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Research and Development of Homogeneous Charge Compression Ignition (HCCI) Engine

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***Abstract:* -- Homogeneous Charge Compression Ignition is the mode of engine which will provide the advantages of both the SI and CI engine and consider as an alternative to the gasoline and diesel engine due to its capability of very low NOX emissions and operating with higher efficiency. The HCCI concept involves pre-mixing of charge prior to its induction as in present Spark Ignition (SI) engine, then ignite the air fuel mixture through the compression as in Compression Ignition (CI) engine and has no throttle loss, which leads to high efficiency. HCCI engine can operate on gasoline, diesel and most of the alternatives fuels. In HCCI, the combustion occurs simultaneously throughout the cylinder volume, as opposed to the turbulent flame propagation or mixing controlled combustion used in conventional engines. Instead of having advantages there are some challenges to the operation of the HCCI Engine. The main limitation of HCCI is the narrow operating window which results from the lack of direct ignition timing control. This paper reviews the technology involved in HCCI engine development, its advantages and disadvantages. The challenges involved in HCCI and the future developments in the same are also discussed in the paper.**

Index Terms— HCCI, SI, CI, Ignition timing, Exhaust Gas Recirculation (EGR), Emission.

I. INTRODUCTION

Internal Combustion (IC) Engine is the backbone of the development and energy source for all the automobiles. The living standard which we are getting today is possible just due to the existence of IC engine only. Currently, Spark Ignition (SI) and the Compression Ignition (CI) are the commercial types of IC engines. Gasoline and diesel are the principal fuel used for SI and CI engines respectively. Oxidation of the air and fuel mixture inside the chamber will produce useful power. Besides of this, IC engine is producing various emissions like carbon monoxide (CO), carbon dioxide (CO2), Nitrogen Oxides (NOX), Unburned Hydrocarbon (HC), and Particulate Matter (PM) which are directly or in directly harmful for mankind. Developing the emission less IC Engine and increasing the fuel economy is one of the biggest challenges for researchers.

The Homogeneous Charge Compression Ignition (HCCI) engine is a promising concept for future engine of automobile and stationary power plants. The main features of HCCI are introducing premixed charge, as in conventional Spark Ignition (SI) engines, and igniting without a spark plug, as in conventional Compression Ignition (CI) engines. HCCI engines can be widely developed because its efficiency is close to diesel engines, with low levels of emissions of NOX and PM. Hence HCCI technology will give the benefits of both spark engine and compression engine. In addition, HCCI engines can operate with a gasoline, diesel and other alternatives fuel. HCCI combustion allows the engines with efficiency comparable to, or potentially higher than that of diesel engines. Due to the absence of flame propagation, the temperature inside the combustion chamber will reduce, resulting in significantly less NOX emission.

II. HCCI FUNDAMENTALS

HCCI is a technology developed under IC Engine which has the possibility of both lower emission and higher efficiency. Spark ignition engine intakes the homogeneous air fuel mixture that is compressed and subsequently ignited by spark plug. Compression Ignition engines compress the air charge to a higher level than SI engines and then the fuel is injected inside the cylinder which temperature is sufficient after compression to ignite the fuel. This results in a highly un-homogeneous mixture. The temperature inside a conventional diesel engine is about 2700k, which leads to the excess of NOX emissions. HCCI technology claimed that the thermal efficiency can be improve and reduce the emission by modifying either SI or CI engines using any fuels. After a lot of research it has been shown that an engine can be run using a combination of the SI and CI strategies, by utilizing a homogeneous mixture, but relying on the compression to ignite the mixture. This approach is called the HCCI.

The schematic diagram of HCCI mode engine setup is as shown in fig 1. The system consists of a Exhaust Gas Recirculation (EGR), Variable Compression Ratio and variable temperature control system to make the controlled combustion with less knocking.

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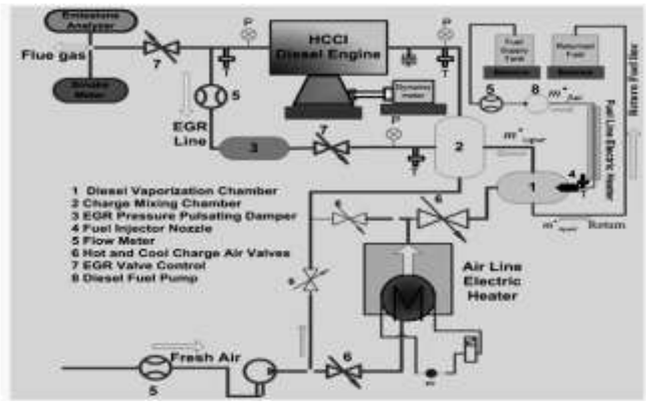

Fig 1: Schematic of Experimental Setup of HCCI mode

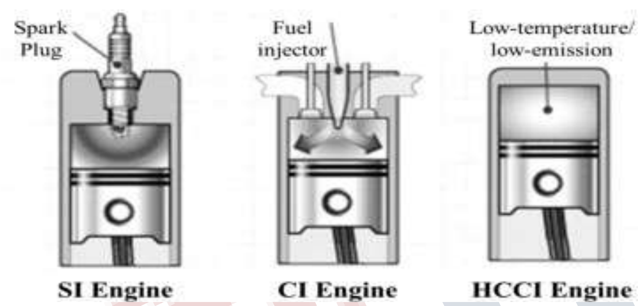

Fig 2: Schematic Diagram of SI, CI, and HCCI Engine

The diagram shows the combustion phenomenon occurs inside the respective engine. The premixed air fuel mixture will ignite with the help of spark plug in SI Engine. In CIDI Engine, the air will introduce inside the cylinder and get compressed, the fuel will inject at the end of compression and before the ignition. Due to the temperature of compressed air fuel will ignite. In HCCI mode, well-mixed fuel and oxidizer are compressed with a high compression ratio. During the end of compression stroke, ignition occurs through auto-ignition in the whole combustion chamber at once.

III. HCCI COMBUSTION CHEMISTRY

The HCCI auto-ignition combustion process is chemically controlled. The homogeneous air fuel mixture is compressed until ignition occurs simultaneously at multiple spots across the combustion chamber. Due to homogeneous nature of mixture, the influence of turbulence is limited hence it will not alter composition of mixture, and there are no diffusion combustion i.e. no flame fronts to affect the process. Combustion system of HCCI can be divided into 2 phases: a low temp and a high temp reaction phase. The low temperature reactions in HCCI start approximately at 700 K and the process can be divided into initiation, chain propagation, degenerate branching and chain terminating. Radicals are formed in the initiation steps which react further with fuel molecules to form more radicals during chain propagation stage. Branching steps involves the splitting of molecules which were formed in previous step into two radicals. Hydrogen peroxide H2O2 is formed during chain propagation step which will dissociate at temp of around 1100K into 2 oxygen and hydrogen (OH) radicals. This dissociation phase is taken as an important step, as the reaction of the OH radicals with fuel molecules initiates the main combustion process. The low temperature combustion process is dependent on both temperature and pressure. The high temperature combustion will start after altering the ambient conditions during the compression due to affecting the low temperature reactions. The low temperature reactions are clearly distinguished. At a temperature below 1100K, high temperature reactions start in which hydrogen peroxide decomposition starts, but it should be noted that the temperature curve represents the average gas temperature, rather than the local temperature where the H2O2 decomposition occurs.

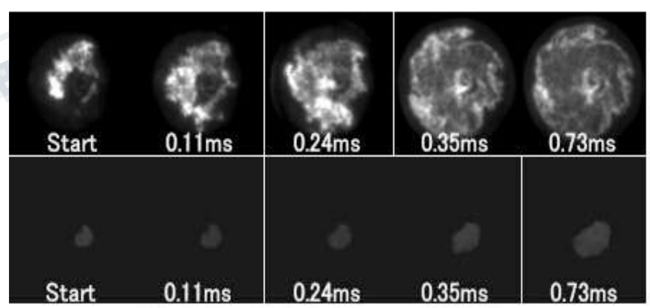

Fig 3: Comparison of Combustion Process through Visualization (Above HCCI, Below Conventional Combustion)

Figure shows the photos of HCCI and Conventional Combustion processes using engine affording visualization. In this figure, the portions shining white indicate combustion. It suggests that the combustion in HCCI engine completed in a short space of time and throughout the combustion chamber. While with in the same time, flame still remains near the Spark Plug.

IV. EARLIER WORK OUT IN HCCI

Onishi et al [1979] used Schlieren photography to visualize the combustion process in an engine operating with spark-ignited and HCCI modes. While observing the Schlieren image it shows very distinct flame propagation during the SI operation but no apparent flame propagation during the HCCI operation.

Thring [1989] performed a research on 4-stroke Diesel fuelled HCCI mode engine with control by maintaining an intake temp and EGR fraction over a limit of equivalence ratios. Results suggest that the indicated specific fuel consumption will be will lower for Diesel fuelled HCCI engine than the Conventional Diesel Engines. Although the energy needed for intake preheating was not accounted for in this assessment.

Christensen et al [1997] conclude that NOX emissions in the HCCI mode engine is vary with the nature of fuel. The fuel with high octane number will result higher NOX as these fuels require higher temperature for auto-ignition. Due to the lower peak cylinder temperature, NOX emission will significantly reduce in HCCI combustion compared to SI and CI combustion.

Ishibashi et al [1998] performed the emission test of HCCI Motor Cycle engines and 2-stroke Spark Ignited engines. They made the conclusion that HCCI engine will have higher HC and CO emission compared with the automotive emission standards. After a lot of research, HCCI engine with improved fuel economy and emission has been already evaluated.

Richter et al [1999] adopted absorption spectroscopy technique to study the effect of different fuels on HCCI combustion. Result suggests that methanol, ethanol, or isooctane as a fuel will give similar absorption spectra. Distinct absorption features were found at 310 nm and 284 nm, which is Oxygen and Hydrogen (OH) radical absorption. They performed the research with mixture of isooctane and n-heptane fuel, and observed the spectra which showed a significant absorption in the Ultra Violet (UV) region from about 200 Before Top Dead Center (BTDC) until the start of the main heat release, which was attributed to the presence of the cool flame.

Stanglmaier et al [2001] perform an efficiency test of dual fuel HCCI mode engine with natural gas. Then they conclude that blending of two fuels will control the ignition timing due to their different auto-ignition characteristics. Finally they suggest that this system of control timing will work only over a small range, but to obtain a wider load range control, HCCI engine would likely need to be coupled with another type of system like Exhaust Gas Recirculation.

Dae and Chang [2006] investigated to establish controlled combustion in HCCI from partial HCCI. They use a Diesel, Gasoline and n-heptane as a pre-mixed fuel in this experiment. Results made that NOX and soot emission can be decrease with diesel premixed by increasing the premixed ratio. If the inlet charge will heated to obtain improved vaporization of diesel fuel, higher inlet temperature will exist which restricted the operating range of HCCI combustion due to several engine knocking. Their research conclude that NOX and soot emission can be reduced by Gasoline premixing up to greater extent compared to other premixed fuels.

Lei et al [2006] performed Combustion and Emission performance of Diesel fuel HCCI engine using the Exhaust Gas Recirculation (Internal and External). Homogeneous Mixture achieving with fuel injection before the Top Dead Centre of an exhaust stroke and the negative valve overlap will result low NOX and smoke emissions.

V. REQUIREMENT FOR HCCI

There are two major condition which should be establishes to perform HCCI combustion. The temperature at the end of the compression stroke should be equal to auto-ignition temperature of the air fuel mixture. Noted that every fuel have their own auto-ignition temperature. Next is, to establish the reasonable burn rate the mixture should be diluted enough.

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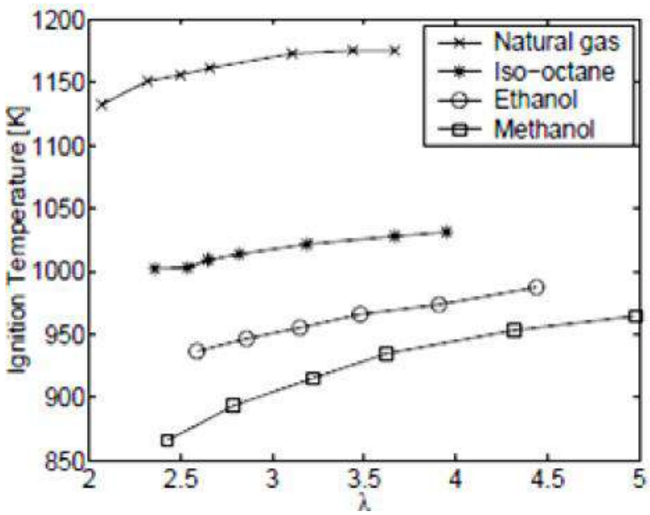

Fig 4: Ignition Temperature for a few fuels as a Function of Dilution

The above graph shows the relation between Ignition temperature and function of dilution. If we take an isooctane, the auto-ignition temperature of it is roughly 1000K. This suggests that at the end of the compression stroke the temperature should be 1000k to start the reactions. This can be achieved in two ways, either temp in the combustion chamber at the start of compression is controlled or increase the temp due to compression i.e. compression ratio is controlled. Self-ignition temp is a very weak function of air fuel ratio. If we take an example of isooctane, with a factor 2 change in λ, the auto-ignition temperature will only change by 50k. Above graph shows the normal rich and lean limits found in HCCI Engine. The nature of reactiveness of charge is too high for rich mixture. In additions, for rich mixture the burn rate will becomes extremely high. HCCI engine which run in too rich mixture of charge, the charge can be consumed within a fraction of crank angle which leads to rate of pressure rise and hence noise and stress in engine. For the fuel with a high auto ignition temp closely to a natural gas, the load limiting factor may be the function of NOX formation.

VI. PERFORMANCE AND EMISSION

Engine performance refers to the combustion, Brake thermal efficiency, Specific fuel consumption and exhaust gas emission. Heat release during combustion in HCCI engine depends on the nature of fuel used. Heat release rate is dependent on combustion percentage and combustion starting point in chamber. Heat release rate will increase if the combustion will start at the end of compression stroke which leads to the reduced combustion efficiency.

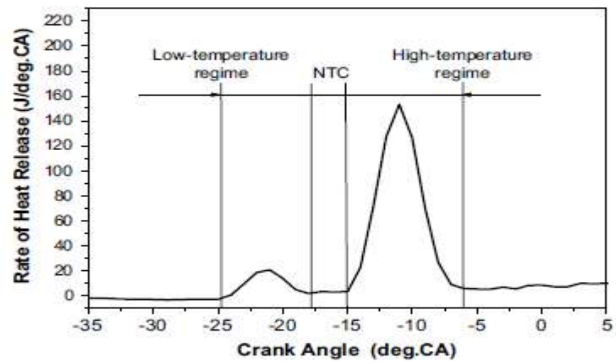

Fig 5: Heat release curve for HCCI mode combustion

The heat release rate for HCCI engine will be higher than that of conventional CI engine. Due to low temp distributed reactions and non-luminous combustion, heat rejection to the engine get reduce. Hence HCCI mode engine combustion is, in itself, conducive to high thermodynamic efficiency. The premixed homogeneous air fuel mixture leads to reduce ignition delay and combustion duration. Brake thermal Efficiency is the ratio of brake output power to an input power of an engine. The efficiency will get increase due to no throttle loss in CI Engine.

Emissions from the engine have become the major focus for researchers due to the strict regulatory standards, such as Euro Norm, US Norm etc. as per the country. The main target for studying the HCCI engine is its potential for significant reduction in emissions compared to the conventional CI and SI engine. HCCI can reduce the NOX emission by 90-98% compared to conventional combustion due to absence of high temperature regions within the combustion chamber. HCCI combustion produces low levels of smoke and PM emissions. But HCCI results higher HC and CO emissions than conventional CI engines. The factors contribute for these emissions is low in-cylinder temperature due to lean mix and high levels of Exhaust Gas Recirculation which are necessary for HCCI engine to operate satisfactorily.

VII. CHALLENGES FOR HCCI

HCCI mode only can achieve after overcome some of the challenges like controlling the temperature, pressure and composition of the air and fuel mixture so that self-ignition can take place near the TDC at the end of compression stroke. In this mode ignition is difficult to control as compared to the conventional SI and CI engine. To gain the optimum benefits of the HCCI mode engine, different obstacles has to be overcome. The challenges that have been arise in the HCCI technology is as follows.

Controlling Ignition Timing over the Range of Loads and Speeds

The ignition in the HCCI engine is depends on the air fuel mixture composition and its temperature history. In HCCI, it is difficult to control the operation under a range of speeds and loads. The start of combustion cannot be control in HCCI likewise as in conventional SI and CI engine. To obtain the range of power output in HCCI Engine, fuel rate and charge mixture should also change. As a result the temperature history must be adjusted to maintain proper combustion timing. Similarly, changing the speed of engine will change the time duration for auto-ignition chemistry to occur relative to the piston motion. Again the temperature history of the mixture must be adjusted to compensate. These controlling issues of ignition timing over the range of loads and speeds become particularly challenging during rapid transients.

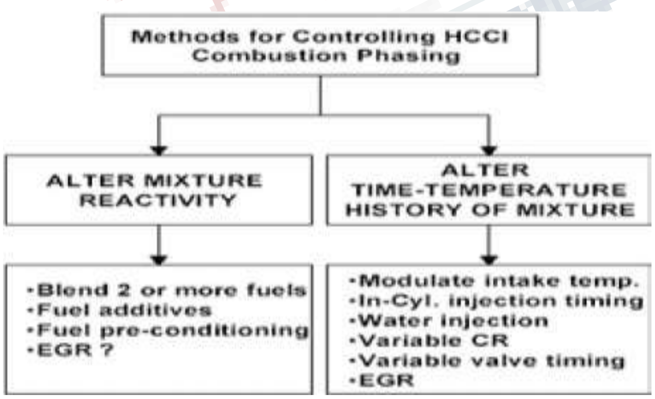

Fig 6: Methods of Controlling HCCI Combustion Phasing

Researcher has already adopted several techniques to control the combustion phasing. Variable valve timing, Variable compression ratio, EGR, Water injection is the methods to control combustion phasing in HCCI mode engine.

Extending the Operating Range to High Loads

Presently, HCCI combustion can operate only for limited power output. HCCI can operate well only in low to medium loads condition. Researchers at Nissan has successfully applied HCCI mode which can operate well in low load condition but difficulties have been encountered while it will operate in high load condition. Under high loads, combustion rate will excessively increase causing unacceptable noise, potential engine damage, and very high level of NOX emissions.

Way to achieve HCCI:

-Variable Compression Engine
-Variable Intake Temperature Control
-Variable Exhaust Gas Recirculation
-Variable Valve Timing

The difficulty lies in controlling the operation of an HCCI engine over a wide range of speeds and loads can be controlled through several methods. Variable Compression Ratio (VCR) and Variable Valve Timing (VVT) technologies are particularly attractive because their time response could be made sufficiently fast to handle rapid transients, it means accelerations or decelerations. The power output limitation can be solved with the development of “Dual-Mode” engines that employ HCCI combustion at low loads condition and CI or may be SI combustion at high loads condition.

Cold-Start Capability

The temperature of the compressed gas will reduced at cold start as the charge will not receive preheating from the intake manifold and the compressed charge will rapidly cooled due to heat transferred to the cold combustion cylinder walls. The temperature of the low compressed charge may prevent an HCCI engine from firing, without some compensating mechanism. Researchers has been attempted various mechanism for cold-starting in HCCI mode like Glow Plugs using a different fuel or a fuel additive, Variable Compression Ratio or Variable Valve Timing.

Probably, this challenge can be solve if the engine will start in spark-ignition mode and transition to HCCI after warm-up.

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Hydrocarbon and Carbon Monoxide Emission

In HCCI mode engine, the emission of NOX and Particulate Matter can be reduced but relatively Hydrocarbons and Carbon monoxide emission will be high. Catalyst technology that has been already applied to reduces the HC and CO emission from automobiles. However, the cooler exhaust temp of HCCI mode engines may increase the light-off time and decrease average effectiveness. As a result, meeting the future emission standard for HC and CO emission will likely require further development of oxidation catalysts which can operate for low temp exhaust streams.

VIII. RECENT DEVELOPMENTS IN HCCI

The challenges that have been arise in HCCI engine has been now solving by the recent technology. Automobiles companies like Ford, General Motors, Nissans, Cummins have been exploring the possibility in HCCI technology. Many researchers have performed the performance and emission test of HCCI mode under blending of fuels. Initially, turbo charging is proposed to increase the power but the challenges for turbo charging is low exhaust gases temp (300-5000C) due to high compression ratio. Variable Geometric Turbine VGT, is the solution for turbo charging which will allows for a greater range of turbine nozzle area, better the chances to achieve high boost. Exhaust Gas Recirculation can be adopted for lower hydrocarbon and carbon monoxide emission and higher efficiencies. EGR dilutes the fresh charge, delaying ignition and reducing the chemical energy and engine work. The numbers of researches are going on HCCI engine worldwide.

IX. SCOPE FOR FURTHER STUDY ON HCCI ENGINE

To overcome the challenges and limitation found in HCCI mode combustion, further study on the HCCI engine may be in the following field.

-Cold-Start of Engine
-Ignition Timing Control
-Fuel System
-Engine Transient Operation
-Multi-Cylinder Engine Effects
-Engine Control Strategies and Systems
-Heat Release Rate

X. CONCLUSIONS

The conclusion of review on research and development of Homogeneous Charge Compression Ignition engine is as follows.

●The HCCI engines will improve brake thermal efficiencies with consuming less quantity of fuels. It has low NOX and PM Emission. However, it has high emission of unburned HC and CO.

●Conversion of DI mode Engine into HCCI mode is one of the main targets of HCCI Research. Specially, injection timing is crucial to develop the HCCI mode engine.

●Review shows that the main challenges of HCCI engine is to control ignition timing, which directly influences the emissions and efficiency. Chemical kinetics of fuel, method of EGR, intake charge temperature, is responsible for HCCI mode engine combustion.

●Controlling the combustion process in HCCI through EGR was one of the effective methods. EGR will dilute the fresh charge and it lengthens the ignition timing.

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