HCCI Engines - Concept and Recent Advancements

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ABSTRACT

Homogenous-charge-compression-ignition (HCCI) engines incorporate the benefits of high efficiency of CI engines and low NO_x and particulate emissions of SI engines. These benefits are due to auto-ignition process of the lean mixture of fuel and air during compression. A key characteristic of HCCI combustion is the rapid burning of the fuel/air mixture because of the combustion occurring almost simultaneously throughout the cylinder. Challenges in the successful operation of HCCI engines, such as controlling the combustion phasing, extending the operating range, high unburned hydrocarbon and CO emissions etc are tough enough. Advancements in the control strategies of HCCI includes variable valve actuation, EGR, VCR, multimode, variable induction temperature etc.

Keywords: *HCCI, Diesel fuelled HCCI, Gasoline fuelled HCCI*

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1. INTRODUCTION

There are two types of internal combustion engines: spark ignition (SI) and compression ignition (CI). The conventional SI combustion is characterized by a flame propagation process. The onset of combustion in SI engines can be controlled by varying ignition timing from the spark discharge. Because the mixture is premixed and typically stoichiometric, the emissions of soot are orders of magnitude lower than that in the diesel processes. SI engines nowadays run on a stoichiometric mixture to utilize the catalyst for exhaust after treatment. Using a fixed air/fuel ratio means that the load controlling is possible only by controlling the air mass flow into the combustion chamber. The throttle used for this purpose gives rise to pumping losses and a reduction in efficiency. As a result, the major disadvantage of SI engines is its low efficiency at partial loads. The compression ratio in SI engines is limited by knock and can normally be limited in the range from 8 to 12 contributing to the low efficiency [1-3].

Conventional diesel combustion, as a typical representation of CI combustion, operates at higher compression ratios (12–24) than SI engines. In this type of engine, the air–fuel mixture auto-ignites as a consequence of piston compression instead of ignition by a spark plug [2]. The processes which occur between the two moments when the liquid fuel leaves the injector nozzles and when the fuel starts to burn are complex and include droplet formation, collisions, break-up, and evaporation and vapor diffusion. The rate of combustion is effectively limited by these processes. A part of the air and fuel will be premixed and burn fast, but for the larger fraction of the fuel, the time scale of evaporation, diffusion, etc. is larger than the chemical time scale.

The in-cylinder temperature in a conventional diesel engine is about 2700 K, which leads to a great deal of NOx emissions. For diesel engines, a trade-off between these two emissions is observed, and their problem is how to break through the compromise between NOx and PM emissions. After treatment reduction of NOx and particulates is expensive. Consequently, the obvious ideal combination would be to find an engine type with high efficiency of diesel engines and very low emissions of gasoline engines with catalytic converters. One such candidate is the process known as homogeneous charge compression ignition, HCCI, which we shall now discuss upon. [6-8]

Table1. SI – HCCI COMPARISON [1]

Basis of Comparison	SI Engine	HCCI Engine
Efficiency	Less	More
Throttle losses	More	No
Compression Ratios	Low	High
Combustion Duration	More	Less

NOx Emissions	Comapatively More	Less

Table2. DIESEL - HCCI COMPARISON [1]

Basis of Comparison	Diesel Engine	HCCI Engine
Efficiency	High	Equally High
Combustion Temperatures	1900-2100 K	800-1100 K
Cost	Comapatively High	Less
Combustion Duration	More	Less
PM & NOx Emissions	More	Less

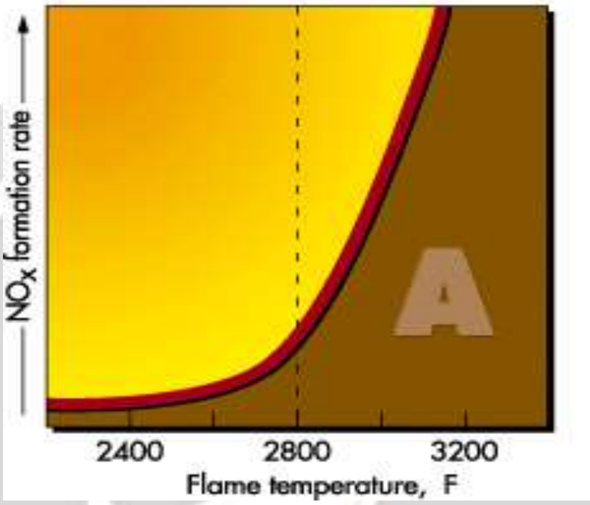

Fig.1 NO_X Formation With Respect To Temperature

2. HCCI PRINCIPLE

HCCI has characteristics of the two most popular forms of combustion used in SI engines (gasoline engines) and CI engines (diesel engines). As in homogeneous charge spark ignition, the fuel and oxidizer are mixed together. However, rather than using an electric discharge to ignite a portion of the mixture, the density and temperature of the mixture are raised by compression until the entire mixture reacts spontaneously. Stratified charge compression ignition also relies on temperature and density increase resulting from compression, but combustion occurs at the boundary of fuel-air mixing, caused by an injection event, to initiate combustion.

The defining characteristic of HCCI is that the ignition occurs at several places at a time which makes the fuel/air mixture burn nearly simultaneously. There is no direct initiator of combustion. This makes the process inherently challenging to control. However, with advances in microprocessors and a physical understanding of the ignition process, HCCI can be controlled to achieve gasoline engine-like emissions along with diesel engine-like efficiency. In fact, HCCI engines have been shown to achieve extremely low levels of Nitrogen oxide emissions (NOX) without an after treatment catalytic converter [14-17]. The unburned hydrocarbon and carbon monoxide emissions are still high (due to lower peak temperatures), as in gasoline engines, and must still be treated to meet automotive emission regulations.

Recent research has shown that the use of two fuels with different reactivity (such as gasoline and diesel) can help solve some of the difficulties of controlling HCCI ignition and burn rates. RCCI or Reactivity Controlled Compression Ignition has been demonstrated to provide highly efficient, low emissions operation over wide load and speed ranges. [2]

Once ignited, combustion occurs very quickly. When auto-ignition occurs too early or with too much chemical energy, combustion is too fast and high in-cylinder pressures can destroy an engine. For this reason, HCCI is typically operated at lean overall fuel mixtures.

3. ADVANTAGES OF HCCI COMBUSTION

- HCCI provides up to a 30-percent fuel savings, while meeting current emissions standards.
- Since HCCI engines are fuel-lean, they can operate at a Diesel-like compression ratios (>15), thus achieving higher efficiencies than conventional spark-ignited gasoline engines.
- Homogeneous mixing of fuel and air leads to cleaner combustion and lower emissions. Actually, because peak temperatures are significantly lower than in typical spark ignited engines, NO_X levels are almost negligible (Fig.1) Additionally, the premixed lean mixture does not produce soot.
- HCCI engines can operate on gasoline, diesel fuel, and most alternative fuels.
- In regards to gasoline engines, the omission of throttle losses improves HCCI efficiency. [21-29]

4. CHALLENGES TO HCCI

- High in-cylinder peak pressures may cause damage to the engine [6].
- High heat release and pressure rise rates contribute to engine wear [10].
- The auto ignition event is difficult to control, unlike the ignition event in spark ignition (SI) and diesel engines which are controlled by spark plugs and in-cylinder fuel injectors, respectively [12].
- HCCI engines have a small power range, constrained at low loads by lean flammability limits and high loads by in-cylinder pressure restrictions [14].
- Carbon monoxide (CO) and hydrocarbon (HC) pre-catalyst emissions are higher than a typical spark ignition engine, caused by incomplete oxidation (due to the rapid combustion event and low in-cylinder temperatures) and trapped crevice gases, respectively [22]
- Cold Start [19]

5. EFFECTS OF FUEL CHARACTERISTICS

Since ignition occurs by auto ignition the fuel must have high volatility and auto ignition characteristics. Christensen et al. studied the relationship between the fuel's octane number & compression ratio and found that almost any liquid fuel can be used in an HCCI engine using a VCR. [3] The effects of cetane number (CN) on HCCI auto-ignition, performance, and emissions were also investigated by some researchers. It was found that decreasing cetane number in fuels significantly reduces smoke emission due to an extension in ignition delay and the subsequent improvement in mixture formation.

5.1 Effects of additives and fuel modification

- Some chemical components have the ability to inhibit or promote the heat release process of auto-ignition.[4]
- Aceves et al. gave a numerical evaluation of fuels and additives for HCCI combustion. Additives were ranked according to their ability to advance HCCI ignition. [5]
- Several additives were identified for advancing combustion by almost 11 CA degrees when added to the intake mixture at a concentration of 10 ppm
- For fuel modification, addition of EGR into intake is the most practical means of controlling charge temperature in an HCCI engine. [6]
- The results indicate that the EGR rate can broaden the HCCI operating region, but it has little effect on the maximum load of the HCCI engine fuelled with DME/methanol [21].

6. CONTROL STRATEGIES OF DIESEL-FUELLED HCCI ENGINES

In diesel HCCI combustion, it is difficult to prepare homogeneous mixture because of the lower volatility, higher viscosity and lower resistance to auto-ignition of diesel fuel. The essential factor needed to achieve diesel HCCI combustion is mixture preparation of both charge components and temperature in the whole combustion process and high pre-ignition mixing rates. This can be obtained by two ways-

6.1 Improving mixing rate

Control strategies to improve the mixing rate.

6.1.1 High pressure injection and small pressure hole

Increasing injection pressure can greatly increase the energy of fuel injection [6]. Hence, atomization is improved, which leads to an improvement in the mixing rate of fuel and air, whilst reducing the size of nozzle holes increases the relative velocity of the fuel injected into the cylinder and the surrounding air.

6.1.2 High boost pressure

Enhancing boost pressure leads to an increase of in-cylinder density. And then, adequate atomization of the fuel injected into the cylinder improves the mixing process. [4]

6.2 Extending ignition delay

Control strategies of extending ignition delay

6.2.1 Variable compression ratio

Variable compression ratio technology changes in-cylinder pressure and density, which can produce effects on auto-ignition of fuel, and by which the in-cylinder temperature is controlled. Variable valve technology (timing or lift, VVT&L) can control mixing time by controlling the histories of in-cylinder temperature and pressure. It is an effective method combining reduced effective compression ratios with variable valve technology.

6.2.2 Variable valve actuation

It is for controlling the effective compression ratio. It controls the point at which the intake valve closes. If the closing of valve occurs after BDC, the effective volume and compression ratio change. [7]

6.2.3 Exhaust gas recirculation

EGR mixes with fresh air as diluter can lead to the increase of specific heat capacity in the cylinder. Hence, compression temperatures before ignition rise more slowly and ignition delay becomes longer. In addition, flame temperatures after ignition decrease, which is beneficial in reducing NOx emissions. The MK combustion system mentioned above is a successful example that employs this method. In addition, high level EGR is used in LTC. Therefore, EGR becomes one of the most important techniques used to control combustion.[4]

7. CONTROL STRATEGIES OF GASOLINE-FUELLED HCCI ENGINES

Combustion control of gasoline-fuelled HCCI engines can be divided into two areas. One covers heat release control, which could be of great benefit to enlarge the operation range. The other is auto-ignition timing control. The key factor for the ignition control is the in-cylinder gas temperature. Some approaches to control gasoline fuelled HCCI combustion are common here.

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7.1 Fuel injection strategies

To obtain the most homogeneous mixture, it is desirable to have a long mixing time between fresh air and fuel. Thus it seems that early injection using conventional port fuel injection would be more advantageous to obtain good homogeneous HCCI combustion. Successful HCCI operations have been achieved by many researchers using port fuel injection [8,9], but there are drawbacks to this operating mode. Port fuel injection offers no potential for additional combustion phasing control and limits the maximum usable compression ratio. A switch to direct injection offers the potential for increasing compression ratios and thus extension of the HCCI light load limits. Direct injection also offers the potential for combustion phasing control under conditions where the spark discharge is no longer effective.

7.2 Charge Boost

A considerable increase in engine load can be achieved with increasing boost pressure. At a maximum boost pressure of 1.4 bars boost, the IMEP has reached 7.6 bar. This is approximately 75% of the total engine load possible in this engine configuration with SI combustion.[10]

7.3 EGR

In the research of Cairns and Blaxill [11], a combination of internal and external EGR has been used to increase the attainableload in a multi-cylinder engine operated in gasoline controlled auto-ignition. The amount of residual gas trapped in the cylinder was adjusted via the NVO method (recompression). The flow of externally re-circulated exhaust gas was varied using a typical production level valve. Under stoichiometric fuelling conditions, the highest output achieved using internal exhaust gas was limited by excessive pressure rise and unacceptable levels of knock. Introducing additional external exhaust gas was found to retard ignition, reduce the rate of heat release and limit the peak knocking pressure. In Fig. 2, it can be seen that addition of external EGR enabled significant increase in peak engine output, rising from 350 kPa to 580 kPa (~65%). In addition, under conditions of combined EGR, NOx values further decreased at high loads.

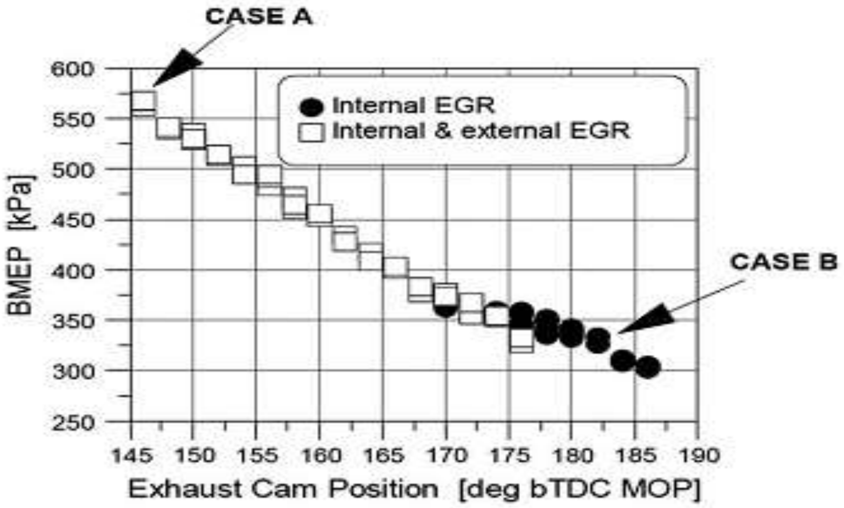

Fig.2 BMEP v/s Exhaust cam position[11]

7.4 VCR

Operating ranges in Figs. 3 & 4 show that lower compression ratios are used at intermediate loads as well as intermediate and high engine speeds to increase combustion efficiency, whilst compression ratios are close to maximum both at low load and high load. At low load and idle mode, maximum compression ratio and maximum available inlet air temperature are needed to initiate combustion and increase combustion efficiency.[12]

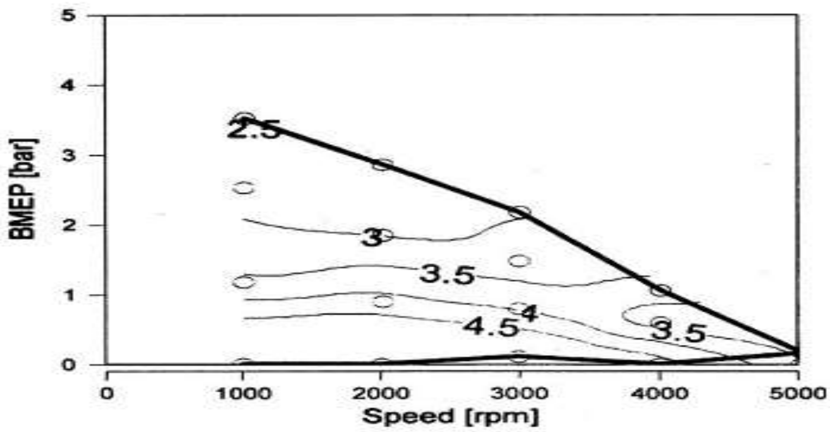

Fig.3 Operating range and lambda iso-lines with gasoline fuel [12].

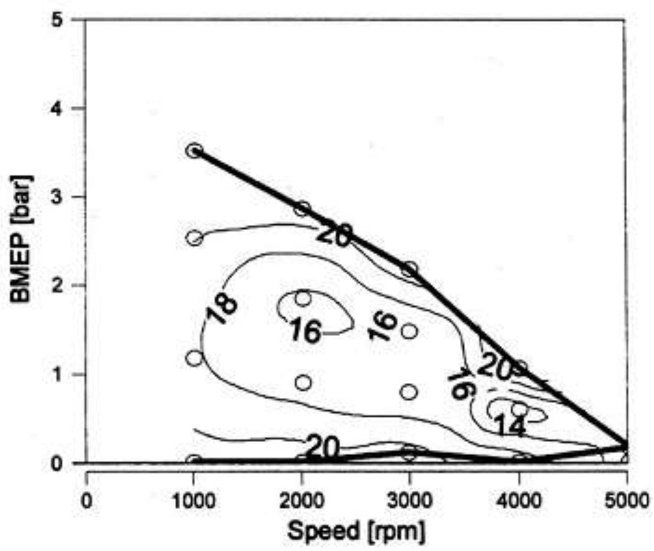

Fig.4 Operating range and compression ratio iso-lines with gasoline fuel [12]

7.5 Multimode

Multi-mode combustion is an idle combustion strategy to utilize HCCI for internal combustion engines. It combines HCCI combustion mode at low to medium loads with traditional SI mode at high speed and high loads.[4]

8. CONCLUSIONS

- HCCI combustion demonstrates a strong potential to improve the thermal efficiency of gasoline-fuelled engines and substantially reduce NOx and soot emissions of diesel-fuelled engines
- Difficulties associated with the successful operation of HCCI engines need to be overcome including:
  i) Combustion phasing control
  ii) High HC and CO emissions
  iii) Extending the operation range
  iv) Cold start problems and homogeneous mixture preparation;

9. FUTURE RESEARCH SCOPE

- The combustion mode design will be become one of the most interesting topics in the future.
- For the diesel-fuelled HCCI engines, more attention should be paid to extend the LTC operation to higher loads, even the full load, while maintaining good fuel economy and low emissions.

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