Homogenous Charged Compression Ignition Engine (HCCI) – A Review

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Abstract - *The growing emissions and pollution from automobile engines and the necessity of a combustion engine that produces lower emissions and better economy gave rise to the HCCI engine. In this type of engine there is no spark plug to assist the combustion process and the fuel-air mixture is auto ignited. HCCI engines have a long history and can produce lower emissions also increase the fuel efficiency by almost 30%. Even though they have more advantages when compared to the regular IC engines they have not been commercialized because of their disadvantages, the absence of spark plug makes the combustion hard to control and cold starting is also a problem. They are not very reliable at high speeds and have a smaller power range when compared to traditional SI and CI engines. The objective of this paper is to review the history, various parameters, problems and recent developments of HCCI engine. The paper is concluded by highlighting the advantages and disadvantages of commercializing HCCI engine.*

Key Words: **HCCI, SI, CI, VVT, Combustion, HC, CO, NO_x.**

1.INTRODUCTION

Internal combustion engines have been playing a key role in the development of humankind from the past one and half century. Even though they have a lot of advantages, there are also many problems associated with them. The emissions that are being produced from automobiles is increasing at an alarming rate. These emissions include various pollutants like Carbon Monoxide (CO), Nitrous Oxides (NO_x), Particulate matter, Sulphur oxides (SO_x), Hydrocarbons (HC). There is a necessity of a combustion engine that produces low emissions and better economy. [1] The HCCI engine is a concept that satisfies the requirement of lower emissions and better economy. HCCI engine is mainly considered as an alternative to diesel engine. It requires lean and homogenous mixture which are the main reasons for its advantages.[2] HCCI engine represents a major step forward when compared to SIDI engines, they cost less than CIDI engines because HCCI runs on low pressure fuel injection systems. [3]

In this concept the fuel and air are premixed before being inducted into the cylinder and then the mixture is ignited during combustion stroke for power output. The NO_x and Soot emissions form a HCCI engine are 98% low when compared to conventional diesel engines [4]. The fuel consumption also reduces by 10-15% when using a HCCI engine. The main advantage of HCCI engine is its fuel flexibility, gasoline particularly is well suited.[5][6] The maximum thermal efficiency is 46% and maximum combustion efficiency is 98%.

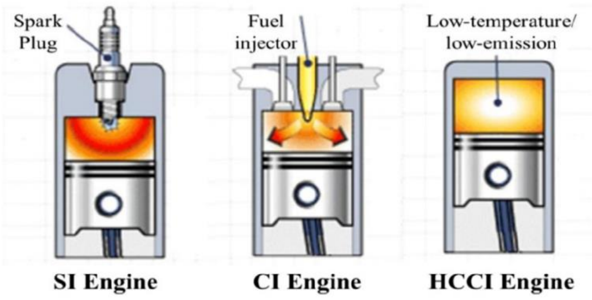

Fig 1: Schematic diagram of HCCI Engine [8]

Along with all the advantages that the HCCI concept provides there are few problems associated with this engine concept that is keeping it from being commercialized. Even though The NO_x and soot emissions are very low when compared to conventional engines the HC and CO emissions increase dramatically. The HC and CO emissions are highly dependent on engine speed [7]. There also other challenges like combustion phase control, controlled auto ignition, operating range, homogenous charge preparation, cold starting problem. [8][9] This paper reviews briefly about some of the research that has been done to overcome a few problems associated with the engine to help make it commercialized.

2. HISTORY

HCCI engines were first discovered as an alternative to the two stroke engines. 'Onishi et al' [49]was the first person to study this kind of a combustion process in 1979. It was first called Active thermos atmosphere combustion and it was believed to be a promising alternative for existing spark and diesel engines. The main problem with the two stroke engines was the high emissions at low and medium loads and the knocking effect. In HCCI engine the conditions were created in such a way that the charge is ignited spontaneously which resulted in a significant reduction in emissions and improvement in fuel economy. Very soon after this technology was developed Toyota was the first company to demonstrate in public.

The experiment was conducted on HCCI opposed piston two stroke engine. The results observed were interesting as the HCCI combustion works efficiently under low loads, also it has been noticed that HCCI engines run very smoothly under low loads and are very fuel efficient. [10]. The first four stroke HCCI engine was tested in 1983. Experimental analysis was made using different mixtures of fuel and varying over different ranges of engine speed. It was observed that HCCI combustion is a chemical kinetic process. In 1989 further research was done on the HCCI engine configurations using the traditional Spark Ignition at full loads and at part loads [11]. Low compression ratio is required to use a diesel fuel, otherwise ignition occurred too early during the combustion stroke.

In 1994, further experiments were conducted which showed that if methanol was used as a fuel the operating conditions for stable two stroke HCCI combustion could be significantly expanded. In 1996, very interesting researches were made in 1996 the combustion process was called premixed charge compression ignition (PCCI). PCCI, diesel and GDI were compared together and a surprising fact was noticed that the PCCI engines had the lowest fuel consumption and NO_x emissions. [12] However, HC emissions were comparatively higher. In 1997, the effects of intake and exhaust throttling on HCCI combustion in a production engine was investigated. In 2000, testing of a four-stroke single cylinder indirect fuel injection engine using a fuel mixture with an octane rating of 35 was done.

3. Combustion Challenges

Along with all the benefits that the HCCI concept provides there are a few challenges that needs to be taken care of before moving ahead and commercializing this concept. The main problems associated with this concept are: (i) Combustion Phase Control, (ii) Operating range, (iii) Homogenous charge preparation, (iv) Cold start, (v) High HC and CO emissions.

3.1 Combustion Phase Control

Controlling Combustion is the most important parameter in HCCI engine. Unlike Conventional engines that have a direct mechanism which controls the combustion. In HCCI engine the fuel air charge is premixed homogenously and is auto-ignited. The combustion control over a wide range of speeds and loads is a very difficult task.[13] The combustion control is affected by many factors like the compression ratio, EGR, engine temperature, engine speed, etc. It is necessary to control the combustion because it directly affects the efficiency and power output of an engine. The engine might get damaged and could result in power loss if the combustion takes place early. On the other hand, if combustion occurs late misfire can occur which will limit the operation and can damage the exhaust system. [14] Two zone HCCI results in sequential combustion which helps in control of combustion.

3.2 Operating Range

Comparing to the conventional SI or CI engines the operating range of HCCI engines is limited. It is hard to control the ignition timing over various loads and speed ranges because the mixture is auto-ignited. As the inlet air temperature gets higher it limits the operating range because of high knocking intensity, high NO_x emissions and misfire of charge. [15] These problems only allow HCCI engine to operate a low loads and speeds. Maintaining a higher equivalence ratio at all conditions was considered optimum. [16]

3.3 Homogenous Charge Preparation

In a HCCI engine Homogenous Charge preparation is the most important part. The performance and emission characteristics are based on the achieving good homogenous mixture. A good homogenous mixture reduces the particulate matter and reduces the NO_x emissions. Preparation of homogenous mixture is a difficult task because of the lack of time available[17]. The two types of homogenous mixture preparation are in-cylinder injection or external mixture. The main disadvantage with in-cylinder mixture is oil dilution and the external mixture is low on volumetric efficiency. There is no direct way to determine the mixture homogeneity. [18]

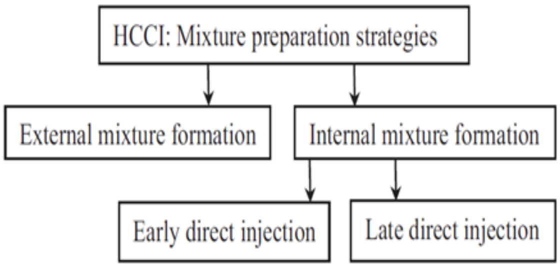

Fig 2: Mixture Preparation [8]

3.4 Cold Start

Cold start is always a problem when it comes to HCCI engine as the charge loses more heat when the cylinder walls are at low temperature and auto ignition is difficult to take place. Starting the engine in conventional mode will help solve the cold start problem. [19] The engine can be started in conventional mode for warm up and then switched to HCCI mode.

3.5 HC & CO Emissions

The HC and CO emissions are highly dependent on the engine speed. External mixture preparation technique helps reduce NO_x and soot but increases the rate of HC and CO emissions. [20][21] The main reason of HC emissions in HCCI engine is because of incomplete oxidation of fuel and also the valve over lapping can cause HC emissions. Since the exhaust gas temperature is very low the oxidation of UHC and CO into CO_2 and H_2o is difficult to take place.

In HCCI combustion there is a low conversion efficiency in terms of hydrocarbon oxidation and emissions of few hydrocarbons can be problematic for future application of HCCI engine. Early injection strategies can affect the CO emissions. [22][23] HCCI engine with a pre-combustion chamber shows a significant decrease in HC and CO emissions but there was an increase in NO_x emissions. [24] Wen Zeng in his paper suggests that using in-cylinder catalysts can help reduce the HC emissions by approximately 15% when a platinum catalyst is present on the piston head and partial coating the in-cylinder catalyst HC emissions can reduce up to 20%. [25]

4. Control Strategies for HCCI Combustion

It is very important to control the combustion because it directly affects the efficiency and economy of the engine. The main strategies for controlling the combustion are by increasing the mixture homogeneity and by delaying auto injection.

4.1 Increasing the Mixture Homogeneity

It is difficult to prepare a perfectly homogenous mixture of air and fuel because of the low volatility of diesel. Akhilendra Pratap Singh [26] investigated that a dedicated diesel vaporizer with an electronic control system helps overcome this problem. The use of diesel vaporizer resulted in 80% reduction of NO_x emissions and 50% reduction in smoke. On the contrary, there was a significant increase in HC and CO emissions. Usage of Integrated Starter Generator (ISG) assistance helps reduce the fuel consumption if HCCI engine and lower the emissions. [27]

Another method which helps in increasing the mixture homogeneity is the high swirl ratio. As investigated by Karthikeya Sharma [1], a premixed charge was induced into the combustion chamber which was assisted with a swirl motion to enhance the convective heat transfer. The results show that high swirl ratio improves the mixing rate of fuel and air mixture and high swirl is necessary for faster homogenous preparation. Also, the convective heat transfer rate was improved along with lower emissions[28].

As mentioned by Gunwoong Bahng [29] The drawback caused by lean burning of charge which limits power range can be overcome by injecting vaporized liquid gasoline. This can be done with help of water electrolysis of gas and air. The results show that there is 50% reduction in fuel consumption by using this method.

4.2 Delaying the Auto-Ignition

Varying the compression ratio of the engine helps in delaying the ignition. Decreasing the compression ratio delays the start of ignition. Christensen et al. [50] demonstrated that low octane or a high octane or medium octane fuel is best suitable for HCCI operating conditions. Changing the compression ratio helps burn any fuel in an HCCI engine.

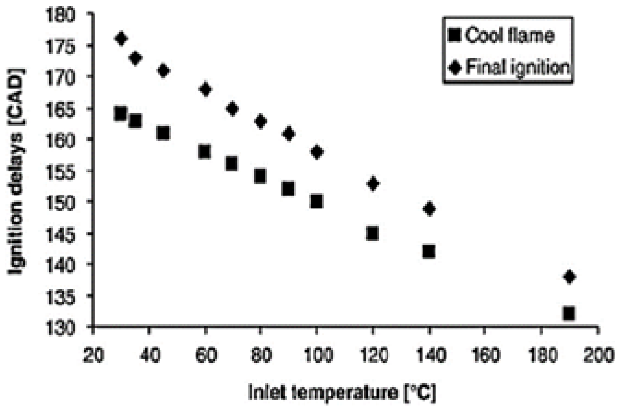

Chart 1: Ignition delay as a function of inlet temperature [8]

Residual gases have a remarkable effect on HCCI combustion timing and engine performance. [30] Exhaust gas recirculation (EGR) is widely used in HCCI combustion because it helps in controlling of auto-ignition temperature also reduces NO_x emissions [31] but at and expense of HC and CO emissions. HCCI combustion mainly consists of late injection timing, high injection pressure and heavy EGR rate [32] . With higher EGR levels the auto-ignition can be delayed. As suggested by Stuart Daw [33] in low levels of EGR conventional SI engine is stable and at higher EGR levels HCCI engine was stable. The HC, CO and NO_x emissions are directly influenced by engine speed and exhaust gas recirculation [7]. Even though EGR helps provide better combustion rate and improves emission behavior it comes at a cost of slightly inferior engine performance. HCCI engine which runs on diesel is highly sensitive to EGR [20]. Moretza Fathi [34] conducted an experiment to check the influence of EGR on combustion and emissions of natural gas fueled HCCI engine and the main goal of the experiment was to check the possibility of controlling the combustion by varying the EGR fractions. The results showed that it is possible to control the combustion and ignition timing of the engine by varying the EGR fractions. [35]

Using Variable Valve mechanism as demonstrated by Can Cinar [36] increases the thermal efficiency and reduces the exhaust emissions. Variable Valve mechanism also control the auto-ignition phenomena. As the inlet temperature increased the test engine was run on leaner air-fuel ratio. Also, using VV mechanism can help reduce CO and HC emission even at higher inlet temperatures. Internal EGR can be controlled by varying the negative valve overlap using Variable Valve timing [37]. On the contrary, increasing internal EGR results in engine knocking but the increase of external EGR would decrease the knocking occurrence. [38]

HCCI combustion is also very sensitive to the temperature of air-fuel mixture. The higher inlet temperature limits the operating range of the engine and can cause knocking and higher emissions. Auto-ignition timing needs to be controlled for the heat release process to take place at the appropriate time in the engine cycle [39].

5. Other Techniques

Various alternatives are available for improving the efficiency of the HCCI Engine. Kinetic modeling [40], multi-zone modeling [41], chemical studies, cycle to cycle variations, etc. have been done to predict the efficiency and emissions of the engine. Many tests have been conducted on the HCCI engine using alternative fuels such as natural gas, ethanol, methanol, hydrogen, etc. A few of the experiments and their results are discussed below.

5.1 Alternative Fuels

HCCI engine with ethanol as fuel offers promising solutions to many challenges of the engine. The problem with misfire which limits the engine operation and damages the exhaust systems.

Methanol and Ethanol powered HCCI engine are auto-ignited at relatively low intake air temperature. The misfire can be detected by ANN misfire detection (AMD) model. Since, variation of combustion parameters of often inefficient in detecting misfire AMD model is an optimum solution. Ethanol and Methanol exhibited good characteristics and can prevent knocking they can also be used as an alternative to gasoline. [42][43] [44][45]

An Experiment conducted by Giuseppe Genchi [46] shows that when a mixture of Natural gas and gasoline is used as a fuel during the combustion process, the engine was able to run without knocking occurrence for low to medium engine load. The main noticeable advantage would be that the engine efficiency was much higher when compared to conventional engines and there are strong reduction NOx emissions.

When an HCCI engine is run using hydrogen as a fuel the heat release was extremely high and this limits the operating range of the engine. However, the fuel efficiency was increased significantly, and the NO_x emissions and soot particle emissions were decreased. As suggested by Gomes Antunes [47] it is hard to control ignition because of the high heat release and this can be partly controlled by preheating the charge.

Ebrahimi et al. [48] has developed a physics based 4 state non-linear control-oriented model for HCCI engine. This model is used to predict the combustion timing and the work output. The model developed can also be used as a feedback control design for HCCI engine which predicts the ignition timing and load not leaving behind the constraints like emissions.

3. CONCLUSIONS

The main target of the research is to check if the HCCI technology is feasible and is it practical to convert from traditional SI and CI engines to HCCI technology. This paper compares the HCCI technology with the traditional HCCI engine technology and the concluded data is as follows.

- A brief history on the HCCI technology has been discussed which shows how the technology was developed.
- HCCI engine technology is excellent when it comes to reducing the NO_x emissions and formation of soot particles, but it has higher level of unburnt hydrocarbon and carbon monoxide level when compared to the conventional engines.
- Many tests also show that the fuel economy is improved by almost 30%. However, there were a few problems that were observed under varying load and speed conditions.
- HCCI engine produces higher HC and CO emissions which can be controlled by using catalysts in cylinder.
- Another challenging factor is the preparation of homogenous mixture which governs the fuel economy and emissions of the engine. This can be controlled by using swirl motion techniques and by supplying vaporized fuel.
- To control ignition timing strategies like pre-heating the intake air, pressurizing the intake air by using turbo chargers and super chargers, using exhaust gas recirculation for early injection helps overcome the difficulties that are faced in the engine.
- Further development must be there in terms of high load and speed performance, control of ignition and preparation of mixture to help commercialize this technology.

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