INTRODUCTION

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. However, the IC engine is certainly not the best apparatus in every aspect but seems to be a good compromise overall. It is possible to further develop the IC engine to be better in some property but this is usually at the “cost” of another. The four-stroke internal combustion engine has had the same operating principle and materials for more than 130 years but still there are many areas left for improvement. As the engine type of choice for transportation it relies heavily on the availability of a suitable energy source. This has so far been met by the vast amount of oil that has been available. The demand for reduced fuel consumption and increased efficiency becomes more important when the fuel prices are rising. Lately the green house effect has set new challenges to further increase the efficiency of the internal combustion engine. Increased environmental concern has focused more and more on the released exhaust pollutants from engines.

Over the past decade, numerous studies have been conducted to improve engine performance and reduce exhaust emissions. Although there have been advances in both areas, still more research needs to be done in order to meet the strict upcoming emission regulations [Christensen et al., 2001]. New engine applicable technology emerges continuously that, if or when economically sensible, can provide improvements in some or several aspects without cost in others. However, the demands are constantly increasing; less emissions, lower fuel consumption, more power and lower costs. A continuous development is always required. There are many alternatives being researched to improve the engine-out emission further. An alternative combustion process that has received considerable interest in recent times due to lower emissions is the homogeneous charge compression ignition (HCCI) [Christensen et al., 2000].

Before describing HCCI engines, the limitation of spark ignition (SI) and compression ignition (CI) engines is discussed to establish a baseline and context for HCCI. The diesel engine has through its high compression ratio a very good thermal efficiency but due to the combustion principle (diffusion flame) it produces lots of nitrogen oxide (NOx) emissions. In addition, high peak pressures and soot formation limit the diesel engine load. The ignition principle is self-ignition and a high ignitability is wanted in order to get well controlled combustion timing. The ignitability is measured by the cetane number (CN) of the fuel. The major emissions of concern from the diesel engine are, besides CO₂, NOx and soot particulates. It is possible to use soot traps that collect a major part of the particulates but the traps have to be cleaned somehow. One way is to burn off the trapped particulates by temporarily increasing the temperature in the trap by using additional fuel injection during the exhaust stroke or even upstream the trap. To better succeed with this catalytic material can be used in the trap. It is more difficult with the NOx emissions because of the idea is to convert them into N₂. This is very difficult to do in diesel exhaust gases because the high amount of oxygen present. De NOx catalysts exist but are in general very sensitive to sulfur, and most diesel engine fuels contain some amounts of sulfur. Technology that uses a reducing media, like urea or ammonia has also been tested but it then requires “refueling” in order to work properly.

The SI engine uses a premix of fuel and air and it utilizes a spark plug (forced ignition) that sets of premixed turbulent flame combustion. This combustion principle makes it sensitive to self-ignition, “knocking”, which can result in structural damage, mainly to the piston. This phenomenon limits the compression ratio of the SI engine, which in turn limits the thermal efficiency. The fuels for the SI engines have a certain degree of knocking resistance, measured by the octane number (ON) of the fuel.

The SI engine has through the lower compression ratio a possibility to use higher rpm’s in order to get high specific power because the pressures are limited, thus a more lightweight design can
be used that allows higher rpm’s. Load control is achieved by throttling which means that the inlet pressure, and hence the air mass flow through the engine, is controlled by a restriction, usually a butterfly valve. This forces the engine to work like a compressor at part load, which also reduces efficiency. In car applications, the major operating point of the engine is low to medium load, which means that the overall efficiency becomes quite low. For the diesel engine, it is almost the opposite situation. This has contributed to an increase of the number of diesel-propelled cars.

To overcome the shortcoming of diesel engine and SI engine there is a need to find a combination of the diesel engine and the spark ignited engine that only inherit the good properties of the diesel and SI engine i.e. efficiency like a diesel engine and exhaust emissions that are as clean as from the SI engine, or at least possible to after-treat to the same level. This is quite difficult and there have been very few attempts that have reached any commercial success. There are two such concepts that are worth to be mentioned: lean burn SI engines with either homogeneous mixtures or stratified charge.

**Homogeneous Charge Compression Ignition (HCCI) is a new combustion concept.**

The Homogeneous Charge Compression Ignition (HCCI) engine is often described as a hybrid between the spark ignition engine and the diesel engine. 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 NO\textsubscript{X} 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.

![HCCI engine versus traditional engines](image)

**Figure:1 HCCI engine versus traditional engines [Heywood et al., 1988].**

The fundamental idea of HCCI is using a very lean fuel/air mixture in order to achieve low emissions of nitric oxides and high efficiency. Its operation can be described as a combination of a SI engine and a DICI engine. A homogeneous charge is prepared in the intake manifold; fuel and air are mixed before the intake stroke of the engine - just like in a SI engine. After the intake stroke, valves are closed and the onset of combustion is governed by a compression of the pre-mixed charge - Compression Ignition, the same operation as in CI engines.

The emissions from the HCCI engine are mainly hydrocarbons (HC) caused by incomplete combustion and quenching due to wall effects. HC emissions are in general considered more treatable than NO\textsubscript{x} emissions.

Despite advantages, there are a few challenges to practical HCCI engine implementations. One such challenge is the limited operating range of current HCCI engines. The auto-ignited combustion of a homogeneous charge is violent, leading to a rapid increase in cylinder pressure. When the mass of fuel combusted per cycle increases, the rate of pressure rise increases and can exceed the mechanical limits of the engine. Thus, compared to their SI and Diesel counterparts, HCCI engines suffer from low power densities. HC and CO emissions are another challenge. The lean operation prevents
modern catalytic exhaust after treatment though the NOx emissions are low and may not require after treatment, the hydrocarbon (HC) and carbon monoxide (CO) emissions may be an issue.

Controlling the combustion timing in an HCCI engine is a significant challenge. Unlike SI and Diesel engines, HCCI engines lack direct in-cylinder mechanisms for controlling the combustion timing. In an SI engine, the combustion event is initiated by the spark timing. The injection timing of Diesel fuel is used to control the combustion timing in a Diesel engine. The HCCI engine does not have spark plugs and the fuel is typically premixed and port injected during the intake stroke. Being able to automatically adjust the combustion timing to achieve peak performance and avoid misfire is a prerequisite to any practical HCCI engine implementation. If combustion occurs too early, efficiency suffers and engine damage can occur. If combustion occurs too late, the risk of misfire increases. Like Diesel engines, HCCI engines typically run lean, the air-fuel ratio is allowed to fluctuate, and the fueling affects the power. Sensing when combustion occurs is another challenge.

Nowadays R&D is carried out to develop a fuel delivery system because it is a key enabling technology to overcome the challenge of maintaining proper ignition timing, smooth combustion rates, and low emissions over the operating range of the engine. Various types of fuel systems have been proposed including port fuel injectors, DI fuel injectors similar to those designed for SI engines, DI diesel engine injectors, and combinations of these injectors. Each type has advantages for different operating regimes and fuel types.

For diesel fuel, the type of injector required depends on the strategy selected for fuel-air mixing and combustion. This is the most promising approach. For this approach, an injector based on a DI diesel injector would be needed. However, modifications would likely be required to achieve the very high mixing rates necessary for HCCI-like combustion.

For gasoline-type fuels, DI injectors for SI engines appear attractive. However, as HCCI research evolves it may indicate that changes in these injectors are required to meet the needs of HCCI engines. For example, partial charge stratification appears to be an attractive method for controlling the combustion rate at high loads and for reducing the HC and CO emissions at light loads. However, a different type of stratification would be required for each of these cases. Achieving the desired stratification under all operating conditions would likely require specialized HCCI injectors with spray characteristics different from those of current DI gasoline injectors. R&D will be required to adapt existing injectors or to develop advanced injectors that provide the spray characteristics desired for HCCI.

HCCI engine modeling, control, and combustion sensing are the focus of this synopsis, and are thoroughly addressed for 4-cylinder 4-stroke diesel and other alternative fuels for HCCI engines.