Advanced combustion engines for low emissions and high efficiency

CONCAWE literature review on HCCI combustion technologies

European road traffic has increased dramatically over the past several decades and the same growth is now being seen in many other parts of the world. This increased demand has brought new challenges for the vehicle and fuel industries, especially the need to lower exhaust emissions from vehicles while improving fuel economy. Fortunately, improvements in engine and aftertreatment technologies are dramatically reducing emissions and cleaner fuels are enabling their performance.

While vehicle emissions continue to fall, attention is increasingly focused on vehicle efficiency and fuel consumption in order to address new concerns over future energy supplies and greenhouse gas (GHG) emissions. Among the technologies able to deliver significant improvements, alternative power plants, such as fuel cells, still face many research and development challenges and most projections show them making relatively little impact on the vehicle market before at least 2030. Hybrid electric vehicles, including plug-in hybrids, seem more likely to contribute although cost and performance relative to more conventional options may limit their penetration. For this reason, internal combustion engines (ICEs) are expected to continue to provide almost all of the engine needs for road vehicles in the near future.

Light-duty vehicles, powered by advanced ICEs, are evolving rapidly to respond to these new challenges. In the search for lower emissions, improved performance, and better fuel consumption, research and development is concentrating on new and advanced combustion concepts. Because these concepts combine the best features of both spark-ignition and compression-ignition engines, the optimum fuel characteristics could be quite different from those needed by today's conventional gasoline and diesel engines.

CONCAWE's literature review

In order to better understand the state of development of these new concepts and the potential implications for future fuels, CONCAWE recently completed a review of the rapidly expanding body of technical literature[1]. This review focused on two advanced combustion schemes generically known as Homogeneous Charge Compression Ignition (HCCI) for diesel engines and Controlled Auto-Ignition (CAI) for gasoline engines. Highlights from this literature review are reported here and address three important questions:

- What is HCCI/CAI?
- What engine improvements will enable HCCI/CAI performance?
- What fuel properties will influence HCCI/CAI performance?

The HCCI/CAI concept

Broadly speaking, HCCI and CAI describe advanced combustion concepts in which the fuel and air are premixed, either outside the engine cylinder or by early injection of fuel into the cylinder. After injection, the fuel-air mixture is compressed to the point where ignition occurs without the aid of a spark or glow plug. Combustion takes place at relatively low temperatures with a rapid and complete heat release. Higher levels of cooled exhaust gas recirculation (EGR) are often used to lower the combustion temperature even further and reduce the oxygen content of the combustion air. This approach helps to simultaneously reduce the formation of soot and nitrogen oxides (NO_x) from the combustion process, breaking the so-called NO_x/PM trade-off that is typical of conventional diesel engines (Figure 1).

The search for practical systems has inevitably led to many new acronyms describing different variations of engine hardware and fuel injection strategies, some of

[1] *CONCAWE Report 4/08:* Advanced Combustion for Low Emissions and High Efficiency: a Literature Review of HCCI Combustion Concepts.

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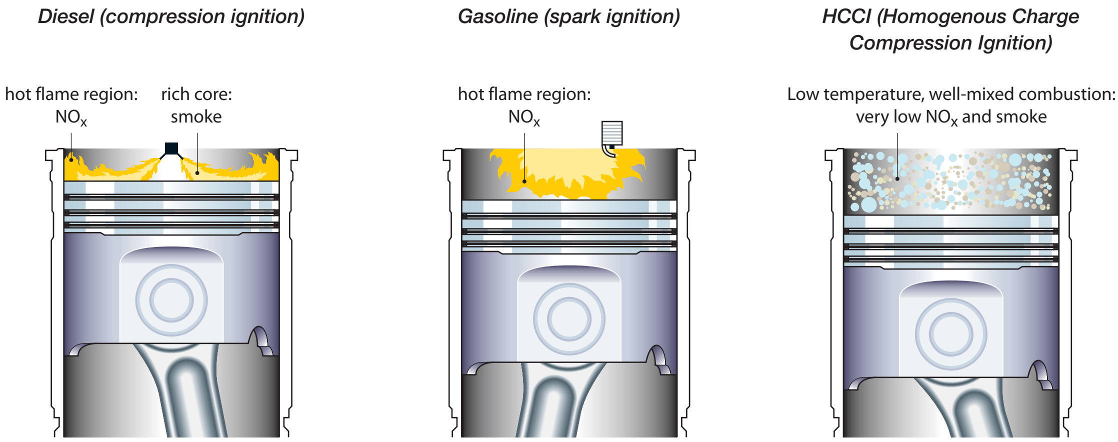
Figure 1 HCCI combustion is a cross between compression-ignition and spark-ignition approaches



Some examples of advanced combustion concepts	
ACCP	Advanced Common Rail Combustion Process
CAI	Controlled Auto-Ignition
HPCC	Highly Premixed Cool Combustion
HCCI	Homogeneous Charge Compression Ignition
HCLI	Homogeneous Charge Late Injection
HPLI	Highly Premixed Late Injection
NADI™	Narrow Angle Direct Injection
PCCI	Premixed Charge Compression Ignition
pHCCI	Partial HCCI

which are shown in the box above. To simplify this discussion, the term 'HCCI' is used in this review to describe all of these advanced combustion concepts that seek to provide:

- low engine-out emissions (CO, HC, NO_x, PM etc);
- low fuel consumption (comparable to, or better than, today's compression-ignition engines); and
- stable engine operation over a wide load range.

The engine challenge

'True' HCCI combustion involves injecting fuel into the combustion chamber very early in the engine cycle so that there is sufficient time to achieve thorough fuel-air mixing. Although this achieves good dispersion of the fuel in air, it also makes it more difficult to control the ignition process. Most researchers now favour injecting fuel later in the engine cycle in order to retain most of the benefits of HCCI combustion while achieving better control of the auto-ignition process.

HCCI combustion can be achieved most easily at lower engine loads and becomes increasingly difficult as the engine power increases. For this reason, early production engines are expected to be 'part-time' HCCI engines, reverting to conventional diesel or gasoline operation at higher load conditions. As long as this is the norm, these engines will need fuels similar to today's and will cope with the fuel's properties as best they can under part-time HCCI conditions.

Based on the technical literature, good performance has been demonstrated under test bench conditions, and under steady state speeds and loads. Extending this performance to transient conditions remains a significant challenge and engine designers face a number of hurdles to develop robust engines. Here are a few examples:

- In conventional engines, the start of combustion is controlled by the spark plug in spark-ignition engines or by fuel injection in compression-ignition engines. In HCCI combustion, however, these control mechanisms are not available. In fact, the temperature and pressure at the desired ignition timing determine the start of combustion and these are governed by conditions that are defined well before the combustion process actually begins. For example, the temperature of the intake air mixture, the composition of the fuel-air mixture, the compression ratio, and other factors determine when combustion starts and how rapidly it progresses. Controlling the combustion process is therefore challenging, particularly for engines where operating conditions can vary quite rapidly on a second-by-second basis.

- In order to achieve the benefits described earlier, HCCI combustion must retain good thermal efficiency through rapid and complete combustion. If not properly controlled, however, combustion can be too rapid, producing, in the worst case, explosive heat release within the cylinder. This not only produces very high engine noise levels but can also lead to engine damage, especially at high engine loads.
- Like diesel engines, HCCI engines are throttle-less and engine power is varied by increasing or decreasing the amount of fuel injected. Complete combustion can be difficult to achieve, especially at the very lean air-fuel ratios or high EGR levels needed for light load operation. While HCCI combustion can produce very low levels of soot and NO_x at these conditions, significant increases in HC and CO emissions can occur at the same time and oxidation catalysts will probably be needed to reduce these to acceptable levels.

Because of these problems, an engine that uses HCCI combustion throughout the entire load range seems to be some way down the road. In the near term we are more likely to see engines that use HCCI at lower loads and then revert to conventional operation at higher loads.

Diesel or gasoline engine?

Since HCCI combustion shares characteristics of diesel and gasoline combustion, practical advanced combustion designs begin from either a compression-ignition or a spark-ignition engine platform.

Starting from a diesel engine, HCCI helps to reduce engine-out PM and NO_x emissions, especially under light and intermediate load conditions. Even if this does not completely eliminate the need for PM filters and NO_x traps, the cost and complexity of these aftertreatment devices could be reduced if the engine-out emissions are low enough over a large enough portion of the driving cycle. The diesel engine also provides a good platform for advanced engine developments because of its robust construction and use of high pressure fuel injection which aids fuel dispersion.

Starting from a gasoline engine platform where exhaust emissions are already very low, HCCI is expected to improve fuel consumption. Reductions in fuel consumption have been demonstrated at low loads but the effects are reduced over driving cycles that emphasise higher speeds and loads, such as the New European Driving Cycle (NEDC). Gasoline HCCI must also compete with other less expensive developments in conventional gasoline engines, such as engine downsizing, that offer similar improvements. For gasoline CAI to win over these alternatives, the relative cost of engine hardware and improvements in fuel consumption could be the determining factors.

If HCCI operation can only be used at part load conditions, the benefits will be limited to the load conditions where it can be effectively and routinely used. There is also a risk that, whilst advanced combustion vehicles may be able to meet emissions limits over the regulated cycles, this may be at the price of higher emissions outside the cycle limits or during transient operation.

On the other hand, part-time HCCI offers a way for advanced technology to be introduced progressively into otherwise conventional gasoline and diesel engines. Investments in some hardware improvements seem likely to enhance even conventional engine performance in the shorter term and enable HCCI operation in the longer term. This provides a path for gradual expansion of the speed and load range for HCCI combustion as engineering experience and innovation develop.

At the current stage of development, diesel engines seem more likely than gasoline engines to provide a basis for full-time HCCI since they provide high fuel injection pressures, large amounts of EGR, and high turbocharger boost that are not readily available on gasoline engines.

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Much more work is needed, however, to turn current research results into practical engines that can use HCCI combustion throughout the operating range. Increasing the maximum power for HCCI remains a significant challenge and cycle-by-cycle engine control systems using combustion pressure sensors (called Closed Loop Combustion Control) will be needed in order to help the engine management system respond to rapidly changing conditions.

While engines having some of these capabilities are likely to be introduced over the next few years, a practical and robust full-time HCCI engine remains a long-term objective and seems unlikely to be commercialized within the next decade. Continuous improvements in conventional engine technology could also surpass the performance and cost benefits of full-time HCCI engines in the meantime.

The influence of fuel properties

HCCI engines rely on the right fuel-air mixture conditions to start and sustain combustion. Without an ignition source, the engine must be closely matched to the characteristics of the injected fuel and respond quickly to changing speed and load conditions. On the test bench, HCCI operation has been achieved with a wide range of fuels but the preferred fuel for advanced combustion is still an open question. Some researchers suggest that completely new fuels or even dual-fuelling will be needed to successfully achieve HCCI operation. Whether these are practical options depends on whether HCCI operation can be sustained up to full load conditions. If an HCCI engine must revert to conventional diesel or gasoline operation at high loads, then the fuels will also need to retain the essential characteristics of diesel or gasoline.

Previous studies have suggested that three fuel properties are especially important to promote HCCI combustion:

- longer ignition delays—to lengthen the time available to achieve fuel-air mixing after fuel injection;
- higher volatility—to reduce the time needed to achieve fuel-air mixing before auto-ignition occurs; and
- fuel composition—to promote combustion and reduce engine-out emissions.

The importance of the fuel's ignition delay depends on the starting point for the combustion concept. Since gasoline engines are designed to avoid uncontrolled auto-ignition, measures are needed to encourage gasoline-like fuels to auto-ignite under controlled conditions through, for example, higher intake air temperatures, higher compression ratios, or lower octane fuels. If the starting point is a diesel engine, the problem is reversed and ways must be found to slow down the auto-ignition process. Practical measures to achieve this include lower compression ratios, lower intake air temperatures, higher EGR, or lower cetane levels compared to today's fuels.

Many HCCI studies have studied fuels in the gasoline-diesel boiling range. Ignition quality has played a prominent role in most of these studies since it is a key factor in controlling the degree of mixing before combustion starts. Although HCCI performance has been demonstrated with a wide range of fuels, it seems clear that the current European diesel and gasoline grades are not the ideal choice for full-time HCCI. High cetane number diesel fuels have ignition delays that are too short while high octane number gasolines are too resistant to auto-ignition.

Lower cetane numbers then make it easier to achieve HCCI combustion and some researchers suggest that cetane numbers should be in the 40–45 range. Others propose more radical changes, for example, using gasolines having cetane numbers below 35. HCCI engines could potentially utilise gasoline components that are already in the marketplace but only if HCCI combustion could be sustained throughout the whole load range or the engine reverted to spark-ignition at higher loads.

The second fuel property influencing mixture formation is fuel volatility. If the objective is to create a more homogeneous fuel-air mixture in a diesel engine, then fuels with a higher volatility are expected to promote rapid evaporation and mixing. For this reason, the successful performance of gasoline fuels in HCCI engines is not very surprising.

The evidence is mixed, however, on the importance of fuel volatility compared to ignition delay. High pressure fuel injection systems already achieve good dispersion of diesel fuels and can deliver a high degree of mixing if the ignition delay is long enough. In fact, a completely homogeneous mixture is now seen as rather undesirable because it gives no effective means to control the timing of the combustion event. For this reason, research is increasingly focused on intentionally introducing some degree of fuel-air inhomogeneity. Higher volatility should improve mixture formation but ignition quality seems to be much more important.

The third fuel property is molecular composition, especially the fuel's aromatics content. HCCI combustion has now been demonstrated on a wide range of fuel compositions and there seems to be little evidence that molecular composition is an important factor in sustaining combustion, except through its impact on ignition delay.

The literature contains many studies of HCCI combustion using alternative fuels such as ethanol, DME or natural gas. When used as neat fuels, none of these alternatives seem to offer significant advantages compared with fuels in the gasoline/diesel range. Natural gas is difficult to ignite while ethanol shows advantages in some areas and problems in others. Radical fuel changes can only be considered if full-time HCCI is feasible.

With the trend toward greater use of biofuels, a more meaningful question is whether the presence of biodiesel or ethanol in a fuel blend is likely to cause any additional problems for HCCI combustion. Current evidence suggests that low-level biofuel blends present no new problems, but more work will be needed in this area as the engine technology moves toward commercialization.

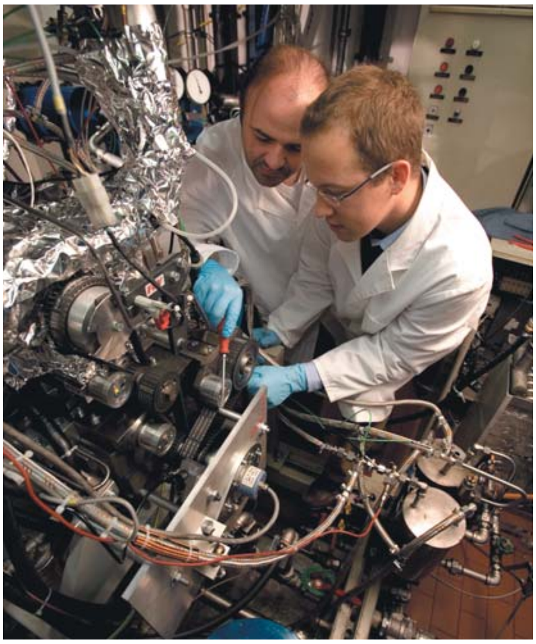
Based on our literature review, significant progress has clearly been made in the development of advanced combustion engines but much more work is needed before full-time HCCI becomes a commercial reality. At the same time, more work is also needed to determine the influence of fuel properties on advanced combustion performance.

CONCAWE's HCCI test programme

Although HCCI is a promising new technology, it is not yet possible to predict precisely how it will develop. For this reason, CONCAWE has completed an HCCI engine test programme together with FEV Motorentechnik in Aachen, Germany.

In this programme, a single-cylinder diesel engine (see photograph), benchmarked for Euro 6 emissions, has been used to investigate what HCCI performance can be achieved by different engine hardware configurations and by changes in fuel properties. The basic engine hardware was enhanced through stepwise changes that included a lower compression ratio, higher maximum cylinder peak pressure and rail pressure, enhanced swirl inside the combustion chamber, adjustment of fuel injection timing and intensified EGR. After this work was completed, a broad range of fuels was evaluated on an optimized engine configuration to study the influence of ignition delay, volatility, and molecular composition on engine-out emissions, performance and noise.

This programme is providing further insights on the relative importance of engine hardware and fuel properties for HCCI combustion performance. The results of this research will be reported in an upcoming CONCAWE *Review*.



CONCAWE is investigating the influence of engine hardware and fuel properties on advanced combustion at FEV's facilities in Germany.