A Review on New Technology in Internal Combustion Engine-HCCI engine

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Abstract. In present study a concise literature review on Homogeneous Charge Compression Ignition (HCCI) engine have been performed by taking the many practical problem which are hurdle for implementation of this concept. HCCI combustion is also termed as Low Temperature Combustion (LTC) technology because of its prospective to attain high efficiency and low Nox and particulate matter emission. The typical quality of HCCI technique is the need of preparation of homogeneous mixture early at combustion. Combustion processes in HCCI engine were controlled by chemical kinetics and proper mixing of fuel. Numerous researchers are working towards the challenges and solution for commercialization of this engine. Present review covers the elementary feature for the evaluation of HCCI engine, its working principle and challenges for practical implementation. This study elaborates the prospective solution and future growth in HCCI engine. The most critical challenges for HCCI engine is controlling method for direct ignition of combustion. Therefore in HCCI combustion engine implementation of this problem is way for practical availability of this concept.

Keywords: HCCI, Injection timing, low temperature combustion, EGR, VCR.

1. Introduction

The requirements for the crude oil are continuing increasing and it is anticipated to increase about 280 million ton by the upcoming days. It is shown by India Energy Outlook –IEA 2017 in their report that almost three-fourth of Indian energy demand is met by fossil fuels. According to the world energy outlook 2011 it is reported that, India and China will be reach in very high growth rate in consumption of primary energy requirements by the year 2035, which will be more energy demand from the rest of the world. The interest for higher mileage and lower fumes gas outflows of pressure start motor can't be accomplished by simply utilizing mechanically administered fuel infusion frameworks. The extreme need of an automobile industry is new technologies which can minimize the gas emissions in effective manner. They should be clean and more efficient, increase the atmosphere air condition and also support in energy protection. It is well known that Internal Combustion (IC) engine is old decade technique used in automotive sector. Due to the strict emission norm provided by the government such as Europe and Bharat Stages, it is required to change in combustion technologies as well as in design concept. In today’s scenario automotive industry are facing twin challenges. The challenges are improve the fuel economy simultaneously reducing the emission. Researchers are moving to find out the solution for the problem.
Many peoples are working on development of highly effective and more friendly environment combustion technique. Experimental studies are carried out for developing the system which is capable of applying the alternative fuel. Low Temperature Combustion (LTC) has shown the future prospectus which meets the environmental emission standard. Researchers has focused their attention on new LTC technique which shows its prospective for minimizing the emission and attain the higher efficiency as compared to normal combustion modes. Low temperature Combustion (LTC) is classified in different techniques. All techniques are different only with respect to their function but the fundamental principal remains the same. The present paper review the fundamental understanding for the development of HCCI engine, its research area with various challenges and different method which can commercialize this new technique.

2. Principal of HCCI engine

HCCI was suggested as a new combustion concept at the end of 1970s. The reason for the proposed HCCI was difficulties facing by the peoples in operation of conventional SI and CI engines. The credit for the most acknowledgeable and established original work towards the development of HCCI engine goes to Onishi [1] who developed the concept of Active Thermo Atmospheric Combustion (ATA C) and Noguchi et al.[2] who introduced the concept of Toyota-Soken (TS) combustion on two stroke engines. They was motivated to achieve controlled irregular combustion which caused by auto-ignition of charge present in cylinder. The objective behind is to get stable lean combustion in traditional two stroke gasoline engine on part load. There work was to development of HCCI principal on two stroke engine. To gain an additional understanding and the physic behind the HCCI engine, Najt and Foster was the first investigator to apply this principal on four stroke engine. Performance evaluation had done on HCCI engine which was operated with full blended gasoline four stroke engines [3, 4]. The concept which distinguishes between conventional engine and HCCI engine is its mixing phenomenon in combustion chamber before ignition. The air-fuel mixture is prepared in such a way that it auto-ignite and combustion starts. It is observed that concept of Homogeneous Charge Compression Ignition (HCCI) is somehow alike to Spark Ignition (SI) by the fact that both required the premixed charge and it is also close to Compression Ignition (CI) engine as it is required auto-ignition temperature of fuel for staring the combustion. The HCCI engines are more effective as compared to SI engine in terms of thermal efficiency which is nearer to Compression Ignition engine. A homogeneous mixed air fuel charge is introduced in the combustion chamber of the cylinder during intake stroke. Piston will start move toward to Top Dead Centre (TDC) in compression stroke while the inlet valve close. In compression stroke, temperature and pressure of the charge increased. When the piston reaches the TDC, charge gains the auto-ignition point. The Figure 1 describes the HCCI combustion phenomena. In HCCI engine the start of combustion can be direct by various parameters like compression ratio (CR), intake charge pressure and temperature, ignition timing, swirl, and charge preparation. It has been found that during the compression stroke when the fuel reached its auto ignition temperature it get oxidized and instantaneously released its chemical energy. There are many locations in HCCI engine where auto ignition occurs simultaneously called as hot spots. As compared to traditional engines the pressure increase significantly in minimum time period because of quick heat release rate; on the other hand the maximum temperature in the cylinder keep relatively low. During, combustion process the charge temperature and pressure increase further. The work done by the piston in the expansion stroke due to expanding the hot burn gases will be available at the crank shaft. The cycle competed when piston reaches the TDC after performing the exhaust stroke, in which the burn hot gases thrown out from the cylinder. In brief the processes are summarized in following steps:

i. Exhaust Gas Recirculation (EGR) approach used for preparing the To control the combustion and heat removal rate highly dilute fuel –air mixture was prepared using the exhaust gas recirculation (EGR).
ii. The charge reaches the auto-ignition temperature at the end of the compression stroke, which lead the simultaneous instant ignition at several location of the engine.

iii. Exact control of heat removal rate to attains trade-off between combustion efficiency and exhaust emissions.

![Figure 1: HCCI process](image)

### 3. Advantages of HCCI

In consideration to strict engine emission norm, researches are doing effort to make HCCI combustion as an alternate to traditional combustion concept. Homogeneous Charge Compression Ignition provides the multiple advantages over the traditional engine combustion concept.

i. HCCI has almost similar heat addition like Otto cycle. In which combustion takes place at constant volume and attains the higher relatively thermal efficiency due to its higher compression ratio and shorter combustion timing.

ii. It has the lower radiation as well throttling losses due to its low temperature combustion.

iii. It has potential for lower emission compared to compression ignition (CI) and Spark Ignition (SI) engine. Simultaneously it decreases the NOx and Particulate Matter (PM).

iv. HCCI has its main advantages of fuel flexibility. It has the ability to operate on gasoline as well as mineral fuel like diesel. It can also use the combination of mineral fuel with alternative fuels such as biodiesel.

v. HCCI engines can be joined with traditional engine to get higher efficiency i.e. they can utilized in due mode also. This engine is suitable for replacement of traditional engine such as CI and SI engine.

### 4. Challenges of HCCI

The concept of HCCI engine has been known over the past three decade but because of number of challenges coupled with it; this technology has not been commercialized today. HCCI engine can work only for those engines which having highly equipped with modern electronic system. Researchers are working on several challenges which are hurdles for replacement of this engine in traditional engine. Some of the challenges are listed below:

a) Injection timing

b) Maximum levels of Noise, UHC and CO emissions

c) Cold start capability

d) Operation range

e) Homogeneous mixture preparation

f) Intake charge temperature

#### 4.1 Injection Timing
Unlike traditional engines, HCCI engines do not have direct method of controlling start of combustion. Start of combustion in HCCI engine occurs due to chemical kinetics. So homogeneous charge is required for combustion in HCCI. Initially the port fuel injection would appear to produce the homogeneous mixture by providing sufficient time for mixing. Because of the high boiling property of mineral diesel fuel poor vaporization take place at intake manifold. The delivery of the diesel fuel is not feasible via port injection [6].

4.2 High levels of emissions and Noise
In continuation with the injection timing exhaust emission and high level of noise are one of the practical hurdles for the implementation of HCCI engine over conventional engine [7]. In homogeneous combustion technology, some part of fuel has been already kept in cylinder at the same time of the compression stroke. When unburned fuel re-enters in the cylinder at the time of expansion stroke, they comes in contact with too low burned gas temperature. That process significantly increases both CO and HC emission level as compared to traditional combustion. The combustion efficiency degenerates suddenly due to the too low temperature (less than 1400K) of burned gas. This completes the CO to CO$_2$ oxidation at low loads [8].

The effectiveness of the HCCI combustion at particular higher load was up to the limit due to the difficulties faced in loss of combustion efficiency. The engine noise increases significantly and it becomes too large enough at higher load due to increase in pressure rise. The effectiveness of HCCI combustion limits at lighter load found difficulties due to loss of combustion efficiency [9]. After treatment techniques which can control the HC and CO emission at higher engine loads. The CO emission can be reduced at low engine loads by applying the direct in-cylinder method [10]. It is found that most of the Un-burn Hydro Carbons present during the last stage of exhaust process in cylinder. It indicates that origin of the un-burn hydro carbons from the wall of the cylinder and on the top of the piston layer [11].

For identifying the source of CO and HC emission they used two dimensional planer laser-induced fluorescence (PLIF). The circulation of carbon oxides and hydrocarbon emissions which was affected by concentration of oxygen and injection timing was evaluated [12]. A comparison was further been made in between the hydrocarbon and carbon oxides emission for the thermal efficiency of dilution controlled of HCCI engine [13]. For removal of HC and CO emission catalyst convertor technique is well understood. It was found that hydrocarbons and carbon oxide emission decreased in the range of 90-95% over the prototype catalyst on the other hand maximum NOx reduced in the range of 35-55% under the lean engine operating condition [14].

Engine-operating conditions appear to exert a strong influence on the total mass emissions of carbonyls measured before catalyst [15]. It was found that a twin way catalytic convertor under HCCI combustion conditions showed minimum hydrocarbon conversion performance. It was found that conversion efficiency for homogeneous charge compression ignition varied in the range of 53 to 61%, while for SI combustion it was around 85% [37].

4.3 Cold Start capability
One major difficulty which HCCI engine facing is its firing in cold start operation. Heat loss from the compressed charge is too high and temperature is very low in combustion chamber. To control this difficulty, the engine should have start in traditional mode, then redirect to HCCI mode. The temperature needed for achieving the auto ignition changes with respect to properties of test fuel and operating condition of engine.

For enhancement of HCCI combustion during the cold start, there are lots of technique on which peoples are working they include fuel additives, increasing the compression ratio and variable valve timing [12]. Although the dual mode method is known as most realistic, during this approach engine have to go two way combustion. In first phase engine has to run on SI or CI mode and in second phase it will switch to HCCI mode [48]. Hence, it is a tough challenge to keep real homogeneous combustion after cold start. This is the area of HCCI operation where more development efforts are required.

4.4 Operation range
Incorporation with other obstacle, one more basic hurdle in HCCI development is its operating range. To get maximum benefit from HCCI engine it should be operated on high load. Increasing the operation range is very important parameter, as auto ignition depends on it. Insufficient thermal energy at the end of compression stroke which required for auto ignition of charge is also one limitation. Studies rivals that when an engine is operating at higher load, combustion rate is increasing, which result in increasing in high rate of pressure leads to pressure oscillation. Due to inadequate noise engine can be damage and NOx emission increase. Due to that power decreased and increased the basic load requirement on HCCI engine [48]. Therefore the better understanding towards to reduce the chemical kinetics of homogeneous charge new techniques should be developed. So it will help to minimize the higher noise and damage of engine when duration of combustion increased particularly at higher load. To expand the operating range of HCCI engine there are different techniques such as supercharging [16,17] and turbocharging [18-20] have been used. Operating range can also be increased by using the dual fuel mode like SI-HCCI [21, 22] and CI-HCCI [23, 24].

4.5 Preparation of Homogeneous charge

Efficient preparation of homogeneous charge and keep away the interaction between fuel and wall is critical for attaining the maximum thermal efficiency, minimizing the hydrocarbons and particulate matter emission and intercepting the oil dilution [16]. The homogeneous mixture preparation had an effect on auto-ignition reactions, which can control the combustion phasing in HCCI engine [17]. Outstanding proof has been found that with less degree of mixture inhomogeneity low Nox emission can be produced within the combustion chamber.

It is found that preparation of homogeneous mixture is most difficult for such types of fuel which has minimum volatility like diesel. For preparation of homogeneous air fuel mixture, injection of fuel had been done at a maximum turbulent port flow in case of gaseous fuel and highly volatile in case of liquid fuel [45,46].

Possible Solution of HCCI engine. Researchers presented various techniques or methodology by using them one can go for practical implementation of HCCI technology. Various parameters can affect the performance of HCCI engine. In present paper some of the parameters and methodology has been discussed.

4.6 Intake charge temperature

![Figure 2 At various inlet temperature graph between Cylinder pressure and crank angel degree (CAD)](image)

Many researchers have been reported the effect of inlet mixture temperature on working of HCCI combustion. It was showed in 1983, that in spark ignition engine which has a lower compression ratio, a lean mixture for HCCI engine can be achieved with inlet temperature in the range of 300° to 500°C [19]. Intake charge temperature had vigorous effect on combustion timing of HCCI engine. Intake charge temperature significantly affects the Indicating Mean Effective Pressure (IMEP) which is
produced under HCCI combustion mode [66]. Figure 2 shows the relation between cylinder pressure and crank angle variation for different intake temperature. It is observed that by increasing the inlet charge temperature HCCI combustion timing affects significantly. At temperature of 575 K, advanced ignition occur although the combustion is not so effective but by decreasing the intake temperature ignition would retard [99].

The influence of intake temperature on spark assisted and unassisted HCCI combustion for particular load and negative valve overlap condition, experiments have been performed within the limit of 15°C and 50°C [61]. It has been found that ignition of richer mixture is possible in HCCI combustion mode at low inlet temperature [62]. Experiment results revealed that nevertheless of the EGR, by reducing the intake charge temperature, IMEP increased which in turn increases the in-cylinder charge mass. It is shown that while decreasing the temperature from 105°C to 30°C, the IMEP increased from 2.7 bar to 3.7 bar [63].

4.7 Injection pressure
To encourage better mixing of the charge in cylinder higher fuel injector pressure plays a vital role. This is especially applicable when it is used for combination of small nozzle orifice [63]. For better combustion and desirable spray structure a high fuel injection pressure as well as speed is required [64]. Moreover, researcher’s shows that by increasing the fuel injection pressure PCI combustion are produced [65].

4.8 Variable Compression Ratio (VCR)
Research showed that by using higher compression ratio and lean mixture one can achieve high efficiency and low NOx emission [25]. To achieve HCCI combustion control compression ratio is an efficient parameter. They investigated carefully and shows that compression ratio in the range of 9.6 to 22.5 had vigorous impact on ignition timing and decreasing in inlet temperature [38, 39]. The compression ratio in the range of 12 to 18.6 has been demonstrated and present a significantly effect on combustion rate. Their researches reveal that homogeneous charge compression ignition engine showed a higher compression ratio permit for lower inlet mixture temperature and higher inlet density which gives the higher power output. Moreover higher compression ratio provides the higher thermal efficiency [40]. It has been found that the change in compression ratio had a strong influence on homogeneous charge compression ignition combustion [41]. Researchers also studied the effect of higher compression ratio on natural gas fuelled in HCCI engine. They used Variable Compression Ratio (VCR) method for changing the compression ratio. They observed the compression ratio in the range of (21:1, 20:1, 17:1) according to their operating condition [42]. Variable compression ration technique was used in multi cylinder engine in closed loop combustion control for investigating the HCCI combustion phasing. The study showed that acceptable performance was given by fast variable compression ratio [43].

4.9 Exhaust Gas Recirculation (EGR)
Exhaust gas recirculation is the very efficient way to moderate the rise in pressure and extend the homogeneous charge compression ignition operating range to maximum load. EGR is necessary to attain the less soot as well as NOx emission form HCCI engine without using high rate of fuel consumption. Exhaust Gas Recirculation is the generally used method to regulate the temperature within the cylinder which in turn starts of combustion. Early, Thring [44] succeed the HCCI combustion by changing the intake charge temperature and fraction of EGR over a wide range of equivalence ratio. Some of the gas species of combustion like CO2, water, nitrogen, CO, PM, oxygen, HC, NOx which control the reaction constitute high heat capacity of EGR [45-47]. These elements of species describe mainly four effects on emission and combustion. The first effect happen when the hot EGR was mixed with air fuel ratio due to that the intake charge temperature increased this is called preheating effect. Second effect is called as dilution effect, where reduction in the oxygen concentration taken place by introducing the EGR. Next is called heat capacity effect during that all the heat carrying capacity of charge of EGR and fuel would be maximum for higher heat capacity of CO2 and water vapor [48]. Last is the chemical effect, where for completing the reaction unburnt product of EGR would take part.
Considering all these effects and by regulating the EGR quantity overall homogeneous charge compression ignition combustion can be managed. EGR also helps in start of combustion. Consequently, EGR makes it possible to extinguish excessively advanced start of combustion at low temperature in HCCI engine [49]. This quick and unnecessarily combustion causes knocking, in turn which minimize the performing limit of the homogeneous charge compression ignition combustion [51, 53].

Ishikawa et al. [52] studied the influence of efficiency of heat exchanger on an exhaust gas recirculation cooler on combustion. The increases the rejection of cooler heat in the range of 3.1 kW to 8.5 KW. Increasing the charge density and concentration of oxygen, intake temperature decreased from 110°C to 36°C. They observed the minimization in soot emission is because of reduction in equivalence zone, although the hydrocarbon emission increased little bit. Boyarski and Reitz [54] found that exhaust gas recirculation technique is highly effective as controlling parameters for start of combustion. They used up to 68% of EGR. They also concluded that to control the rate of pressure rise high EGR can be used. Approximately 40% of EGR can be used to control the NOx emission [55].

Idicheria and Pickett [56] investigated that due exhaust gas recirculation early development of cool flames taken place after fuel injection in constant volume chamber. The timing of soot emission was largely dependent on EGR, with increasing the EGR delay time for soot emission increases. Hardy et al. [57] studied the influence of maximum equivalence ratio on mixing time used in heavy duty engine. They used high EGR. They showed that by applying the high EGR, high equivalence ratio can be obtain, which in turn slow down the PM and NOx emission.

4.10 Dual Fuel

Two fuels with different auto-ignition properties are used in dual fuel mode. In that system primary fuel with high octane number and secondary fuel with low octane number is used [58]. Wilhelmsson et al. [59] did expanded study on HCCI; they used natural gas (NG) and n-heptane as a dual fuel. The influence of various primary fuel blends on homogeneous charge compassion ignition performance limit, start of combustion and fuel consumption was studied by Atkins and Koch, they concluded that by varying the octane number of fuel performance limit of HCCI engine can be developed [68]. It has been investigated in many studies that use of commercial fuel or mixture of single component fuel and primary reference fuel are advised for HCCI engine [69]. One consider the examples of these types of dual fuel are mixture of ethanol and n-heptane, combination of n-heptane and mineral diesel, mixture of gasoline and mineral diesel, mixture of gasoline and natural gas [76].

5. Conclusion

Currently research happening related to HCCI engine affect the advancement of new combustion technology. Due to certain technical challenges such as ignition timing, preparation of mixture and its operating limitation to lower load, HCCI combustion concept is facing difficulties for its commercialization. It represents a way to replace the conventional combustion with advanced combustion technology. Although for its practical existence for higher load and other application purpose huge research effort is required. Present literature review found some identical gaps toward the developments of HCCI engine:

(i) Enlargement of controlling methods for attain the ignition timing is a major challenge of this technique, which need to be solved.

(ii) Expansion of control system for emission and planning to resolve the challenge of constant level of NOx emission and particulate matter.

(iii) Development of new methodology to reduce the heat removal rate in HCCI engines is another challenge, which needs attention.

(iv) Multi mode engines capability seems to be worthy for adaption in HCCI combustion technique. Research and developments need more effort to analysis the shortcoming in these strategies for easily transition in HCCI to SI or CI mode.

(v) Multi fuel mode is another aspect in HCCI engine. It has capability to operate on two fuels with different octane and cetane number. This technique can also work on biofuels.
In all descendent of HCCI, controlling of combustion is almost a complicated issue, which can be solved using different technique such as variable compression ratio, exhaust gas recirculation, multi-fuel injection, variable valve timing etc. Although, these methods have certain advantages as well as challenges. It was found from published data, many peoples proposed different techniques or methodology for feasibility of this concept. It is observed that dual mode combustion system shows an efficient solution for commercializing the HCCI engine. In this method conventional engines are coupled with HCCI, although complexity and cost will remain a key issue. Exhaust gas recirculation reduce the NOx and particulate emission. Achieving the homogeneous preparation of mixture minimize the soot emission. Extending the operating range of HCCI engine in turns increase the break thermal efficiency. Multiple injections provide the homogeneous mixture preparation but start of combustion is quite difficult. Hence, for continuing the progress of HCCI engine adjustable fuel injection system, exhaust gas recirculation for betterment of mixture preparation and to extend the higher load are few key aspects, which required extensive investigation then only a HCCI engine may be developed and made commercialized.

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