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Research Paper

HOMOGENEOUS CHARGE COMPRESSION IGNITION (HCCI) ENGINE

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Homogeneous Charge Compression Ignition (HCCI) is a new combustion technology that may develop as an alternative to diesel engines with high efficiency and low NOx and particulate matter emissions. HCCI engines can operate on gasoline, diesel fuel and most alternative fuels. The Homogenous Charge Compression Ignition (HCCI) is a promising new engine technology that combines elements of the diesel and gasoline engine operating cycles. 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. With the advantages there are some mechanical limitations to the operation of the HCCI engine. The main drawback of HCCI is the absence of direct combustion timing control. This paper reviews the technology involved in HCCI engine, and its merits and demerits. The challenges encountered and recent developments in HCCI engine are also discussed in this paper.

Keywords: HCCI, Ignition timing, Valve timing, Exhaust gas recirculation, Emission

INTRODUCTION

The internal combustion engine is the key to the modern society. Without the transportation performed by the millions of vehicles on road and at sea we would not have reached the living standard of today. Internal Combustion Engines (ICEs) play a dominant role in the automotive industry owing to their simplicity, robustness and high thermal efficiency. The Internal Combustion (IC) Engine is perhaps the most wide-spread apparatus for transforming liquid and gaseous fuel to useful mechanical work. The reason why it's so well accepted can be explained by its overall appearance regarding properties like performance, economy, durability, controllability but also the lack of other competitive alternatives.

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There are two kinds of internal combustion engines: the Petrol and the Diesel. The combustion processes of them are very different. In the Diesel engine the combustion is initiated because of some special conditions of pressure and temperature. However, in the Petrol engine the combustion is caused by a spark that ignites a mixture that has been premixed before.

Due to these different kinds of combustion, the two engines have different characteristics. The CI has a high efficiency, but it is very contaminating. Contrarily, the SI is not very efficient but it has low emissions.

The obvious ideal combination would be to find an engine type with the high efficiency of the CI engine and the very low emissions of the SI engine with TWC. One such candidate is named Homogeneous Charge Compression Ignition, HCCI.

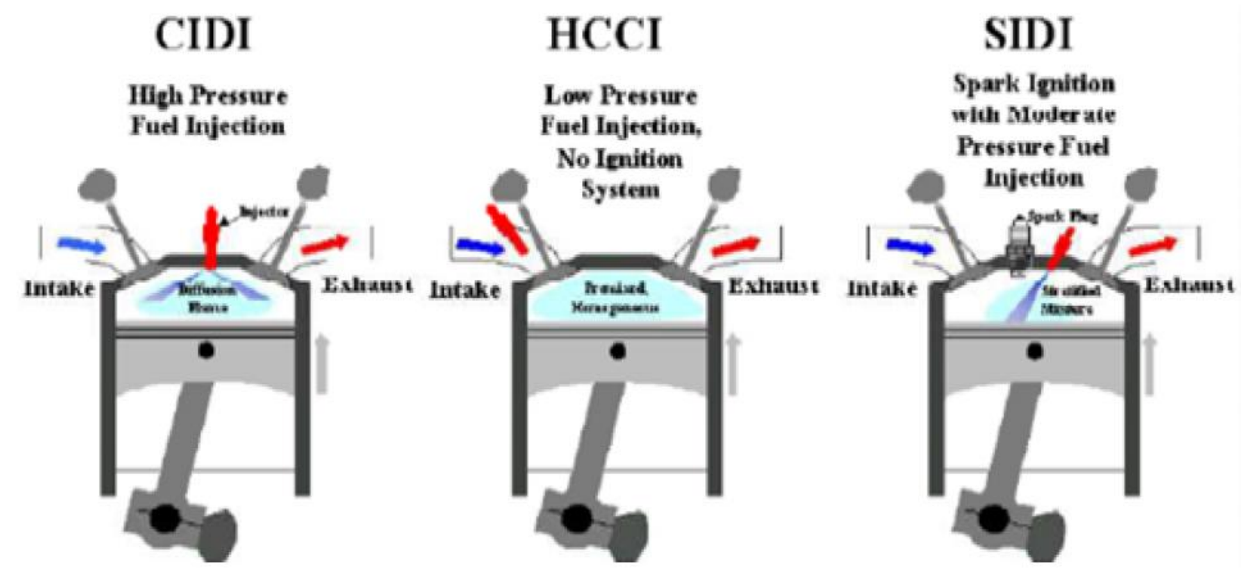
With the advent of increasingly stringent fuel consumption and emissions standards, engine manufacturers face the challenging task of delivering conventional vehicles that abide by these regulations. HCCI combustion has the potential to be highly efficient and to produce low emissions. HCCI engines can 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. HCCI engines have the potential to be lower cost than CIDI engines because they would likely use a lower pressure fuel-injection system. The emission control systems for HCCI engines have the potential to be less costly and less dependent on scarce precious metals than either SI or CIDI engines.

HCCI is an idea whose time has come with nearly all of the parts and pieces of technology and know-how in place to make a real go of it.

HOMOGENEOUS CHARGE COMPRESSION IGNITION (HCCI)

The Homogeneous Charge Compression Ignition (HCCI) engine is often described as a hybrid between the spark ignition engine and the diesel engine. The blending of these two designs offers diesel-like high efficiency without the difficult—and expensive—to deal with NOx and particulate matter emissions. In its most basic form, it simply means that fuel is homogeneously (thoroughly and completely) mixed with air in the combustion chamber very similar to a regular spark ignited gasoline engine, but with a very high proportion of air to fuel, i.e., lean mixture. As the engine's piston reaches its highest point (top dead center) on the compression stroke, the air/fuel mixture auto-ignites from compression heat, much like a diesel engine. The result is the best of both

Figure 1: HCCI (as Most-Typically Envisioned) Would Use Low-Pressure Fuel Injection Outside the Cylinder, and No Ignition System. If Charge Stratification is Desired, it May be Necessary to Use in Cylinder Injection



worlds: low fuel usage and low emissions. As in a diesel engine, the fuel is exposed to sufficiently high temperature for auto-ignition to occur, but for HCCI a homogeneous fuel/air mixture is used. The homogeneous mixture is created in the intake system as in a SI engine, using a low pressure injection system or by direct injection with very early injection timing. The Homogeneous Charge Compression Ignition (HCCI) engine is a promising alternative to the existing Spark Ignition (SI) engines and Compression Ignition (CI) engines. To limit the rate of combustion, much diluted mixtures have to be used.

Compared to the diesel engines the HCCI has a nearly homogeneous charge and virtually no problems with soot and NOX formation. On the other hand HC and CO levels are higher than in conventional SI engines. Overall, the HCCI engine shows high efficiency and fewer emissions than conventional internal combustion engines.

Homogeneous Charge Compression Ignition (HCCI) uses a lean premixed air-fuel mixture that is compressed with a high compression ratio. During the end of the compression stroke, ignition occurs through self-ignition in the whole combustion chamber at once.

Engine efficiency rises with increases in the leanness of the premixed gas (the gas composed of premixed fuel and air), in the combustion rate, and in the compression ratio. In the HCCI engine, ultra-lean premixed gas is highly compressed by the piston and ignited at the self-ignition temperature. Then, combustion occurs in the entire combustion chamber, and the combustion rate is very high. As a result of ultra-lean combustion with a high compression ratio, high thermal efficiency and extremely low NOx emission are achieved as compared to the conventional spark ignition engines. Figure 2 shows photos of the spark ignition and HCCI combustion processes

Figure 2: Comparison of HCCI (Upper Row) and Spark Ignition (Lower Row) Combustion Processes

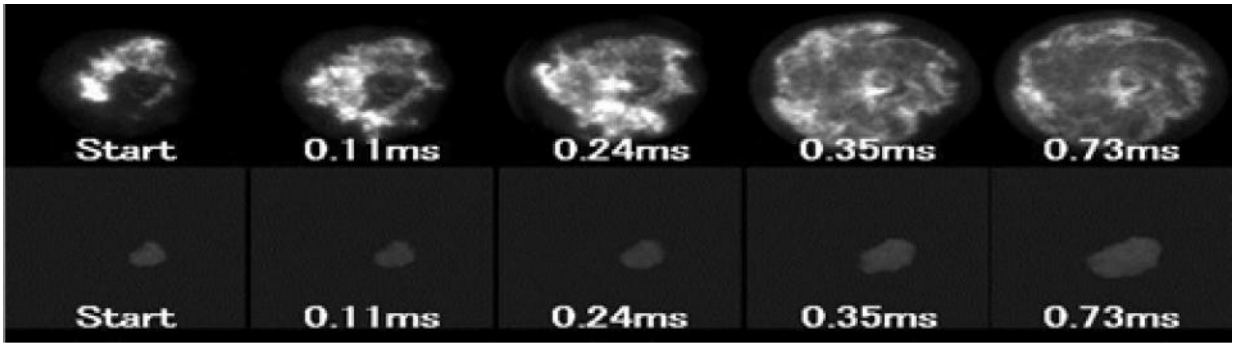
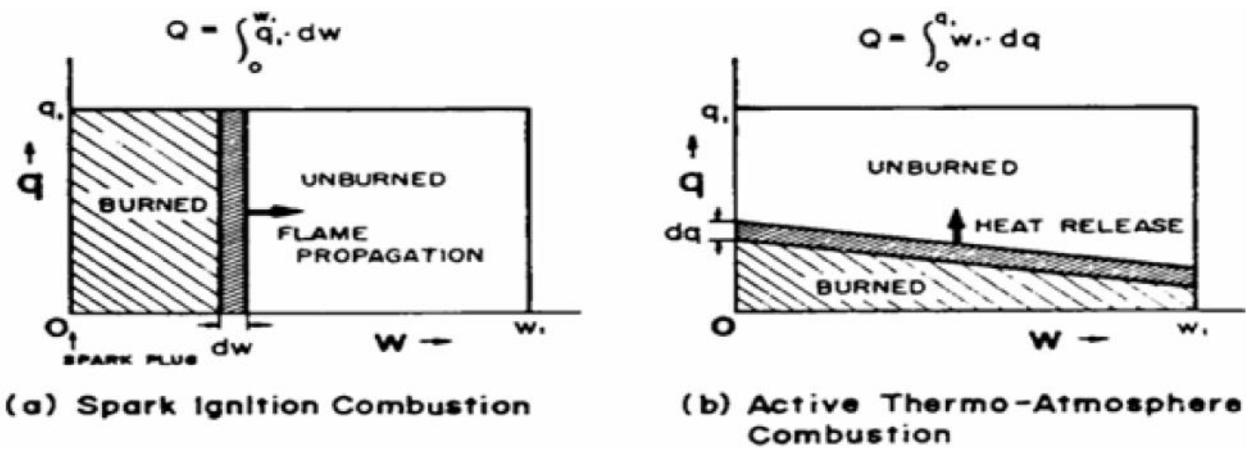


Figure 3: The Difference Between SI and HCCI Combustion Process, Q = Total Amount of Heat, q = Heat per Mass Unit, w = Mass



using engines affording visualization. In this figure, the portions shining white indicate combustion. It can be seen that, unlike the spark ignition combustion, the HCCI combustion occurs rapidly and throughout the combustion chamber.

Figure 3 shows the difference between (a) SI combustion, and (b) HCCI. In the SI engine we have three zones, a burnt zone, and an unburned zone and between them a thin reaction zone where the chemistry takes place. This reaction zone propagates through the combustion chamber and thus we have flame propagation. Even though the reactions are fast in the reaction zone, the combustion process will take some time as the zone must propagate from spark plug (zero mass) to the far liner wall (mass w_i). With the HCCI process the entire mass in the cylinder will react at once. The right part of Figure 3 shows HCCI, or as Onishi called it Active Thermo-Atmosphere Combustion, ATAC. We see that the entire mass is active but the reaction rate is low both locally and globally. This means that the combustion process will take some time even if all the charge is active. The total amount of heat released, Q, will be the same for both processes. It could be noted that the combustion process can have the same duration even though HCCI normally has a faster burn rate.

Since the mixture is lean, the maximum temperature, both locally and overall, becomes low compared to other engines, which effectively reduces NOx formation. However, at richer mixtures the combustion becomes too fast and knocking, or ringing, occurs. Therefore, if a higher load is desired, supercharging, or turbo charging is necessary. The load limit (without supercharging) is said to be either the engine structure capabilities (knocking limit) or NOx emissions. The problem with the HCCI engines is related to the lean mixtures, the fast combustion, and the high compression ratio (high engine efficiency) that causes the exhaust temperature to become quite low. This can make it difficult to get both turbo charging and oxidizing catalysts to work.

Despite advantages, HCCI engines produce high HC and CO emissions as the ignition timing and combustion duration is difficult to control. Therefore, the HCCI operating zone is limited between misfire and knocking. Lack of direct control over ignition initiation is one of the obstacles that need to be addressed.

In self-ignition combustion, the ignition timing varies with the temperature of the intake air, cooling water, and lubricating oil. Because the efficiency changes along with this variation, the ignition timing must be precisely controlled. Studies on HCCI engines have revealed that the load range over which HCCI engines can operate is limited by the risk of misfire, combustion instability, and engine knock. Furthermore, the higher pressure of gas within cylinders due to the higher compression ratio and more rapid combustion creates a need for engines with a higher withstand pressure.

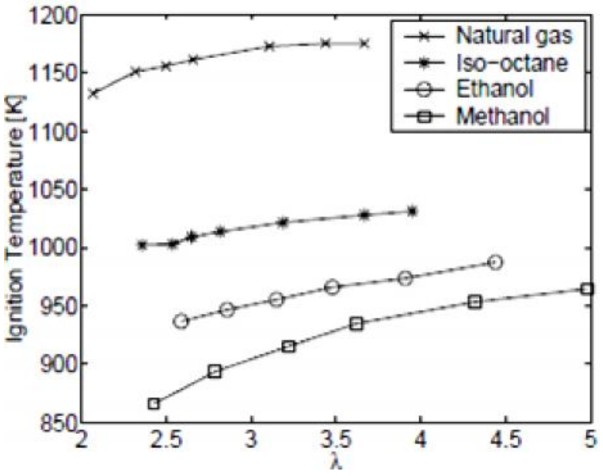
REQUIREMENTS FOR HCCI

The HCCI combustion process puts two major requirements on the conditions in the cylinder:

- The temperature after compression stroke should equal the auto-ignition temperature of the fuel/air mixture.
- The mixture should be diluted enough to give reasonable burn rate.

Figure 4 shows the auto-ignition temperature for a few fuels as a function of ^{a}. The auto-ignition temperature has some correlation with the fuels' resistance of knock in SI engines and thus the octane number. For iso-octane, the auto-ignition temperature is roughly 1000 K. This means that the temperature in the cylinder should be 1000 K at the end of the compression stroke where the reactions should start. This temperature can be reached in two ways, either the temperature in the cylinder at the start of

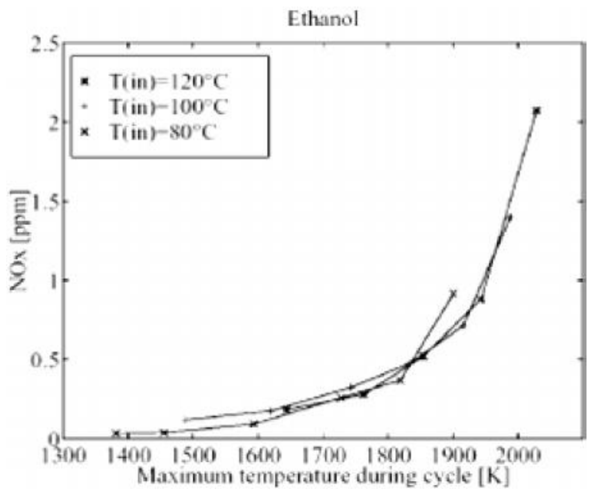
Figure 4: Ignition Temperature for a Few Fuels as a Function of Dilution



compression is controlled or the increase in temperature due to compression, i.e., compression ratio is controlled. It could be interesting to note that the auto-ignition temperature is a very weak function of air/fuel ratio. The change in auto-ignition temperature for iso-octane is only 50 K with a factor 2 change in ^{a}. Figure 4 also shows the normal rich and lean limits found with HCCI. With a too rich mixture the reactivity of the charge is too high. This means that the burn rate becomes extremely high with richer mixtures. If an HCCI engine is run too rich the entire charge can be consumed within a fraction of a crank angle. This gives rise to extreme pressure rise rates and hence mechanical stress and noise. With a high auto-ignition temperature like that of natural gas, it is also possible that formation of NOx can be the load limiting factor.

Figure 5 shows the NO formation as a function of maximum temperature. Very low emission levels are measured with ethanol. If the combustion starts at a higher temperature like with natural gas, the temperature after combustion will also be higher for a given amount of heat released. On the lean side, the temperature increase from the combustion is too low to have complete combustion. Partial oxidation of fuel to CO can occur at extremely lean mixtures; ^{a} above 14 has been tested. However, the oxidation of CO to CO_2 requires a temperature of 1400-1500 K. As a summary, HCCI is governed by three temperatures. We need to reach the auto-ignition temperature to get things started; the combustion should then increase the temperature to at least 1400 K to have good combustion efficiency but it should not be increased to more than 1800 K to prevent NO formation.

Figure 5: NOx as a Function Maximum Temperature Evaluated from the Pressure-Trace



EMISSIONS BEHAVIOUR

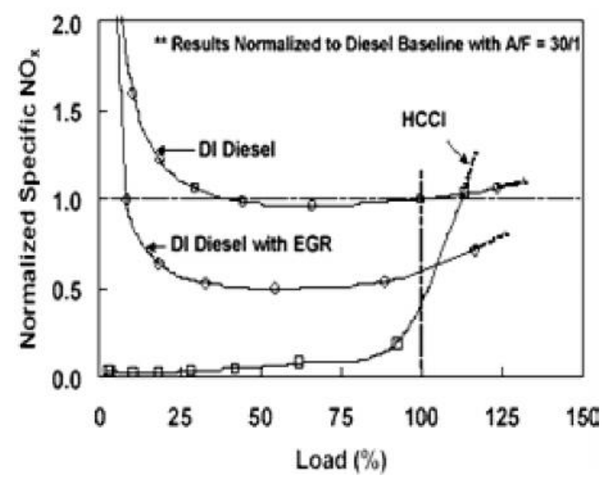
The main motivation for studying HCCI is its potential for significant reductions in exhaust emissions in comparison to conventional compression or spark-ignition combustion. A brief overview of the emissions characteristics from HCCI engines is provided in this section.

Oxides of Nitrogen (NOx)

Perhaps the single largest attraction of HCCI combustion is that it can reduce NOx emissions by 90-98% in comparison to conventional Diesel combustion (Gray & Ryan 1997; Hashizume et al 1998). The underlying mechanism responsible for this reduction in NOx emissions is the absence of high temperature regions within the combustion chamber. HCCI combustions occur at the global air-fuel ratio, which is typically quite lean, and at a temperature significantly below those encountered within the reaction zone in Diesel or Spark-ignition engines.

Figure 6 shows the predicted NOx emissions from HCCI combustion of Diesel fuel compared to a direct-injected Diesel engine (DI Diesel) and DI-Diesel with aggressive EGR levels. The compression ratio in all cases was 16:1.

Figure 6: Predicted NOx Emissions vs. Engine Load for Typical HCCI and DI Diesel Combustion



These results show that HCCI combustion can result in large NOx reductions at part engine load, but that the potential NOx advantage of HCCI combustion vs. DI-Diesel diminishes at higher equivalence ratios.

Particulate Matter

HCCI combustion has also been reported to produce low levels of smoke and PM emissions (Suzuki *et al.*, 1997; and Mase *et al.*, 1998). The mechanisms for these smoke reductions are not as well documented but it is thought that the absence of diffusion-limited combustion and localized fuel-rich regions discourages the formation of soot. One exception to this can occur when poor mixture preparation leads to liquid fuel deposition on the combustion chamber and localized fuel-rich regions of combustion.

Hydrocarbons (HC) and Carbon Monoxide (CO)

In contrast to NOx and PM emissions, HCCI combustion typically results in higher HC and CO emissions than conventional Diesel combustion (Suzuki *et al.*, 1997; and Christensen and Johamsson, 1998). One factor that contributes to these observed levels of HC and CO emissions is the low in-cylinder temperature due to the lean mixtures and/or high levels of EGR which are necessary for satisfactory HCCI operation. It is well known that reduced burned gas temperatures lead to decreased post-combustion oxidation rates within the cylinder (Roberts and Matthews, 1996) and increased levels of HC and CO in the exhaust. Mixture preparation is of great importance to HC emissions for HCCI combustion of liquid fuels; for it is well known that liquid fuel deposition on combustion chamber surfaces can result in dramatic increases in HC emissions (Stangimater *et al.*, 1999). This problem is exacerbated for heavy fuels such as Diesel.

EFFICIENCY

HCCI combustion is generally characterized by high heat-release rates, which can approximate the ideal Otto cycle when properly phased in relation to the engine cycle. The distributed low-temperature reactions and non-luminous combustion result in reduced heat rejection to the engine. Hence HCCI combustion is, in itself, conducive to high thermodynamic cycle efficiencies. HCCI fuel efficiencies comparable to those of conventional Diesel combustion at part load have been reported by several researchers (Aoyama *et al.*, 1996; Suzuki *et al.*, 1997; and Christensen and Johamsson, 1998).

CHALLENGES

HCCI combustion is achieved by controlling the temperature, pressure and composition of the air/fuel mixture so that it auto ignites near Top Dead Centre (TDC) as it is compressed by the piston. This mode of ignition is fundamentally more challenging than using a direct control mechanism such as a spark plug or fuel injector to dictate ignition timing as in SI and CIDI engines, respectively. While HCCI has been known for some twenty years, it is only with the recent advent of electronic engine controls that HCCI combustion can be considered for application to commercial engines.

There are a number of obstacles that must be overcome before the potential benefits of HCCI combustion can be fully realized in production applications. This section describes the main difficulties with this technology.

Controlling Ignition Timing Over a Range of Speeds and Loads

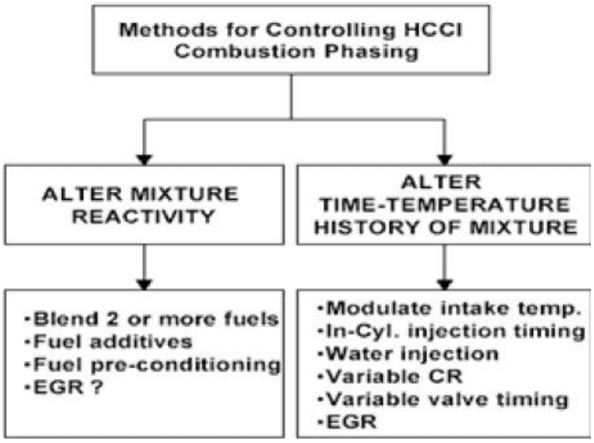
Expanding the controlled operation of an HCCI engine over a wide range of speeds and loads is probably the most difficult hurdle facing HCCI engines. Unlike in spark-ignition or conventional diesel engines, a direct method for controlling the start of combustion is not available. HCCI ignition is determined by the charge mixture composition and its temperature history (and to a lesser extent, its pressure history). Changing the power output of an HCCI engine requires a change in the fuelling rate and, hence, the charge mixture. As a result, the temperature history must be adjusted to maintain proper combustion timing. Similarly, changing the engine speed changes the amount of time for the auto ignition chemistry to occur relative to the piston motion. Again, the temperature history of the mixture must be adjusted to compensate. These control issues become particularly challenging during rapid transients.

Hence, combustion phasing of HCCI engines is affected by:

- Auto-ignition properties of fuel
- Fuel concentration
- Compression Ratio
- Heat transfer to the engine
- Intake temperature, Engine temperature and latent heat of vaporization of fuel
- Mixture homogeneity

Several approaches for controlling the combustion phasing have been attempted, but a fundamental distinction can be made between those methods attempting to control ht time-temperature history to which the mixture is exposed, and methods aimed at altering the propensity for auto-ignition of the mixture as illustrated in Figure 7.

Figure 7: Methods for Controlling HCCI Combustion Phasing



- Exhaust Gas Recirculation (EGR): It is the process of recycling exhaust gases and adding them to the intake air. With EGR it is possible to control temperature, mixture, pressure, and composition. In comparison to the other control methods, EGR is relatively simple, which is a great benefit. EGR can produce more power in an engine because more fuel could be pumped into the cylinder without spontaneous ignition due to the relative inertness of the emissions gas compared to air. It also could be used to control individual cylinder performance.
- Variable Compression Ratio (VCR): This could be achieved through a couple of different methods. One method would be to place a plunger within the cylinder head that could vary the compression ratio. Another option would be to have an opposed-piston design which would include variable phase shifting between the two crankshafts. Other possibilities exist as well but the key is to develop these in order to have excellent response time to handle transient situations. In order to study the Variable Compression Ratio (VCR) effect on the engine performance we could change the amount of compression for each cylinder and can study the effect. This could change the engine characteristics. By incorporating a device that could change cylinder volume rapidly, individual control of each cylinder could be conceivably achieved
- Variable Valve Timing (VVT): VVT allows variation of the compression ratio not through geometric means but through timing of the opening and closing of the intake and exhaust valves. In addition, this system can act as a more direct method of EGR by controlling the amount of trapped residual gases thus allowing temperature and mixture control. As VVT allow the variation of compression ratio not through geometric means but through timing of valve opening hence by changing the timing of the intake/exhaust valve changes the amount of combustible air in the cylinder thus controlling combustion strength and timing. This could be used to change the cylinder performances individually if a good control method is found. It should be noted that typical VVT schemes run cylinders with set timing, whereas these could need flexibility not only in timing but per cylinder.
- Fuel Mixtures and Additives: By using two fuels with varying combustion properties, combustion timing could be improved over a wide operating range. However a two fuel system brings about practical and infrastructural issues that could prevent commercialization. Experiments have shown that ozone as a fuel additive can greatly improve ignition even at very low concentrations add some more effort we will focus on three dimensional simulations of HCCI engine analysis and effects on fuel performance at part load and full load conditions. Mixing an additive into the fuel could change the combustion characteristics of a cylinder. Mixing a combustion retardant such as water would cause a delay in combustion, while mixing a combustion accelerant such as hydrogen gas would increase the speed of combustion. This could be controlled for each cylinder individually.

Some of the most promising include varying the amount of hot exhaust gas recirculation introduced into the incoming charge, using a VCR mechanism to alter TDC temperatures, and using VVT to change the effective compression ratio and/or the amount of hot residual retained in the cylinder. VCR and VVT are particularly attractive because their time response could be made sufficiently fast to handle rapid transients. Although these techniques have shown strong potential, they are not yet fully proven, and cost and reliability issues must be addressed.

Power Output

A current drawback of HCCI combustion is that it is presently limited in power output. Although HCCI engines have been demonstrated to operate well at low-to-medium loads, 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 (Christensen *et al.*, 1997; and Gray and Ryan, 1997). Fuels with inherently lower heat release rates like methane, can be combusted at lower A/F ratios and achieve higher specific engine outputs (Christensen *et al.*, 1997).

Given this apparent limitation in A/F ratio for HCCI combustion, power increases can be obtained by augmenting the air flow through the engine. Supercharging has been proven to be effective in this respect, and it also has a beneficial influence on reducing the heat release rate (Christensen *et al.*, 1998). Increasing the engine speed may also be an effective method of increasing HCCI power output but this approach is not well documented.

Another approach to overcome the limitations in power output has been to pursue the development of “dual-mode” engines that employ HCCI combustion at low loads and Diesel combustion or spark-ignition at high loads.

Cold-Start Capability

At cold start, the compressed-gas temperature in an HCCI engine will be reduced because the charge receives no preheating from the intake manifold and the compressed charge is rapidly cooled by heat transferred to the cold combustion chamber walls. Without some compensating mechanism, the low compressed-charge temperatures could prevent an HCCI engine from firing. Various mechanisms for cold-starting in HCCI mode have been proposed, such as using glow plugs, using a different fuel or fuel additive, and increasing the compression ratio using VCR or VVT.

Perhaps the most practical approach would be to start the engine in spark-ignition mode and transition to HCCI mode after warm-up. For engines equipped with VVT, it may be possible to make this warm-up period as short as a few fired cycles, since high levels of hot residual gases could be retained from previous spark-ignited cycles to induce HCCI combustion. Although solutions appear feasible, significant R&D will be required to advance these concepts and prepare them for production engines.

Hydrocarbon and Carbon Monoxide Emissions

HCCI engines have inherently low emissions of NOx and PM, but relatively high emissions of hydrocarbons (HC) and carbon monoxide

(CO). Some potential exists to mitigate these emissions at light load by using direct in-cylinder fuel injection to achieve appropriate partial-charge stratification. However, in most cases, controlling HC and CO emissions from HCCI engines will require exhaust emission control devices. Catalyst technology for HC and CO removal is well understood and has been standard equipment on automobiles for many years. However, the cooler exhaust temperatures of HCCI engines may increase catalyst light-off time and decrease average effectiveness. As a result, meeting future emission standards for HC and CO will likely require further development of oxidation catalysts for low-temperature exhaust streams. However, HC and CO emission control devices are simpler, more durable, and less dependent on scarce, expensive precious metals than are NOx and PM emission control devices. Thus, simultaneous chemical oxidation of HC and CO (in an HCCI engine) is much easier than simultaneous chemical reduction of NOx and oxidation of PM (in a CIDI engine).

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 a wide range of industries, which makes it a 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 blends of fuel mixture so that performance and efficiency of HCCI engines can be tested with different combinations of non conventional fuels. As the demand of conventional fuels is increasing, scope of research and experimentation in HCCI technology will increase only with time.

Of late, many companies have launched HCCI based automobiles in the market among which Mercedes F700, Volkswagen Touran, Opel Vectra, and Saturn Aura the prominent names.

CONCLUSION

The Homogeneous Charge Compression Ignition, HCCI, combustion process is an interesting alternative to the conventional Spark Ignition and Compression Ignition processes. 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 a 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.

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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