A Review on Homogeneous charge compression ignition (HCCI) combustion technology: Recent advancements and control strategies

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Abstract: Homogeneous charge compression ignition (HCCI) engine technology is relatively new and has not matured sufficiently to be commercialized compared with conventional engines. Now a day the challenges facing are mainly emissions (NOx and soot) and Fuel economy. The factors to be considered while designing this kind of technology are, high compression ratio, lean homogeneous air fuel mixture, complete and instantaneous combustion, which lead to homogeneous charge compression ignition (HCCI). It can use spark ignition(SI) or compression ignition(CI) engine configurations, capitalizing on the advantages of both: high engine efficiency with low emissions levels. HCCI engines can use a wide range of fuels with low emissions levels. Due to these advantages, HCCI engines are suitable for use in a hybrid engine configuration, where they can reduce the fuel consumption even further. HCCI engines can operate on gasoline, diesel fuel, and most alternative fuels. This paper reviews the technology involved in HCCI engine development, its advantages and disadvantages However, HCCI engines have some disadvantages, such as knocking and a low to medium operating load range, which need to be resolved before the engine can be commercialized. Therefore, a comprehensive study has to be performed to understand the behavior of HCCI engines.

Keywords: HCCI, IC engine, SI engine, Ci engine.

I. INTRODUCTION

Environmental protection is a huge growth market for the future. In the years ahead, “green” technologies that help improve energy efficiency or reduce emissions will be important growth. With the advent of increasingly stringent fuel consumption and emissions standards, engine manufacturers face the challenging task of delivering conventional vehicles that abide by these regulations. HCCI combustion has the potential to be highly efficient and to produce low emissions. HCCI engines can have efficiencies as high as compression-ignition, direct-injection (CIDI) engines (an advanced version of the commonly known diesel engine), while producing ultra-low oxides of nitrogen (NOx) and particulate matter (PM) emissions. HCCI engines can operate on gasoline, diesel fuel, and most alternative fuels. While HCCI has been demonstrated and known for quite some time, Only the recent advent of electronic sensors and controls has made HCCI engines a potential practical reality. HCCI represents the next major step beyond high efficiency CIDI and spark-ignition, direct injection (SIDI) engines for use in transportation vehicles. In some regards, HCCI engines incorporate the best features of both spark ignition (SI) gasoline engines and CIDI engines. Like an SI engine, the charge is well mixed which minimizes particulate emissions, and like a CIDI engine it is compression ignited and has no throttling losses, which leads to high efficiency. However, unlike either of these conventional engines, combustion occurs simultaneously throughout the cylinder volume rather than in a flame front. To overcome the problems in the present combustion of SI and CI engines alternate searches have been started by the researchers by taking in consideration of both homogeneous combustion of SI engine and Heterogeneous combustion of CI engine. HCCI combustion is the combined mix of these two and has the potential to be high efficient and to produce low emissions and also HCCI engines can have efficiencies as high as compression-ignition, direct-injection (CIDI) engines (an advanced diesel engine), HCCI engines producing ultra-low oxides of nitrogen (NOx) with exhaust gas recirculation(EGR) and low particulate matter (PM) emissions. And also HCCI engines can operate on many fuels like gasoline, diesel fuel, and most alternative fuels. HCCI has been demonstrated and known for quite some time, as it has a potential practical reality, and made as recent advent of electronic sensors and controls HCCI engine. In fact, HCCI technology could be scaled to virtually every size-class of transportation engines from small motorcycle to large ship engines. Chicks also applicable to piston engines used outside the transportation sector such as those used for electrical power generation and pipeline pumping. HCCI engines are particularly well suited to series hybrid vehicle applications because the engine cane optimized for operation over a more limited range of speeds and loads compared to primary engines used with conventional vehicles. Use of HCCI engines in series hybrid vehicles could further leverage the benefits of HCCI to create highly fuel-efficient vehicles.

II. HOMOGENEOUS CHARE COMPRESSION IGNITION (HCCI)

A. What is HCCI?

HCCI is an alternative technology to the present existing combustion process by reciprocating CI engines and can produce efficiencies as high as compared to compression-ignition, direct-injection (CIDI) engines (we known commonly as diesel engine), unlike CIDI engines, producing ultra-low oxides of nitrogen (NOx) and particulate matter (PM) emissions while using HCCI combustion technology with EGR. HCCI engines can operate on the principle of using a dilute, premixed charge that reacts and burns volumetrically throughout the cylinder as it is compressed by the piston. In some cases, HCCI technology incorporates the best features of both spark ignition (SI) and compression ignition (CI).

B. HCCI Combustion:

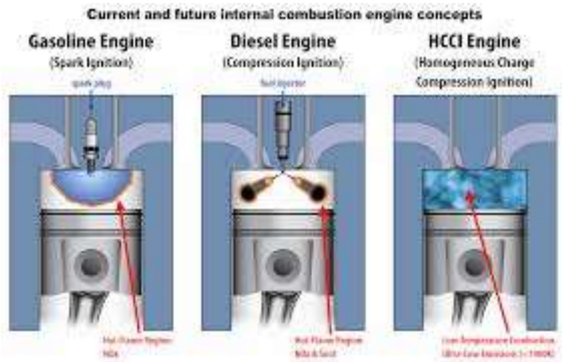
[1] HCCI Principle

In HCCI mode of combustion, the fuel and air are mixed prior to the start of combustion and the mixture is auto-ignited spontaneously at multiple sites throughout the charge volume due to increase in temperature in the compression stroke. In this mode, the combustion process is arranged in such a way that the combustion takes place under very lean and dilute mixture conditions, which results in comparatively lower bulk temperature and localized combustion temperature, which therefore, considerably reduces the NOx emissions. Furthermore, unlike conventional CI combustion, in HCCI mode the fuel and air is well mixed (homogeneous). So, the absence of fuel rich regions in the combustion chamber results in considerable reduction in PM generation. Therefore, due to absence of locally high temperatures and a rich fuel-air mixture during combustion process, the simultaneous reduction of NOx and PM emissions is made possible.

In an HCCI engine (which is based on the four-stroke Otto cycle), fuel delivery control is of paramount importance in controlling the combustion process. On the intake stroke, fuel is injected into each cylinder's combustion chamber via fuel injectors mounted directly in the cylinder head. This is achieved independently from air induction which takes place through the intake plenum. By the end of the intake stroke, fuel and air have been fully introduced and mixed in the cylinder's combustion chamber.

As the piston begins to move back up during the compression stroke, heat begins to build in the combustion chamber. When the piston reaches the end of this stroke, sufficient heat has accumulated to cause the fuel/air mixture to spontaneously combust (no spark is necessary) and force the piston down for the power stroke. Unlike conventional spark engines (and even diesels), the combustion process is a lean, low temperature and flameless release of energy across the entire combustion chamber. The entire fuel and air mixture is burned simultaneously producing equivalent power, but using much less fuel and releasing far fewer emissions in the process.

At the end of the power stroke, the piston reverses direction again and initiates the exhaust stroke, but before all of the exhaust gases can be evacuated, the exhaust valves close early, trapping some of the latent combustion heat. This heat is preserved, and a small quantity of fuel is injected into the combustion chamber for a pre-charge (to help control combustion temperatures and emissions) before the next intake stroke begins.



III. CHALLENGES

The main challenges that have kept HCCI from being applied to commercial engines can be stated as follows:

1) Ignition timing control over wide engine speed-load ranges: It is widely recognized that HCCI combustion is driven by chemical kinetics and is therefore controlled by fuel physical and chemical properties as well as the temperature history of the fuel/air mixture. On the contrary, in-cylinder turbulence and mixing have little influence on combustion timing. As the ignition timing has been shown to be very sensitive to factors such as octane number, intake charge temperature, fuel/air equivalence ratio, mixture composition or EGR rate, and fuel

composition, the most pressing task for HCCI implementation is to ensure that ignition occurs near TDC under variable working conditions.

2) Combustion rate control from high- to full-load engine operation: HCCI combustion has been demonstrated to operate well at low to medium loads but difficulties have been encountered at high loads. Combustion can become very rapid and intense, causing unacceptable noise, potential engine damage, and eventually, unacceptable levels of NOx emissions. Additional work is needed to develop methods that reduce the heat release rate under high-load operation conditions to prevent excessive noise or engine damage.

3) Cold start capacity: HCCI ignition is very sensitive to intake charge temperature, and minor variations alter combustion phasing significantly. Furthermore, the initial temperature required to achieve self-ignition varies with fuel properties and operation conditions. Under cold start and idle operating conditions, the compressed gas temperature will be reduced because the charge receives no preheating from the intake manifold and is rapidly cooled by heat transferred to the cold combustion chamber walls. Without some compensatory mechanism, low compressed charge temperatures could prevent an HCCI engine from firing.

4) Higher levels of HC and CO: HCCI combustion produces inherently low emissions of NOx and PM at lower engine loads but relatively high emissions of HC and CO at low to medium loads as well as high emissions of NOx under large loads. Thus, it is necessary to develop emission control systems and control strategies to overcome the challenge of excessive HC and CO emissions, particularly at low loads.

5) Mixture preparation: This is particularly important for poor volatility diesel-fueled HCCI combustion. The main goals here are to avoid wall impingement, to promote fuel vaporization and air mixing so as to limit PM and HC emissions, and to prevent oil dilution.

6) Relatively higher pressure-rise rate and severe combustion noise: Because the HCCI combustion rate is so high, ignition occurs simultaneously throughout the combustion chamber, producing a high pressure-rise rate and high-frequency noise or intensive ringing when compared to the behavior of a conventional DICI or SI engine, especially under a large equivalence ratio.

7) Engine control strategies and systems: Additional work is needed with regards to the development of a new methodology for feedback and closed-loop control of fuel and air systems, advanced control theory and control arithmetic, next-generation combustion sensors, and next-generation software and hardware specialized for HCCI combustion in order to optimize combustion over wide load-speed ranges.

IV. LIMITATIONS OF HCCI

1) Inability to control the combustion initiation

2) Problems in controlling the rate of combustion over the whole speed and load range.

3) Requirements of some external setups to preheat the air

4) It can be operated only for a selected range of lambda.

5) Depending on the method used to facilitate HCCI combustion, strong cycle-to-cycle variations can occur. This poses a control problem, but is also a threat for the HCCI combustion.

6) The HCCI engine has relatively high friction losses due to the low power density.

7) If misfire occurs, the gas mixture during the next cycle will be too cold for auto-ignition to occur (unless intake air heating is used) and the engine will stop.

V. RECENT DEVELOPMENTS IN HCCI

Recent developments in the HCCI technology have given very positive results to overcome the limitations of this technology. The technology has huge scope of use and it is used in wide range of industries, which makes it promising technology for the coming generations. Automobile giants like GM, Ford and Cummins have been exploring the possibilities in the HCCI technology for more than 15 years. General Motors has started educational programs in various universities to promote the research work in this technology. HCCI has also enabled engineers to experiment with different blend of fuel mixture so that performance and efficiency of HCCI engines can be tested with different combinations of non-conventional fuels.

General Motors has demonstrated Opel Vectra and Saturn Aura with modified HCCI engines. Mercedes-Benz has developed a prototype engine called Dies Otto, with controlled auto ignition. It was displayed in F-700 concept car at the 2007 Frankfurt Auto Show Volkswagen are developing two types of engine for HCCI operation. The first called Combined Combustion System or CCS is based on the VW group 2.0-litre diesel engine but uses homogeneous intake charge rather than traditional diesel injection.

In May 2008, General Motors gave Auto Express access to a Vauxhall Insignia prototype fitted with a 2.2-litre HCCI engine, which will be offered alongside their Eco FLEX range of small-capacity, turbocharged petrol and diesel engines when the car goes into production. Official figures are not available, but fuel economy is expected to be in region of 43mpg (miles per gallon) with carbon dioxide emissions of about 150 grams per kilometer, improving on the 37mpg and 180g/km produced by the current 2.2-litre petrol engine.

VI. CONTROL STRATEGIES:

[1] Exhaust gas recirculation (EGR)

The technology of EGR is widely used in HCCI combustion due to its high potential of controlling the auto-ignition of time– temperature history and enhancement of NO_x emission reduction. The EGR can be categorized into internal and external EGR. Internal EGR is acquired by the exhaust gas trap (EGT) using the negative valve overlap (NVO) and variable valve timing (VVT) methods. The most practical means to delay the auto-ignition in an HCCI engine is through the addition of high levels of EGR into the intake. The inert gases present in the EGR can be used to control the heat release rate due to its impact on chemical reaction rate, which can delay the auto-ignition timing. Hence, EGR reduces the heat release rate, and thus lowers the peak cylinder tempera-ture due to the constituents of EGR (mainly CO_2 and H_2O) having higher specific heat capacities. The MK combustion system uses a high EGR to reduce the NO_x emissions up to 98% less than conventional diesel engine. The combustion limit towards leaner air–fuel mixture and the tolerance to the EGR can be significantly extended. The low heating value of lean mixtures and the high heat capacity of EGR can lower the peak temperature of combustion, thus reduce NO_x emission. Up to 95% reduction in NO_x emission has been obtained experimentally. At low load, the combustion efficiency is the most important one in HCCI combustion which is improved by EGR.The EGR also used to control the HCCI auto-ignition. The hot EGR advances the combustion timing while cold EGR retards the combustion timing.

[2]Charge temperature and equivalence ratio

The auto-ignition of fuel–air mixture is a very sensitive to intake air temperature changes, as small as 5–10 1C . Hence, the combustion control is very difficult task in order to achieve high efficiency without any knock. Diesel fuel doesn't require any charge heating, as it can be burnt easily with a compression ratio of 16. For low cetane fuels, modulate intake air temperature is necessary to reach its auto-ignition tempera-ture near the TDC for combustion. A higher intake temperature advances combustion but the engine volumetric and thermal efficiency can be largely reduced, due to the fact that, if ignition is advanced into the compression stroke, it will cause significant negative work on the piston. Flowers et al. studied cylinder-to-cylinder effects on the variable intake temperature and propane fuel flow rate. Hatim et al. analysed of the influence of the inlet temperature, equivalence ratio and compression ratio on the HCCI auto-ignition process of primary reference fuels shows the ignition delays as a function of the inlet temperature and equivalence ratio respectively for primary reference fuels.

VII. CONCLUSIONS

A high-efficiency, gasoline-fueled HCCI engine represents a major step beyond SIDI engines for light-duty vehicles. HCCI engines have the potential to match or exceed the efficiency of diesel-fueled CIDI engines without the major challenge of NOx and PM emission control or major impact on fuel-refining capability. Also, HCCI engines would probably cost less than CIDI engines because HCCI engines would likely use lower pressure fuel-injection equipment, and the combustion characteristics of HCCI would potentially enable the use of emission control devices that depend less on scarce and expensive precious metals. In addition, for heavy-duty vehicles, successful development of the diesel fueled HCCI engine is an important alternative strategy in the event that CIDI engines cannot achieve future NOx and PM emissions standards. The HCCI combustion engines have the potential to reduce the NOx and PM emissions simultaneously, while maintaining the thermal efficiency close to that of conventional diesel engine. But in HCCI combustion there are many challenges such as the difficulty in combustion phasing control, misfire at low and knocking at high loads, cold start problem, difficulty in homogeneous mixture preparation, high rate of pressure rise and high level of noise, high level of HC and CO emissions etc. The homogeneous mixture preparation and auto-ignition control are the main issues of the HCCI combustion. In HCCI combustion reduction in NOx and PM emissions simultaneously is made possible by eliminating high temperature and fuel-rich zones respectively due to lean or diluted mixture obtained through effective homogeneous mixture preparation. Auto-ignition control in HCCI leads to achieve higher thermal efficiency. HCCI engines are a promising technology that can help reduce some of our energy problems in the near term. However, control remains a challenge because HCCI engines do not have a direct means to control the combustion timing. Two fundamentally different approaches to controlling HCCI combustion phasing are possible.

- Altering the mixture propensity for auto ignition.
- Altering the time-temperature history to which the mixture is exposed

A viable method of controlling the combustion phasing in production applications has not yet been identified.

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