New generation combustion Concepts related research for clean environment

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1. Introduction

There are two different perspectives on the use of combustion engines: some people see in terms of advantages like mobility while others associate with large scale consumption of limited fossil-fuel reserves and production of exhaust gases that harm both the environment and our health. Regardless of one's perspective, it seems reasonable to expect that the number of vehicles will rise in future, especially on account of the rapid economic development. Furthermore, trends for passenger cars indicate that vehicle weight and size are also likely to increase, together with the power requirements of the growing number of electronic devices on-board. All of these factors will increase fuel consumption; hence world-wide fuel consumption and emissions can be realistically reduced only if an alternative for IC engine is developed with characteristics significantly better than those of the present engines. Ideally, such an alternative should not be powered on fossil fuels, emit no harmful products and have a better efficiency.

Theoretically "fuel cell" concept looks a very promising alternative. Unfortunately, however, large-scale introduction of this propulsion technology is expected to take another twenty years or so, mainly due to high costs, problems with on-board hydrogen generation/ storage and the lack of hydrogen infrastructure. Furthermore, the well-to-wheel efficiency of fuel cell power-trains with all the necessary auxiliary equipments is estimated to be similar, or even worse than that of optimized Diesel engines [1, 2]. This solution is sustainable if hydrogen is produced from purely renewable sources. Truly clean fuel cell technology would have to be based on renewable primary energy source, such as nuclear, wind or solar energy. However, with present technological standards in the renewable energy field, it is far from realistic to believe that a substantial portion of the fossil fuel used for vehicle propulsion could be replaced by sustainable alternatives in the near future.

Recent decades have seen impressive evolutionary steps in the development of the IC engine: fuel consumption and emissions have been substantially decreased, while power output has been raised, mainly due to the application of new technologies, such as the three-way catalyst and improved engine management. Furthermore, other innovative systems and approaches with a wide range of features have recently been introduced or are expected to be applied soon, including: flexible valve operation; cylinder de-activation; cycle-to-cycle, model-based engine control systems; and direct-injection of fuel. Bearing these advances in mind, together with the strict legislation on vehicle emissions that is to be applied in many countries, it seems reasonable to expect future reciprocating engines to be considerably cleaner and to have better fuel economy than current engines.

Engines and fuel for transportation as well as off-road applications are facing double challenge. First, to bring the local pollution to a level mandated by most stringent city air quality standards, and second to reduce CO_2 emissions in order to minimize the global warming threat [3]. These goals stimulate new developments both of conventional and alternative engines and fuel technology as illustrated by figure 1.

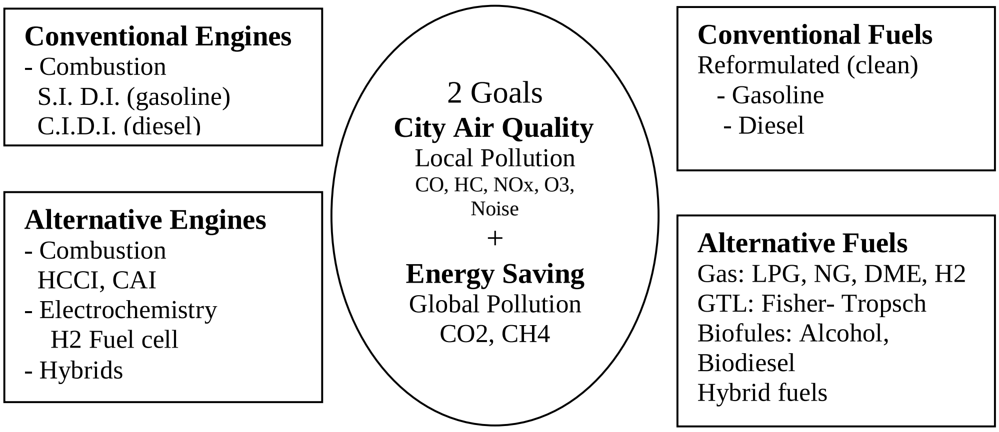

Figure1. Overview of Engines and fuel Technologies for future environmental goals

Engine Research Laboratory (ERL), IIT Kanpur is focussing on investigation of new combustion concepts such as HCCI and alternative fuels for transportation engines.

2. Motivation for HCCI combustion research

Apart from it producing much CO2, the modern conventional SI engine fitted with a three-way catalyst can be regarded as a very clean engine, but it suffers from poor part load efficiency. In other terms, low efficiency means high fuel consumption, resulting in high levels of CO_2. Low part load efficiency of the SI engine is mainly due to the throttling of the inlet, which leads to pumping losses, or in other words, much power is needed for gas exchange. Engines in passenger cars operate at light- and part load conditions most of the time. For some shorter periods of time, during passing and acceleration, they run at high loads, but they seldom run at high loads for long periods. This means that the overall efficiency at normal driving conditions becomes very low.

The Diesel engine has much higher part load efficiency than the SI engine, but it struggles with smoke and NOx problems. Smoke (soot) is mainly formed in the fuel rich regions and NOx in the hot stoichiometric regions. Due to these mechanisms, it is difficult to reduce both smoke and NOx simultaneously through combustion improvement. Today's exhaust gas after-treatment systems for Diesel engines are quite complex and expensive.

It would be desirable to have an engine with efficiency like a Diesel engine and with emission characteristics like a conventional SI engine fitted with a three-way catalyst. This can be achieved with a HCCI engine. The HCCI engine has much higher part load efficiency than the SI engine. Compared to the Diesel engine, it has lesser problem with NOx and soot formation, due to the use of a homogeneous charge. In summary, the HCCI engine beats the SI engine regarding the efficiency and the diesel engine in the emission area. The HCCI engine has, though, problems with high emissions of unburned hydrocarbons. However, there is large potential for taking care of the unburned hydrocarbons with a simple oxidizing catalyst, since there will be enough oxygen present in the exhaust gases. The low the exhaust temperature can, though, be a problem. Another drawback with the HCCI concept is the lack of a direct control of the ignition timing.

3. HCCI combustion Concept

The HCCI can be understood as a hybrid between SI and CI engines. HCCI means that the fuel and air should be mixed homogeneously before combustion starts and the mixture is auto-ignited due to increase in temperature at the end of the compression stroke. Thus HCCI is similar to SI in the sense that both engines use a premixed charge and HCCI is similar to CI as both rely on auto-ignition for combustion initiation. However, the combustion process is totally different for the three types. The HCCI combustion process is shown in Figure 2.

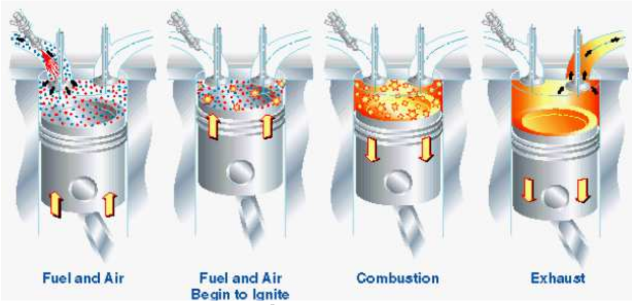

Figure 2: Homogeneous charge compression ignition processes [4]

The principle of HCCI combustion consists of (a) Preparing a highly diluted air/fuel mixture by burnt gases recirculation to give reasonable burn rate. (b) The temperature after compression stroke should equal the auto-ignition temperature of the fuel/air mixture to promote simultaneous ignition in the whole combustion chamber. (c) Controlling precisely the combustion heat release to achieve the best compromise in terms of efficiency and pollutant emissions.

This combustion concept can be applied to two and four stroke engine with liquid or gaseous fuel. Although HCCI combustion applies for both gasoline and diesel engines, the processes involved are often different due to differences in the nature of the fuels; Diesel fuel has a higher evaporation temperature at atmospheric pressure than gasoline and it is less resistant to auto-ignition. For this reason, it is troublesome to inject diesel fuel under relatively cold conditions, i.e. using port-injection or very early direct-injection (e.g. during the intake process). Consequently, it is challenging to obtain a homogeneous mixture of air and diesel fuel at the end of the compression stroke, since too early injection may lead to evaporation problems, such as wall wetting, while too late injection can result in insufficient mixing. Furthermore, it may be necessary for HCCI operation to lower the (effective) compression ratio normally used for conventional diesel combustion and to re-circulate cooled combustion products, since diesel fuel auto-ignites relatively easily.

Gasoline fuel, on the other hand, is more resistant to auto-ignition and, in this case, measures are needed to ensure that mixture temperatures near the end of the compression stroke are sufficiently high to facilitate auto-ignition; some of the approaches described in the literature for this involve raising the compression ratio, heating the intake air, variable valve timing, and re-circulating warm combustion products [5]. The salient features of HCCI combustion concept vis-à-vis SI and CI combustion are summarized in table 2.

Table 2: Summary of combustion concepts

Spark Ignition	Compression Ignition	HCCI
Spark Ignition	Auto Ignition	Auto Ignition
Flame Propagation	Flame Propagation	No Flame Propagation
Premixed combustion	Premixed and diffusive combustion	Premixed volumetric combustion
Throttled	Un-throttled	Un-throttled
Port injection	Direct Injection with swirl	Port and Direct Injection
Stoichiometric	Variable Stoichiometry (Lean to rich)	Lean / dilute Stoichiometry

At ERL, an experimental setup is developed to investigate HCCI combustion in two cylinder diesel engine. The HCCI combustion is successfully achieved. HCCI combustion mode is investigated using Ethanol, methanol and gasoline.

4. Characterization of HCCI Combustion

4.1 Mixture requirements

HCCI has no flame propagation; instead the whole mixture burns close to homogeneous at the same time. As the whole bulk burns almost simultaneously the combustion rate becomes very high. Therefore highly diluted mixtures have to be used to limit the rate of combustion. Either can much excess air be used or much EGR.

4.2 Usable λ (Relative Air-Fuel ratio)

The rich side of the operating range for HCCI is limited by too high combustion rate. The lean limit can be defined as the λ where the combustion falter, and much HC and CO is generated. Figures 3-4 shows successful engine operating range in HCCI combustion mode using Ethanol and Methanol as fuel at different intake air temperature on engine operating speed of 1500 rpm. The HCCI combustion criteria defined for rich limit is rate of pressure rise should be less than 1MPa /CAD and for lean limit; Coefficient of variation of indicated mean effective pressure not exceeds 10%. It can be seen from figures that HCCI combustion engine operates at very lean mixture in both fuels ethanol and methanol. On increasing inlet air temperature leaner mixture boundary expands and leaner mixture can be ignited.

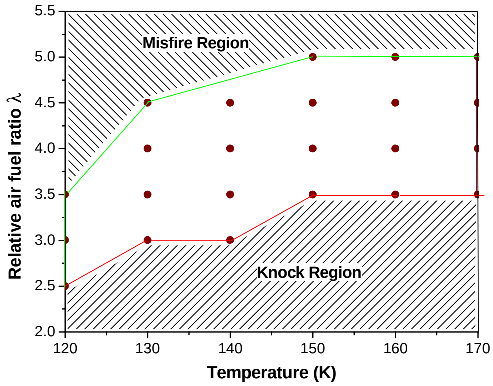

Figure 3: Successful HCCI operating range for Ethanol at 1500 rpm

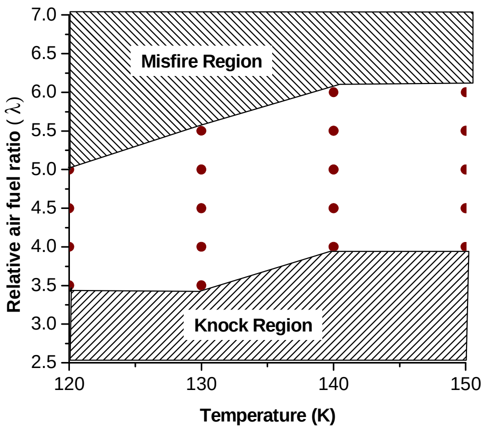

Figure 4: HCCI stable operating range for methanol at 150 rpm.

4.3 Flame Structure

Assume that an adiabatic combustion chamber where fuel, air and internal EGR are perfectly mixed in

HCCI engine. If the temperature and the pressure conditions were increased to the ignition point, the whole mixture would ignite simultaneously. The combustion process would also be completed simultaneously throughout the whole combustion chamber. But in a real engine fuel, air and burned gases are not perfectly mixed and there are heat exchange between mixture and the cylinder walls. This means that ignition will take place where the conditions are locally the most favourable to auto-ignition. Due to heat losses to the cylinder walls, ignition will first take place somewhere in the centre of the combustion chamber. Figure 5, shows a photo sequence of the natural emission from HCCI combustion. The photos were taken at different crank angles, starting 1 °BTDC and ending 10 °ATDC. In Figure 5, it can clearly be seen that ignition occur in many points simultaneously (CAD00). The main combustion phase is characterized by a fast burning core of the charge (CAD+1 to CAD+4). The late combustion phase is characterized by slow burning close to the walls (CAD+5 to CAD+9). It can also be noticed from figure that combustion duration in HCCI combustion is very short as compared to conventional spark and compression ignition engines.

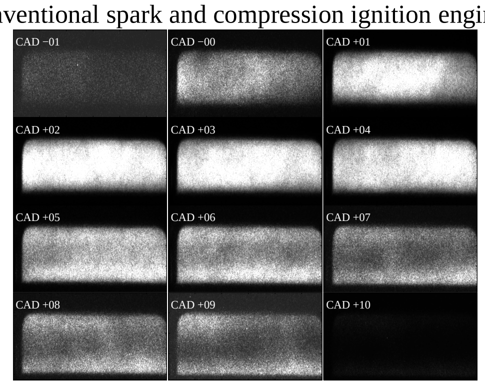

Figure 5: Photos of HCCI combustion visualizing the flame structure [6].

4.4 Rate of Heat release

The in-cylinder pressure was measured for all engine operating conditions. The in-cylinder pressure was analyzed using a single zone heat release model [7], which gives the rate of heat release. Figure 6 show the pressure history and heat release rate for different relative air fuel ratios (λ) at intake air temperatures 130 ^{0}C using methanol as fuel. The trace with the highest maximum pressure corresponds to the operating condition with the richest mixture and the lowest maximum pressure corresponds to the leanest mixture at any given temperature. With the increase in engine load (IMEP), the maximum pressure becomes higher; the crank angle at which maximum pressure occurs decreases. It means the combustion starts earlier. It can also be observed from rate of heat release curve. It is also noticed fro heat release curve that heat release curve is very steep and combustion duration is very short (less than 15CAD). The speed of the chemical reactions is very dependent on temperature and species concentrations. Therefore, the combustion rate is mainly controlled by parameters that affect combustion temperature and species concentrations. This is one of the major challenges in HCCI engine in commercial production is to control the rate of heat release.

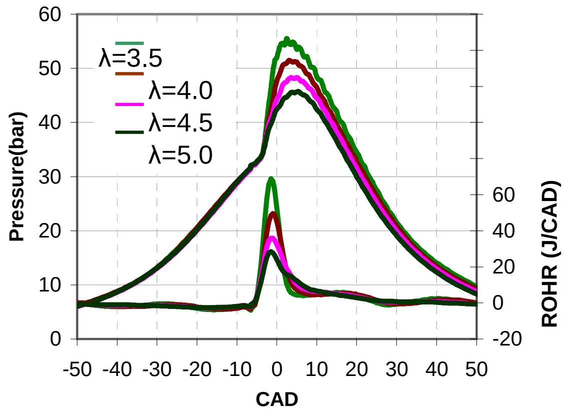

Figure 6: P-θ and Rate of heat release for different relative air fuel ratios (λ) at intake air temperature of 130 ^{0}C using methanol as fuel

5. Summary

Environmental concerns have increased significantly world over in the past decade. As a result, automotive industry has been strongly required to develop technologies of clean and low fuel consumption for ambient air quality improvement, green house gas reduction and energy security. Considering continuously evolving stringent emission regulations, as well as increasing shortage of primary energy resources, the development of new highly efficient and environment friendly combustion systems, associated with alternative fuels has becomes increasingly important and hence research needs to be carried out in this domain. New combustion concepts like HCCI are sustainable options to fulfil the need of energy and healthy environment. HCCI combustion has the potential to combine the best of the spark ignition and compression ignition engines. With high octane number fuel the engine operates with high compression ratio and lean mixtures giving CI engine equivalent fuel consumption or better. Due to premixed charge without rich or stoichiometric zones, the production of soot and NOx can be avoided. The HCCI engine has not yet reached a level of development and cost that makes its market introduction possible. Significant improvements are necessary before the HCCI engine can compete with the SI and Diesel engines. The most important unresolved problems of HCCI combustion are the control of combustion timing and rate of combustion, operating range of (load and speed) is low, excessive CO and HC emissions particularly at light engine load.

Reference:

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