Chapter 5

Homogeneous Charge Compression Ignition Engine

5.1 Introduction

Since last two decades, many automotive industries introduced several modern automotive vehicles, mainly to increase fuel economy, minimize the emissions, and to utilize different alternative fuels. In this regard, the researchers and engineers paid more attention towards the advanced modes of combustion like homogeneous charge compression ignition (HCCI), stratified charge compression ignition (SCCI), and low temperature combustion (LTC) due to superior thermal efficiencies and ultra-low emissions of NOx and soot. Among these, the HCCI engines have a potential to meet the stringent emission standards (EURO VI) and CO₂ emission standards. The HCCI combustion is considered to be one of the best combustion technologies to be adopted wider in the market near future, as it offers wide range of fuel flexibility with a higher thermal efficiency and low emissions (Sudheesh et al, 2010).

5.2. Fundamental of HCCI Engine

Onish et al investigated the first HCCI engine for gasoline applications. The author found that reduction of emissions and improvement in fuel economy. HCCI is characterised by the fact that the fuel and air are mixed before the combustion starts and the mixture auto-ignites as a results of the temperature increase in the compression stroke. The Figure 5.1 shows the working principle of CIDI, HCCI and SIDI engines. Thus HCCI is similar to SI in the sense that both engines use premixed charge and similar to CI as both engines initiate the combustion by the compression of
piston. The HCCI combustion initiates simultaneously at multiple sites within the combustion chamber and that there is no discernable flame propagation.

The HCCI combustion is controlled by chemical kinetics of the charge. There is no direct control of combustion process, such spark plug or fuel injector. The HCCI mode engine performance and emission characteristics are depend on start of ignition process. The rate of heat release, peak in cylinder pressure and temperature of HCCI engine combustion is also determined by the timing of start of ignition. The start of combustion timing is regulated by inlet air temperature, compression ratio and fuel properties.

HCCI is thus a combustion process that combines the ignition process of a compression ignition (CI) engine with the premixed nature of the spark ignition (SI) engine. In HCCI engine, very lean mixtures are used such that the peak flame temperature is below 1,800 K to prevent large amount of thermal NOx formation. The lean premixed charge helps minimize particulate emissions. The HCCI engine platform is nearly the same as the traditional CI engine. This mode of engine operation takes with it many of the advantages of the CI engine, but at the same time,
brings with it some serious challenges. HCCI engines may produce diesel-like efficiency due to high compression ratios and very rapid heat release, while maintaining low nitrogen oxide, particulate matter, and soot emissions. In addition, HCCI engines are fuel flexible and may be cost competitive to manufacture since a high-pressure fuel injection system is not required.

5.3. Combustion in HCCI Engine

In compression ignition engine, the combustion process occurs by the auto ignition of air/fuel mixture. Since the air alone, enter to the chamber and fuel to be injected on the air by the injector at end of the compression stroke. The heterogeneous air/fuel mixtures start to penetrate together when the fuel leaves from the injector nozzle. The rate of combustion is effectively limited by the fuel droplet collision, break up, evaporation and vapour diffusion. The CI engines have formed two different region of charge due to the presents of air concentration. Therefore, the combustion can be divided as high fuel concentration region and high temperature region.

The combustion process in HCCI engine is very different and much complicated than both SI and CI engines. Because of there is no direct control of combustion process. However, in SI and CI engines, the start of combustion can be controlled by spark plug and fuel injector timing, respectively. In HCCI engine, the fuel/air mixed before the start of combustion and auto ignite as a result increase the temperature during the compression stroke. The combustion of HCCI engine is initiated and start at different points throughout the combustion chamber without flame front.
The HCCI combustion may occur before TDC or after TDC at expansion stroke. If the combustion processes take place only before TDC, the combustion rate will be increased and resulted high peak pressure and temperature. If the combustion occur after TDC during the expansion process, the combustion may be slower due to the increased the volume during combustion. The HCCI engine combustion has two stage of heat releases low temperature reaction and high temperature reaction (HTR). It is caused due to ignition delay of the mixture.

The two-stage auto ignition chemistry is also reflected in the heat release patterns observed for combustion of homogeneous mixtures in engine situations. The cool flames arising from the first stage of the auto ignition process provide a significant heat release, followed by a period with no apparent heat release corresponding to the combustion, so called negative temperature coefficient chemistry, which lasts up to the high temperature stage leading to the main heat release rate, which will control engine performance.

The start of combustion is established by the properties of fuel used in HCCI engine. The combustion process in HCCI engine can be affected by the following factors: auto ignition temperature of fuel, fuel concentration, calorific value and latent heat of vaporisation. The HCCI engine can accept a variety of fuels, since the ignition occur in an HCCI engine by auto ignition of mixture. Different fuels will have different auto ignition temperature. The choice of fuel will have a significant impact on HCCI combustion. The HCCI engine have been operated with gasoline, hydrogen, ethanol, natural gas, diesel, biogas and biodiesel either neat or blends. Each fuel has different HCCI combustion character. The fuel must have high
volatility in order to early form of homogeneous charge. The HCCI combustion can generally be characterised based on the fuel to be used in HCCI engine.

5.4. Methods of Homogeneous Charge Preparation

The HCCI engine have the difficulties in the preparation of the homogeneous mixture, difficulties in control of the starting phases of combustion and control of the combustion rate, high hydrocarbon and CO emissions, and difficulties in extension of the load range. The strategies for mixture preparation are either in cylinder direct injection or in external mixture preparation. Both the preparation methods have their own disadvantages that the external mixture has a low volumetric efficiency and in-cylinder mixture is prone to an oil dilution. This session describes the strategies and implementations of mixture preparation.

5.4.1. Premixed/ Port Fuel Injection HCCI

Considering that time is needed for mixture preparation, fuel injection in the intake port is the most straightforward method to prepare a homogeneous mixture, and the highest rate of homogenization is achieved by port fuel injection compared with other alternatives. The principle is exactly same as in conventional spark-ignition engines, fuel is injected upstream of the intake valve, and consequently requirements on the injection system operation are not very different to those in conventional spark-ignition engines. Mixture is homogenized during the intake and compression strokes, and auto ignition occurs due to compression.

In these systems, the main issue concerns fuel evaporation. In general, full evaporation of diesel fuel only occurs at a temperature that is much higher than that normally found in the intake manifold. If no precautions are taken to enhance the fuel
evaporation, a significant part of the fuel evaporates late in the compression stroke even after the start of combustion. This leads to a heterogeneous mixture losing the benefits found in HCCI combustion.

Moreover, impingement or condensation of fuel on the engine walls can lead to high levels of unburned hydrocarbons and oil dilution. These levels can be so high that they have a significant influence on the combustion efficiency (part of the fuel does not burn). Therefore, a common strategy to enhance evaporation is to heat up the intake charge to enhance evaporation. If the diesel fuel evaporated properly and homogenized adequately at the intake port, this mixture is heated up during the compression stroke up to the ignition temperature.

However, the ignition temperature is reached too early in the compression stroke, far before TDC, leading to problems with efficiency and noise, and this is especially critical if intake charge is heated to enhance fuel evaporation, since this
leads to higher temperature at the start of the compression stroke and consequently combustion will start earlier in the engine cycle. Homogenization, almost all fuel burns simultaneously, leading to a very fast combustion. However, this is not the case in practice. This combustion can be so fast that before medium load is achieved, the pressure gradient is too high and knocking combustion occurs with high risk of engine damage. Commonly, these phenomena are anticipated by reducing the compression, but it can lead to a serious reduction in the maximum achievable efficiency of the engine.

5.4.2. Early Direct Injection HCCI

A homogeneous mixture can also be obtained, when the fuel is injected directly in the combustion chamber during the compression stroke well before TDC. If properly chosen, sufficient time is available between the end of injection and the start of ignition to assure a relatively good homogeneous mixture, which will result in fully premixed combustion (Nathan et al, 2010). Some authors have classified this generic combustion concept with early injection as PCCI (Premixed Charge Compression Ignition) combustion (Das et al, 2015 & Fang et al, 2012). Compared to port fuel injection, there is a major advantage for early injection strategies: since fuel is injected during the compression stroke, the gas temperature and density are higher than at intake conditions, which enhances the evaporation process and thus reduces the time for preparing the mixture, avoiding the need to heat up the intake air.

As a drawback, with early direct injection less time is available for mixing the fuel with the air, compared to a port fuel mixing system (Ganesh, 2010). This results in a less homogeneous mixture, leading to emissions of NOx and soot that are higher
than those achieved with port mixing HCCI (but still much lower than for conventional diesel combustion) (Fang et al, 2012 and Ganesh, 2010).

5.4.3. Late Direct Injection HCCI

In the previous paragraphs, it has been discussed that in early injection HCCI combustion, fuel is injected well before the expected start of ignition, early in the compression stroke, which allows sufficient time to form a homogenized mixture. The more the injection approaches TDC, the higher the gas temperature and density and the shorter the auto ignition delay, up to the moment that the combustion resembles a classic DI combustion than HCCI combustion. However, if the injection is further retarded, starting from a conventional combustion with injection just before TDC, towards later crank angles, then gas temperature and density decrease due to the expansion movement of piston-leading to a longer auto ignition delay, and an improved mixture formation. In fact, the conditions are again favourable for HCCI combustion.

Figure 5.3: Operation map of engine using HCLI and HPLI combustion (39)
The HCLI (Homogeneous Charge Late Injection) and HPLI (Highly Premixed Late Injection) combustion concepts are currently being developed. Moreover, appeared only recently in the international literature (Teoha et al. (2014) & Maurya et al. (2014)). As shown in Figure.5.3, the HCLI combustion is used at low load, HPLI combustion is used at medium load, and high load is achieved with a conventional DI diesel combustion. In the HCLI combustion concept, injection is performed at around 40 degree before TDC, so that a rapid homogenization takes place. As in other early injection HCCI combustion modes, the start of combustion and the burn rate cannot be controlled by the rate of injection but only depend on the reaction kinetics of cylinder charge and are thus determined by the variables and composition of the charge at the end of intake.

5.5. HCCI-Combustion Control Methods

The combustion control of the HCCI mode engine is one of the challenging factors in HCCI development. These challenges should be eradicated for the successful operation of HCCI engine. The major challenges are control the auto ignition temperature of mixture, limit the heat release rate at high load operation, control the exhaust emissions and control and minimise the knocking. The HCCI combustion can be controlled by preheat the inlet air, pressurized inlet air, varying compression ratio, boost injection pressure, varying equivalence ratio, using ignition improver or fuel additives and exhaust gas recirculation.

5.5.1 Pre-Heat Inlet Air

Pre-heat the inlet air is one of the effective methods for combustion control. The inlet air is pre-heated by the heating-coil, which is placed in the inlet manifold.
The temperature of inlet air is used to help the fuel to be vaporised with less time. Which is reduced the ignition delay and combustion starts earlier. The inlet air temperature will affect the combustion process and formation of emissions. The in-cylinder peak pressure can be varied with inlet air temperature, if the inlet air temperature increased, it can be reduced the ignition delay of the charge and combustion start earlier. The NOx emissions were increased with increase the inlet air temperature. The heat release rate of HCCI mode engine can be varied with temperature of inlet air. The high inlet air temperature easily created the homogeneous charge within short time and it can be reduced the ignition delay of charge. Therefore, the combustion process has been taken before top death centre and increased the combustion efficiency.

5.5.2. Pressurized Intake Air

Supercharging and turbo charging are used in HCCI operation to extend the operating load range and reduced the exhaust emissions. The operational concepts of these two devices are the same, which are use to provide a high in take pressure into the combustion chamber, increase the charge density and thereby increase the engine performance. The start of combustion (SOC) is advanced if the intake pressure is increased. This indicates that pressurized intake air is able to improve the auto-ignition of the fuel. By increasing the intake pressure, it was possible to get the auto-ignition to start the combustion process before top dead centre (BTDC). On the other hand, super- charging (pressurizing intake air) is able to increase engine efficiency.

5.5.3 Varying Compression Ratios

Compression ratio is the one of the parameter to control the combustion process. It is the easiest way to control the combustion in HCCI operation compared
to other methods. By lowering the compression ratio, it extends the start of ignition timing and the combustion has been occurring at after TDC. The late ignition could reduce the combustion efficiency and reduced the heat release rate from the charge. The lower compression ratio, HCCI engine has low peak in cylinder pressure and temperature, and have lower NOx emission in the exhaust due to low combustion temperature. Reducing compression ratio from 18:1 to 16:1 was part of the strategy used in the second generation of MK diesel engines to extend low temperature, premixed combustion to higher load conditions. When compression ratio is reduced, the accompanying reduction in temperature rise of the end gas prevents explosive self-ignition from occurring.

### 5.5.4 Fuel Injection Pressure

Increased fuel injection pressure can promote better mixing of the in-cylinder charge especially when used in combination with smaller nozzle orifice. At high fuel injection pressure, injection speed increases leading to a high rate of air entrainment and mixing which results in favourable spray structure and better combustion. If increase the fuel injection pressure from 4 bar to 8 bar in the port fuel injected HCCI engine, the high injected pressure can atomize the fuel and drizzle over the inlet air and create the homogenous charge. The high homogeneity air-fuel mixture favour for complete combustion, increase the combustion efficiency. The well-mixed mixture have been reduced the ignition delay and advance combustion can happen at before TDC. The engine can produce high heat release rate, causes increase the peak in cylinder pressure and temperature.
5.5.5 Air-Fuel Ratio

The HCCI mode engine has been operating with lean air-fuel mixture for different operating conditions. The HCCI engine combustion should be controlled by varying the ratio of air and fuel in the mixture. The higher equivalence ratio ($\varepsilon$) of the charge reduced the ignition delay and has the high flame velocity. If the value of $\varepsilon = 0.421$, it increases the heat release rate and combustion starts slightly advanced.

5.5.6 Internal and External EGR

For early injection HCCI combustion, EGR should be combined with some other combustion control technology such as modification of fuel properties or adoption of some other chemical approach. In the case of late injection system, EGR is typically utilised as a NOx reduction measure with typical levels of approximately 40%. NOx is reduced because of the lowering of flame temperature due to charge dilution and higher heat capacity of the cylinder charge when EGR is introduced. For early injection HCCI diesel combustion, EGR is used as a means of diluting the gas mixture in HCCI diesel engine thereby retarding the ignition timing and reducing the combustion rate. The EGR have been replaced the oxygen molecules with carbon-dioxide, it reduced the combustion temperature.