

A HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE: AN INTRODUCTION

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ABSTRACT

Homogeneous charge compression ignition (HCCI) engine technology is relatively new and has not matured sufficiently to be commercialised compared with conventional engines. 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. The HCCI engines can use a wide range of fuels with low emissions levels. Due to these advantages, the HCCI engines are suitable to be used in a hybrid engine configuration, where it can reduce the fuel consumption even further. However, the HCCI engines have some disadvantages such as knocking and low to medium operating load range, which need to be resolved before the engine can be commercialised. Therefore, a comprehensive study has to be performed to understand the behavior of HCCI engines.

Keywords: Diesel; HCCI; Gasoline; Natural Gas; Hydrogen

BACKGROUND

The greenhouse effect is a worldwide issue as more and more greenhouse gases are released into the atmosphere, leading to global climate change. The effects include an increase in temperature, unstable weather and an increase in ocean levels, resulting in ice melting in the North and South Poles (Bates *et al.*, 2008, Graham *et al.*, 1990, Houghton *et al.*, 2001). This has become a global issue. Members of the Copenhagen Climate Conference in December 2009 (Bodansky, 2010) unable to reach an agreement on climate change. The increase of surface air temperature due to global warming has been simulated by Rob (2005) from NASA (see Figure 1), showing an increase in surface air temperature from 1960 to 2060. According to the report of the World Resources Institute (Jonathan 2006), transportation accounted for about 14% of the global greenhouse gases in 2000, making it a major contributor to global climate change and equivalent to 18% of global CO₂ emissions. Thus, it is imperative to minimise the emissions level from the transportation sector. To counter this issue, many automotive manufacturers are developing electric, fuel-cell or hybrid engines. Electric vehicle is driven by an electric motor, with the energy supplied by a high capacity battery stored in the car trunk or under the car body. The operation of the fuel-cell engine is similar to the electric vehicle by using an electric motor to drive the wheel. However, the difference is on the electricity generation method. Most fuel-cell driven vehicles use hydrogen and oxygen to generate electricity (Ogden *et al.*, 1999, Trimm and Onsan,

2001). Then, this electric energy will be stored in a high capacity battery and is used to drive the electric motor. Hybrid vehicle uses a combination of the conventional internal combustion (IC) engine and electric motor. The IC engine could be Spark Ignition (SI) or Compression Ignition (CI) engine, which is connected to the electric motor either in parallel or in series to drive the wheel. High capacity battery is again used to power the electric motor. Therefore, it can be summarised that the vehicle is driven by two or more power sources in hybrid configurations.

Table 1 summarises the advantages and disadvantages of those technologies and high implementation cost related to each of them leads to a slow commercialisation rate. Thus, an interim solution is required to improve the current IC engines with low implementation cost.

Table 1. Comparison of newly developed engine technology (Chan, 2002).

Engine Type	Advantages	Disadvantages
Hydrogen Fuel Cell	<ul style="list-style-type: none"> • Compact design • relatively long operating life • high efficiency • low temperature operation. 	<ul style="list-style-type: none"> • Higher loads reduce efficiency considerably • high energy cost • high manufacturing cost • heavy auxiliary equipment • complex heat and water management • safety issues
Electric	<ul style="list-style-type: none"> • No fuel • 100% emissions free at the vehicle (substantially reduced emissions overall) • fewer moving parts to wear out. 	<ul style="list-style-type: none"> • Limited operating battery ranges • long recharge time • battery size and weight issues • high battery replacement costs • limited charging facilities
Hybrid	<ul style="list-style-type: none"> • Lower emissions level • better fuel economy over conventional engines. 	<ul style="list-style-type: none"> • Unachievable break-even point before replacing the battery • high and costly maintenance • battery size add the extra weight to the vehicle

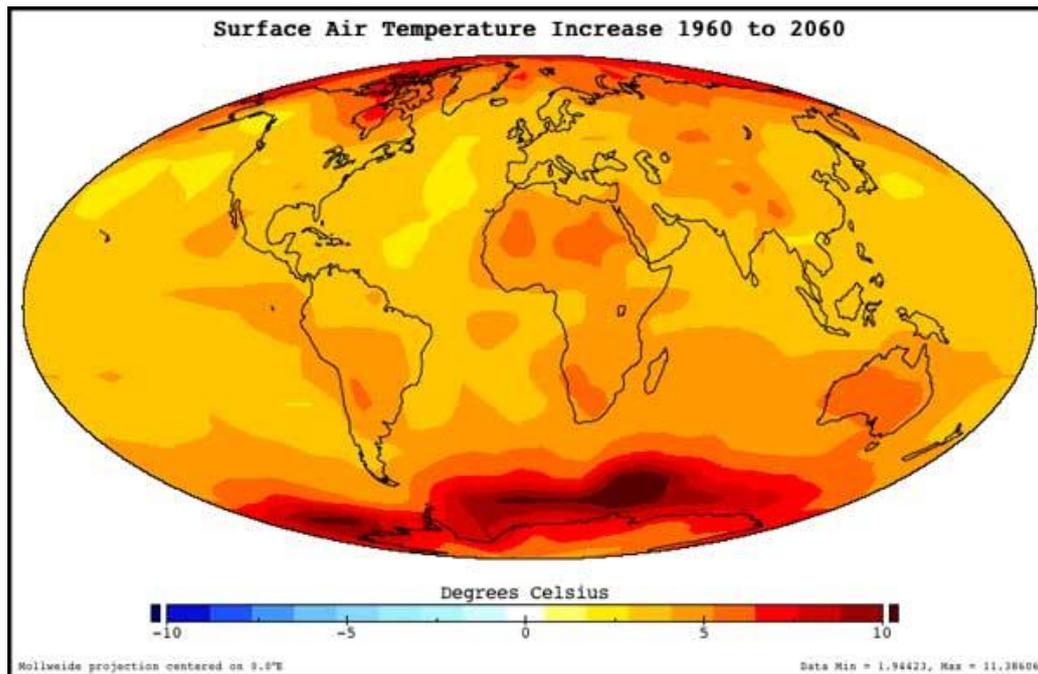


Figure 1. Simulated surface air temperature increase by the year 2060 (Rob, 2005).

INTRODUCTION

IC engines are widely used in numerous applications: vehicle engines, power generation and ships. The emissions generated from these applications have a high impact on the environment, thus alternative solutions have been investigated to achieve low emissions levels (Chan, 2002, Cho and He, 2007, Jonathan, 2006, Taylor, 2008). A new mode of combustion is being sought in order to reduce the emissions levels from these engines: a potential candidate is the Homogeneous Charge Compression Ignition (HCCI) engine. Figure 2 shows the differences among SI, CI and HCCI engines, where SI engines have a spark plug to initiate the combustion with a flame front propagating across the combustion chamber. CI engines have a fuel injector to inject the diesel and the combustion takes place in a compressed hot air region. HCCI engines on the other hand, have no spark plug or fuel injector and the combustion starts spontaneously in multiple locations. High engine efficiency can be achieved with low NO_x and soot emissions.

In HCCI combustion, a homogeneous mixture of air and fuel is compressed until auto-ignition occurs near the end of the compression stroke, followed by a combustion process that is significantly faster than either CI or SI combustion (Rattanapaibule and Aung, 2005). Epping et al. (2002) and Christensen and Johansson (1998) reported that the HCCI technology, using iso-octane as a fuel, has improved the engine efficiency by as much as 37% given a high compression ratio (18:1) and maintains low emissions levels. The efficiency and compression ratio are in the range of CI engines. The technology can be implemented by modifying either SI or CI engines using any fuel or combination of fuels. The air/fuel mixture quality in HCCI engines is normally lean, it auto-ignites in multiple locations and is then burned volumetrically without discernible flame propagation (Kong and Reitz, 2002). Combustion takes place when the homogeneous fuel mixture has reached the chemical activation energy and is fully controlled by chemical kinetics (Najt and Foster, 1983) rather than spark or injection timing.

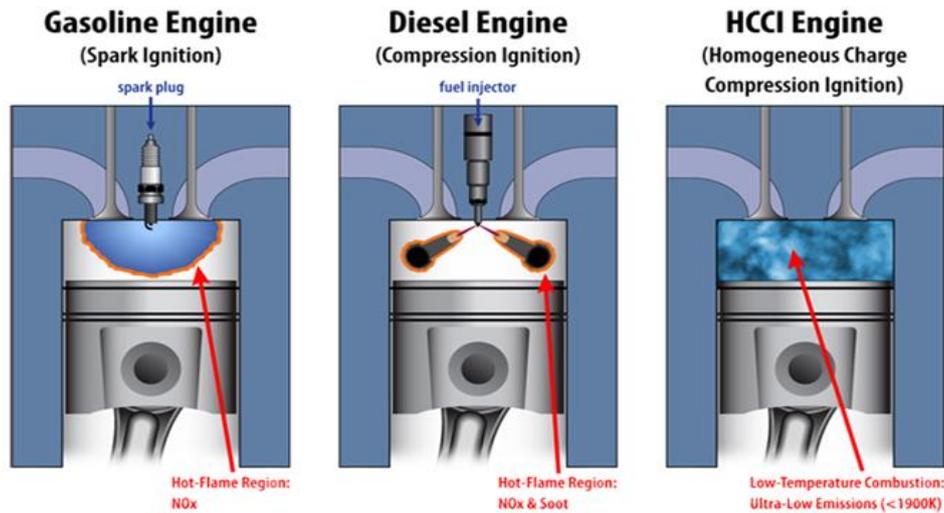


Figure 2. The differences among SI, CI and HCCI engines, reproduced from (William and Charles, 2011).

Since the mixture is lean and is fully controlled by chemical kinetics, there are new challenges in developing HCCI engines: difficult to control the auto-ignition of the mixture and the heat release rate at high load operation, achieve cold start, meet emission standards and control knock (Kong and Reitz, 2003, Soylu, 2005). The advantages of using HCCI technology in IC engines are:

1. High efficiency relative to SI engines - approaching the efficiency of CI engines due to the ability of these engines to use high compression ratio (CR) and fast combustion (Killingsworth *et al.*, 2006, Mack *et al.*, 2009);
2. The ability to operate on a wide range of fuels (Aceves and Flowers, 2004, Mack *et al.*, 2009, Christensen *et al.*, 1997); and
3. The ability to be used in any engine configuration: automobile engines, stationary engines, heavy duty engines or small sized engines (Epping *et al.*, 2002, Hiltner *et al.*, 2002, Kawano *et al.*, 2005).

On the other hand, HCCI engines have some disadvantages such as high levels of unburned hydrocarbons (UHC) and carbon monoxide (CO) (Kong and Reitz, 2003, Nathan *et al.*, 2010, Yap *et al.*, 2006). Knocking is also occurred under certain operating conditions and reduces the operating range of the engine (Andreae *et al.*, 2007, Jun *et al.*, 2003, Kong and Reitz, 2003, Nathan *et al.*, 2010, Yelvington and Green, 2003).

Emissions regulations are becoming more stringent and NO_x and soot emissions levels in HCCI engines have been greatly reduced without sacrificing efficiency, which is close to that of CI engines (Nathan *et al.*, 2010). However, knocking is still the major issue because of its sudden onset and results in a bad engine performance. Knocking is due to premature combustion where the ignition takes place before the piston reaches top dead centre (TDC) and it reduces engine reliability due to high vibration effects. Recently, hybrid engines have been developed by many automotive manufacturers due to its advantages, and the HCCI engine has the potential to replace the IC engine used in a hybrid configuration, which could reduce the emissions levels further. Thus, it is

important to investigate the HCCI engine's performance because it can be used in the near future.

State of the Art Current Internal Combustion Engines

Producing homogenous mixtures to achieve near-complete combustion is a common goal that will lead to the development of low polluting engines. Some technologies including Fuel-Stratified Injection (FSI), Turbo-Stratified Injection (TSI) and HCCI, are used to improve the combustion efficiencies by introducing the homogeneous mixture. FSI and TSI are commercially used by the Volkswagen Aktiengesellschaft (AG), which consists of other child companies: Audi, Skoda, Seat, Bugatti, Lamborghini, Bentley and Scania (Volkswagen, 2009). FSI uses direct injection fuel with high injection pressure, where the evaporating fuel has a significant cooling effect on the cylinder charge (Audi, 2012). This effect helps in reducing the knock and therefore higher compression ratio can be used. The air enters the combustion chamber at a certain angle by using a moveable flap inside the intake manifold (Wurms *et al.*, 2003), while fuel is directly injected during the intake stroke. The fuel injector is located close to the inlet valve in the cylinder head. With the help of the piston crown design, the air will experience tumbling effects inside the chamber. This in turn will help the fuel mix with air homogeneously. TSI engines, on the other hand, uses a high intake pressure (using multipoint injectors) on an FSI engine (Böhme *et al.*, 2006). This allows the fuel to mix homogeneously with the air during the compression stroke. The pressurised intake air will assist the combustion and therefore produce better efficiency, allowing smaller engines to be built with power and torque similar to that of bigger engines. The first engine to use direct injection technology to stratified charge engine was the Texaco combustion process (Barber *et al.*, 1955), as reported by Takagi (1998). HCCI engines can be considered as new technology (Yao *et al.*, 2009) even though the research was initially undertaken by Onishi *et al.* (1979). Researchers worldwide are investigating HCCI engines as this technology has not yet been sufficiently developed and commercially available. General Motors (GM) corporation has unveiled a prototype car with a gasoline HCCI engine, which could cut fuel consumption by 15% (Premier, 2007). The engine is able to virtually eliminate NO_x emissions and lower throttling losses, which improves fuel economy.

Gasoline Operated HCCI Engines

Gasoline could be operated in HCCI mode on its own, however, it would be unstable in a high load operating range. High load difficulties are the common problem for HCCI engines regardless of the fuel being used. The solution for this issue for gasoline fuel is to operate the engine in HCCI mode in the medium load range, and switch to SI mode in the high load range (Yingnan *et al.*, 2010). Wang *et al.* (2006) studied the gasoline HCCI engine with secondary injections and reported that the operating load range could be extended by using two-zone HCCI mode, which utilises secondary injections. However, the two-zone mode yields higher NO_x emissions due to fuel-rich zone developed in the chamber. Iso-octane is generally used as a gasoline surrogate fuel in numerical studies due to its high octane rating. Higher octane numbers cause difficulties in achieving the HCCI mode (Hosseini and Checkel, 2009). Thus the ignition has to be controlled using other means. The use of high octane number fuels, such as gasoline, in a low CR engine allows the engine to be switchable to SI mode in a high load range

(Fuerhapter *et al.*, 2004). It is found that a high CR engine (as high as 18:1) has advantages by producing ultra-low NO_x emissions (1ppm) and higher thermal efficiency (43%) at a fixed operating condition (John and Magnus, 2002).

Gasoline can also be mixed with diesel to operate in HCCI mode. A study by Kim and Lee (2006) on the effect of multiple fuels on emissions showed that the combination of diesel and gasoline (diesel is direct injected while gasoline is port injected) is an effective way to reduce NO_x levels, with the increase of premixed ratio. The premixed ratio is defined as the energy of premixed (port injected) fuel to the energy of total fuel (direct and port injected). Zhong *et al.* (2005) also studied the effect of blended fuels between gasoline and diesel, and reported that UHC and NO_x were significantly reduced throughout the HCCI engine load ranges. The purpose of blending gasoline and diesel is that gasoline has a high volatility and is easy to vaporise, thus can be used to form a homogeneous mixture. Gasoline also has a high octane number, where higher numbers show higher resistivity to knocking. Diesel on the other hand has good ignitability and fast combustion due to its high cetane number. Table 2 compares the characteristics between the gasoline and diesel fuels, where for the selected gasoline (octane number 98) the heating values are almost similar between those fuels.

Table 2. Characteristics between gasoline and diesel fuels (Kim and Lee, 2006).

	Gasoline	Diesel
Octane number	98	-
Cetane number	-	54
Higher heating value (kJ/kg)	47 300	44 800
Lower heating value (kJ/kg)	44 000	42 500
Boiling point (K)	468	553
Density (kg/m ³)	750	814
Stoichiometric air-fuel ratio	14.6	14.5

Natural Gas and Hydrogen with Diesel in HCCI mode

The combination of natural gas or hydrogen with diesel reported to yield low emissions and to some extent increase the engine efficiency, either in HCCI or CI combustion mode (de Risi *et al.*, 2008, Hairuddin *et al.*, 2010, Saravanan *et al.*, 2008a, Saravanan *et al.*, 2008b, Verhelst and Wallner, 2009). Diesel alone is not suitable for HCCI engines due to its low volatility and high propensity to auto-ignite while natural gas has a high resistance to auto-ignition as reported by Kong (2007). Combinations of high octane number fuels (such as natural gas and hydrogen) with high cetane number fuels (such as diesel) are able to increase the engine durability, and under certain operating conditions reduce emissions levels such as soot, HC, CO and NO_x (Szwaja and Grab-Rogalinski, 2009, Tomita, 2004, Tomita *et al.*, 2001, Tomita *et al.*, 2002). It was also reported that these combinations have a high thermal efficiency under early injection timing (Tomita, 2004, Tomita *et al.*, 2002). Fuels with a higher octane number have better resistance to knocking while fuels with a higher cetane number have a shorter ignition delay time, thus providing more time for the fuel to complete the combustion. Therefore, a combination of both (high cetane number fuels and high octane number fuels) provides soft engine run (Szwaja and Grab-Rogalinski, 2009), whereby the mixture can be operated at high CR and has a longer combustion duration.

Hydrogen has a high octane number (approximately 130) and a high Lower Heating Value (LHV) (119.93 MJ/kg). Its combination with diesel helps to increase engine efficiency (Saravanan *et al.*, 2008a) and control the auto-ignition point in HCCI engines (Szwaja and Grab-Rogalinski, 2009). Natural gas, on the other hand, has a higher auto-ignition temperature and it can be used in high CR engines (Akansu *et al.*, 2004). Table 3 compares the physical and chemical properties of diesel with natural gas and hydrogen.

Table 3. Diesel Properties Compared to Hydrogen and Natural Gas (Liu and Karim, 2008, Saravanan and Nagarajan, 2010, Saravanan *et al.*, 2008b, Verhelst and Wallner, 2009).

Properties	Diesel	Hydrogen	Natural Gas
Main component	C ₁₂ H ₂₃	H ₂	Methane (CH ₄)
Auto-ignition temperature (K)	553	858	923
Lower heating value (MJ/kg)	42.5	119.93	50
Density (kg/m ³)	833-881	0.08	0.862
Molecular weight (g/mol)	170	2.016	16.043
Flammability limits in air (vol%) (LFL–UFL)	0.7-5	4-75	5-15
Flame velocity (m/s)	0.3	2.65-3.25	0.45
Specific gravity	0.83	0.091	0.55
Boiling point (K)	453-653	20.2	111.5
Cetane number	40-60	-	-
Octane number	30	130	120
CO ₂ emissions (%)	13.4	0	9.5
Diffusivity in air (cm ² /s)	-	0.61	0.16
Min ignition energy (mJ)	-	0.02	0.28

From the Table 3, hydrogen has the highest LHV or Lower Calorific Value (LCV) compared to both diesel and natural gas, which means it releases a high amount of energy during combustion and thus produces the highest flame speed. A wide range of the flammability limits in air allows a wider range of engine power outputs through changes in the mixture equivalence ratio. Flammable mixtures of hydrogen can go from as lean as $\lambda = 10$ to as rich as $\lambda = 0.14$ (Verhelst and Wallner, 2009), where λ is the air-to-fuel ratio actual divided by the air-to-fuel ratio stoichiometric.

CONCLUSION

Therefore, it is feasible to use gasoline, diesel, natural gas, hydrogen or a combination of those in HCCI engines, because the engine could be operated in a wide range of fuels. From practicality point of view, the HCCI engine could be used in a hybrid configuration, where it might help reduce the fuel consumption even further. Many studies show the HCCI engine has a low NO_x emissions, soot and particulates. However, HCCI engines still have unresolved issues, which are knocking and high levels of unburned HC and CO emissions. Further studies have to be performed in order to solve these remaining issues. To achieve this, the numerical method is proposed for early study because it has great advantage over experiments in terms of cost and time.

To this end, a simulation model has been developed to investigate the combustion behavior and, once completed, it has to be validated against experiments.

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