Homogeneous Charge Compression Ignition (HCCI) Engine

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ABSTRACT

In the context of environmental restrictions and sustainable development, pollution standards have become more and more stringent. The design of most fuel efficient and environmental friendly internal combustion engine so as to meet the future emission standards is currently one of the main goals of engine researchers. Homogeneous Charge Compression Ignition (HCCI) combustion has the potential to be highly efficient and to produce low emissions. HCCI engines can have efficiencies as high as compression-ignition direct-injection (CIDI) engines (an advanced version of the commonly known diesel engine), while producing ultra-low oxides of nitrogen (NOx) and particulate matter (PM) emissions. HCCI engines can operate on gasoline, diesel fuel, and most alternative fuels. 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. 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.

INTRODUCTION

Environmental protection is a huge growth market for the future. In the years ahead, “green” technologies that help improve energy efficiency or reduce emissions will be important growth. 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 have efficiencies as high as compression-ignition, direct-injection (CIDI) engines (an advanced version of the commonly known diesel engine), while producing ultra-low oxides of nitrogen (NOx) and particulate matter (PM) 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 engines might be commercialized in light-duty passenger vehicles and as much as a half-million barrels of primary oil per day may be saved.

HCCI is potentially applicable to both light and heavy-duty engines. Light-duty HCCI engines can run on gasoline and 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 impacting fuel-refining capability. 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.

In fact, HCCI technology could be scaled to virtually every size-class of transportation engines from small motorcycle to large ship engines. HCCI is also applicable to piston engines used outside the transportation sector such as those used for electrical power generation and pipeline pumping. HCCI engines are particularly well suited to series hybrid vehicle applications because the engine can be optimized for operation over a more limited range of speeds and loads compared to primary engines used with conventional vehicles. Use of HCCI engines in series hybrid vehicles could further leverage the benefits of HCCI to create highly fuel-efficient vehicles.

Japan and European countries have aggressive research and development (R&D) programs in HCCI, including both public- and private-sector components. Many of the leading HCCI developments to date have come from these countries. In fact, two engines are already in production in Japan that use HCCI during a portion of their operating range: Nissan is producing a light truck engine that uses intermittent HCCI operation and diesel fuel, and Honda is producing a 2-stroke cycle gasoline engine using HCCI for motorcycles. HCCI engines cannot be ignored. HCCI combustion is achieved by controlling the temperature, pressure, and composition of the fuel and air mixture so that it spontaneously ignites in the engine. This control system is fundamentally more challenging than using a spark plug or fuel injector to determine ignition timing as used in SI and CIDI engines, respectively. The recent advent of electronic engine controls has enabled consideration of HCCI combustion for application to commercial engines. Even so, several technical barriers must be overcome to make HCCI engines applicable to a wide range of vehicles and viable for high volume production. Significant challenges include:

- Controlling Ignition Timing and Burn Rate Over a Range of Engine Speeds and Loads
- Extending the Operating Range of HCCI to High Engine Loads
- Cold-Starts and transient response with HCCI Engines
- Minimizing Hydrocarbon and Carbon Monoxide Emissions

Controlling the operation of an HCCI engine over a wide range of speeds and loads is probably the most difficult hurdle facing HCCI engines. HCCI ignition is determined by the charge mixture composition, its time-temperature history, and to a lesser extent pressure. Several potential control methods have been proposed to control HCCI combustion: varying the amount of exhaust gas recirculation (EGR), using a variable compression ratio (VCR), and using variable valve timing (VVT) to change the effective compression ratio and/or the amount of hot exhaust gases retained in the cylinder. VCR and VVT technologies are particularly attractive because their time response could be made sufficiently fast to handle rapid transients (i.e., accelerations/decelerations). Although these technologies have shown strong potential, performance is not yet fully proven, and cost and reliability issues must be addressed.

Although HCCI engines have been demonstrated to operate well at low to medium loads, difficulties have been encountered at high-load conditions. The combustion process can become very rapid and intense causing unacceptable noise, potential engine damage, and eventually, unacceptable levels of NOx emissions. Preliminary research indicates the operating range can be extended significantly by partially stratifying the fuel/air/residual charge at high loads (mixture and/or temperature stratification). Several potential mechanisms exist for achieving partial charge stratification, including: in-cylinder fuel injection, water injection, varying the intake and in-cylinder mixing processes, and altering in-cylinder flows to vary heat transfer. The extent to which these techniques can extend the operating range, while preserving HCCI benefits, is currently unknown. Because of the difficulty of high-load operation, most initial concepts involve switching to traditional SI or CIDI combustion for operating conditions where HCCI operation is more difficult. This configuration allows the benefits of HCCI to be realized over a significant portion of the driving cycle but adds the complexity of switching the engine between operating modes.

The fundamental processes of HCCI combustion make cold-starts difficult without some compensating mechanism. 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. Spark-ignition may be the most viable approach to cold-start, though it adds cost and complexity.

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. However, regardless of the ability to minimize engine-out HC and CO emissions, controlling HC and CO emissions from HCCI engines will likely require use of an exhaust emission control device. Catalyst technology for HC and CO removal is well understood and has been standard equipment on gasoline-fueled automobiles for 25 years. In addition, reducing HC and CO emissions from HCCI engines is much easier than reducing NOx and PM emissions from CIDI engines. However, the cooler exhaust temperatures of HCCI engines may increase catalyst light-off time and decrease average effectiveness. Consequently, achieving stringent future emission standards for HC and CO will likely require some further development of oxidation catalysts for use with HCCI engines.

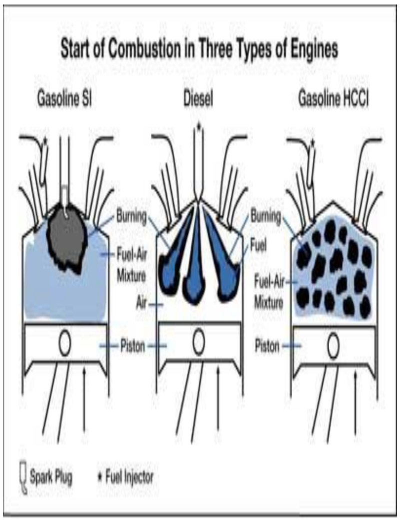

Figure:1 Homogeneous Charge Compression Ignition

What is HCCI?

HCCI is an alternative piston-engine combustion process that can provide efficiencies as high as compression-ignition, direct-injection (CIDI) engines (an advanced version of the commonly known diesel engine) while, unlike CIDI engines, producing ultra-low oxides of nitrogen (NOx) and particulate matter (PM) emissions. HCCI engines operate on the principle of having a dilute, premixed charge that reacts and burns volumetrically throughout the cylinder as it is compressed by the piston. In some regards, HCCI incorporates the best features of both spark ignition (SI) and compression ignition (CI), as shown in Figure 1 . As in an SI engine, the charge is well mixed, which minimizes particulate emissions, and as in a CIDI engine, the charge is compression ignited and has no throttling losses, which leads to high efficiency. However, unlike either of these conventional engines, the combustion occurs simultaneously throughout the volume rather than in a flame front. This important attribute of HCCI allows combustion to occur at much lower temperatures, dramatically reducing engine-out emissions of NOx.

Most engines employing HCCI to date have dual mode combustion systems in which traditional SI or CI combustion is used for operating conditions where HCCI operation is more difficult. Typically, the engine is cold-started as an SI or CIDI engine, then switched to HCCI mode for idle and low- to mid-load operation to obtain the benefits of HCCI in this regime, which comprises a large portion of typical automotive driving cycles. For high-load operation, the engine would again be switched to SI or CIDI operation. Research efforts are underway to extend the range of HCCI operation.

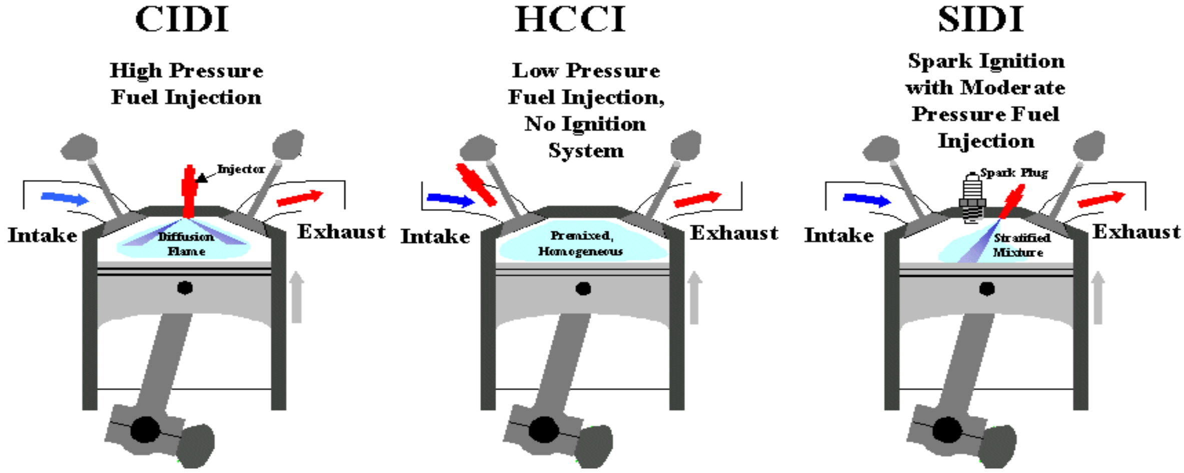

Figure: 2 HCCI (as most-typically envisioned) would use low-pressure fuel injection outside the cylinder, and no ignition system. If charge stratification is desired, it may be necessary to use in cylinder injection.

ADVANTAGES OF HCCI

The advantages of HCCI are numerous and depend on the combustion system to which it is compared. Relative to SI gasoline engines, HCCI engines are more efficient, approaching the efficiency of a CIDI engine. This improved efficiency results from three sources: the elimination of throttling losses, the use of high compression ratios (similar to a CIDI engine), and a shorter combustion duration (since it is not necessary for a flame to propagate across the cylinder). HCCI engines also have lower engine-out NOx than SI engines. Although three-way catalysts are adequate for removing NOx from current-technology SI engine exhaust, low NOx is an important advantage relative to spark-ignition, direct-injection (SIDI) technology, which is being considered for future SI engines.

Relative to CIDI engines, HCCI engines have substantially lower emissions of PM and NOx. (Emissions of PM and NOx are the major impediments to CIDI engines meeting future emissions standards and are the focus of extensive current research.) The low emissions of PM and NOx in HCCI engines are a result of the dilute homogeneous air and fuel mixture in addition to low combustion temperatures. The charge in an HCCI engine may be made dilute by being very lean, by stratification, by using exhaust gas recirculation (EGR), or some combination of these. Because flame propagation is not required, dilution levels can be much higher than the levels tolerated by either SI or CIDI engines. Combustion is induced throughout the charge volume by compression heating due to the piston motion, and it will occur in almost any fuel/air/exhaust-gas mixture once the 800 to 1100 K ignition temperature (depending on the type of fuel) is reached. In contrast, in typical CI engines, minimum flame temperatures are 1900 to 2100 K, high enough to make unacceptable levels of NOx. Additionally, the combustion duration in HCCI engines is much shorter than in CIDI engines since it is not limited by the rate of fuel/air mixing. This shorter combustion duration gives the HCCI engine an efficiency advantage. Finally, HCCI engines may be lower cost than CIDI engines since they would likely use lower-pressure fuel-injection equipment.

Another advantage of HCCI combustion is its fuel-flexibility. HCCI operation has been shown using a wide range of fuels. Gasoline is particularly well suited for HCCI operation. Highly efficient CIDI engines, on the other hand, cannot run on gasoline due to its low cetane number. HCCI engines might be commercialized in light-duty passenger vehicles as much as a half-million barrels of oil per day may be saved.

Tests have also shown that under optimized conditions HCCI combustion can be very repeatable, resulting in smooth engine operation. 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 potentially applicable to both automobile and heavy truck engines. In fact, it could be scaled to virtually every size-class of transportation engines from small motorcycle to large ship engines. HCCI is also applicable to piston engines used outside the transportation sector such as those used for electrical power generation and pipeline pumping.

CHALLENGES

HCCI combustion is achieved by controlling the temperature, pressure and composition of the air/fuel mixture so that it autoignites 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. Even so, several technical barriers must be overcome before HCCI engines will be viable for high-volume production and application to a wide range of vehicles. The following describes the more significant challenges for developing practical HCCI engines for transportation. Greater detail regarding these technical barriers, potential solutions, and the R&D needed to overcome them are provided in this section. Some of these issues could be mitigated or eliminated if the HCCI engine was used in a series hybrid-electric application, as discussed above.

1. 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. 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 fueling 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 autoignition 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.

Several potential control methods have been proposed to provide the compensation required for changes in speed and load. Some of the most promising include varying the amount of hot EGR 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.

2. Extending the Operating Range to High Loads

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. Preliminary research indicates the operating range can be extended significantly by partially stratifying the charge (temperature and mixture stratification) at high loads to stretch out the heat-release event. Several potential mechanisms exist for achieving partial charge stratification, including varying in-cylinder fuel injection, injecting water, varying the intake and in-cylinder mixing processes to obtain non-uniform fuel/air/residual mixtures, and altering cylinder flows to vary heat transfer. The extent to which these techniques can extend the operating range is currently unknown and R&D will be required. Because of the difficulty of high-load operation, most initial concepts involve switching to traditional SI or CI combustion for operating conditions where HCCI operation is more difficult. This dual mode operation provides the benefits of HCCI over a significant portion of the driving cycle but adds to the complexity by switching the engine between operating modes.

3. 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.

4. 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). In addition, HC and CO emission control devices are simpler, more durable, and less dependent on scarce, expensive precious metals.

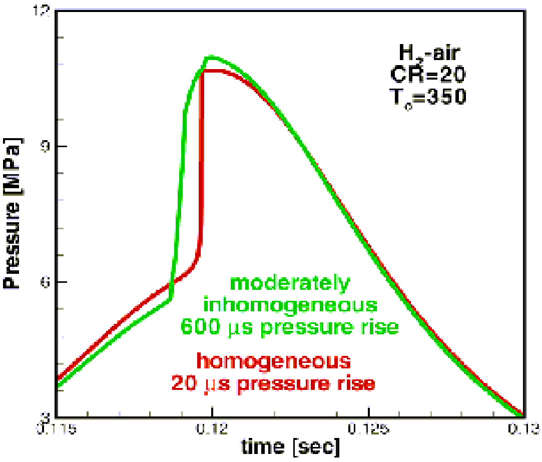

Figure: 3 This pressure trace shows the differences between completely homogeneous mixtures and mixtures with small-scale inhomogeneities.

RECENT DEVELOPMENTS IN HCCI

There has been an exhaustive literature search of worldwide R&D on HCCI. Table 1 shows a summary of recent developments in HCCI technology. In addition, Ford, General Motors (GM), and Cummins Engine Company have been performing research on HCCI combustion.

Ford motor company has an active research program in HCCI combustion. Researchers are using optical diagnostics in single-cylinder engines to explore viable HCCI operating regimes and to investigate methods of combustion control. In addition, chemical kinetic and cycle simulation models are being applied to better understand the fundamentals of the HCCI process and to explore methods of implementing HCCI technology. GM at a research level, is evaluating the potential for incorporating HCCI combustion into engine systems. This work includes assessing the strengths and weaknesses of HCCI operation relative to other advanced concepts, assessing how best to integrate HCCI combustion into a viable powertrain, and the development of appropriate modeling tools. Work is focused on fuels, combustion control, combustion modeling, and mode transitioning between HCCI and traditional SI or CI combustion. GM is also supporting HCCI work at the university level.

Cummins has been researching HCCI for almost 15 years. Industrial engines run in-house using HCCI combustion of natural gas have achieved remarkable emission and efficiency results. However, Cummins has found that it is quite challenging to control the combustion phasing over a real-world operating envelope including variations in ambient conditions, fuel quality variation, speed and load. Because the new diesel emissions targets are beyond the capability of conventional diesel engines, Cummins is investigating all options, including HCCI, as part of their design palette and future engine strategy.

CONCLUSION

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.

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