primarily driven by the possibility of significant pollution reductions when compared to spark and compression ignition engines. Although HCCI reduces NO_X and PM, they release more hydrocarbons and carbon monoxide than traditional engines. Low in-cylinder temperatures make HCCI combustion challenging to complete. In this manner, the peak gas temperature often stays below 1500 K, making it challenging for CO to completely oxidize to CO_2, releasing a significant quantity of CO. Additionally, the incomplete combustion results in higher HC emissions [84].

Direct in-cylinder injection method is one way to combat excessive HC and CO emissions at lower loads, while after-treatment devices are crucial for reducing HC and CO emissions at greater loads [17]. However, the low Exhaust Gas Temperature (EGT) of HCCI makes after-treatment devices less effective than they would be. A low temperature oxidation catalyst must be created in this regard. A third option is to enable the employment of a three-way catalyst, however, to do so, the HCCI engine must run at stoichiometric air-fuel ratios and with exhaust gas temperatures greater than the catalysts' light-off temperatures.

D. Cold start capability

The charge temperature is crucial for the ignition process in HCCI engines and can affect cold start performance. A low charge temperature can result in insufficient ignition and prevent the engine from starting. According to Agawal [17], Various techniques have been studied to improve the cold start capability in HCCI engines, including the use of glow plugs, higher compression ratios, fuel additives, and VVT. The dual-mode technique, which involves starting the engine with conventional combustion (SI or CI) and then switching to HCCI mode, has shown to be effective. In VVT, the initial charge temperature can be controlled by retaining residual gas or rebreathing hot exhaust gas through the exhaust valve [17].

E. Homogeneous mixture preparation

The way the mixture is prepared plays a significant role in HCCI combustion, affecting both efficiency and emissions. There are three basic mixture preparation methods: internal charge preparation (port fuel injection), external charge preparation (direct injection), and mixed charge preparation (combination of both). Direct injection is used for internal charge preparation, while dual-fuel mode uses both port fuel injection and direct injection. [17].

Each mixture preparation method has its own advantages and disadvantages. Port fuel injection is limited at low loads when combustion temperature is below 1400-1500 K and produces high levels of CO and HC [85]. Direct injection requires precise control of fuel penetration to prevent liquid fuel droplets from condensing or sticking to cylinder walls [17]. Proper spray angle and combustion chamber design also need to be considered. To ensure mixture homogeneity, it's important to choose the mixture preparation method that best suits the engine's needs.

VI. Conclusions

The key tenets of HCCI combustion technology were reviewed in this article. Additionally, it emphasized the benefits of this combustion mechanism and its historical development. Finally, the primary issues and potential fixes were outlined and debated.

In order to increase thermal efficiency and lower NO_X and soot emissions, HCCI combustion technology evolved throughout the years. The dominance of chemical kinetics in combustion is one of the most crucial tenets of the HCCI concept. In other words, chemical kinetics, pressure, and temperature history have a considerable impact on numerous performance characteristics. Chemical kinetics, pressure, and temperature history also have an impact on combustion phasing. Compared to traditional combustion modes, the HCCI combustion offers various benefits. In comparison to SI or CI engines, the HCCI idea can achieve better thermal efficiency and lower NO_X and PM emissions. In addition, HCCI engines may run on a variety of fuels, making it possible to switch from fossil fuel to renewable fuel, reducing the need for fossil fuels and certain harmful emissions for the environment. On the other hand, compared to conventional engines, the HC and CO emissions are often greater. The low power output with a constrained operating range, combustion timing control, and greater CO and HC emissions are the key barriers to HCCI's commercial acceptability. There are number of useful strategies established for low load applications, but for full load applications, there aren't many good alternatives to pure HCCI engines. Increasing the intake air volume is one way to increase the load range. In this regard, further research is required to increase the operating range of HCCI engines. High emissions of hydrocarbons and carbon monoxide are other issues, but they might be mitigated by creating an after-treatment system that can operate well at low exhaust gas temperatures and a lean air-to-fuel ratio.

In the HCCI combustion idea, combustion time control is the most important problem. Several methods exist to manage auto-ignition, including VCR, VVT, variable EGR, residual/exhaust gas trapping, modifying intake charge temperature, water injection, ozone injection, two fuels to alter mixture reactivity, and fuel additives. These techniques, however, have advantages and disadvantages of their own. The combination of dual combustion mode, HCCI, and SI or CI systems have been suggested as a solution for many sorts of research to aid in combustion control and expand the limitations of a pure HCCI engine. This approach appears to be a workable alternative for short- and medium-term HCCI commercialization. The complete management of EGR to enhance charge preparation, intake temperature control, and finally combustion timing control are some of the crucial aspects that need to be looked at and improved quickly regarding the use of HCCI engines. To increase the operational limitations, it is also crucial to research a large rise in the intake air system. Considering above all factors, the utilization of renewable fuels in HCCI engines is still a very alluring area for research and will receive even more attention in the upcoming years.

APPENDIX

A. LTC- low temperature combustion
B. HCCI- homogeneous charge compression ignition
C. CO_2- carbon dioxide
D. I C E- internal combustion engine
E. NO- nitrogen oxide
F. CI- compression ignition
G. SI- spark ignition
H. A/F, λ- air-fuel ratio
I. HC- hydrocarbon
J. CO- carbon monoxide
K. UHC- unburnt hydrocarbon
L. ATAC- active thermo atmosphere combustion
M. TS- Toyota soken
N. CH_2O- Formaldehyde
O. HO_2-hydroperoxly
P. O-oxygen
Q. EGR- exhaust gas recirculation
R. VW- volkswagen
S. CAI- controlled auto ignition
T. GDI- gasoline direct injection
U. PPM- parts per million
V. VCR- variable compression ratio
W. VVT- variable valve timing
X. IMEP- indicated mean effective pressure
Y. BMEP- brake mean effective pressure
Z. RPM- revolutions per minute
AA. EGT- exhaust gas temperature
BB. DI – direct injection

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