HCCI ENGINE – A PRELIMINARY ANALYSIS

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Abstract

This paper briefly describes history of origin, worldwide research work results, advantages and problems following from specific combustion process, typical for HCCI engines which is so different from well known and widely used spark and diesel engines. More than twenty years left since the HCCI concept was first proposed and demonstrated and steady progress has been made in developing the technology.

Previous and current research works in the world have indicated that engine working in HCCI mode can be supplied by means of different fuels at extremely low emissions and high efficiencies. All world observations have been included and described in current work.

Introduction

Reducing exhaust emissions and increasing the fuel economy of internal combustion engines are of global importance. To meet the demand of economy, energy conservation, less environmental harmful exhaust emissions, especially carcinogenic NO_x and responsibility for a greenhouse effect CO_2 and higher thermal efficiency present generation engines must be characterized by: low fuel consumption; high efficiency; reliability; low price and low cost of usage. Although there is a lack of direct ignition control, the HCCI combustion concept is an effective way to meet these requirements. This new concept of engine that achieves higher efficiency at lower fuel consumption and generates less NO_x emissions has recently been proposed. Many institutes already have studied that type of engine, which is called Homogeneous Charge Compression Ignition (HCCI), but only several of them performed experiments using natural gas as a potential alternative fuel.

New engine combustion process such as Homogeneous Charge Compression Ignition supplied by means of methane is seen among the most promising ways to meet the environment challenges of the future engines used in transportation with associated robust ultra low pollutant emissions. Besides that, HCCI engine offers thermal efficiencies comparable to those attained by high compression ratio throttleless diesel engines while maintaining the smoke free operation of spark ignited engines. Many researchers working on this technology performed numerical calculations of the HCCI process for natural gas as an alternative fuel. Results of their investigations confirmed those assumptions. Although the calculated parameters such as efficiency, fuel consumption and emissions agreed well with the experimental findings, HCCI generated more HC and CO than SI operation.

Historical outline of HCCI combustion

HCCI combustion was discovered as an alternative way for two stroke engines. A first study on such type of combustion process was made by Onishi et al. in 1979 [1]. This completely new type of combustion adopted to the piston engines has been called Active-Thermo Atmosphere Combustion as a promising alternative for existing spark and diesel engines. The drawbacks of two stroke engines are a high residuals emissions at low and partially loads, and the tendency to run on (knock effect) when the engine is stopped. Onishi and coworkers turned these deficiencies into strengths by devising a combustion mode that relied on both high levels of internal residuals and high initial charge temperature. By creating conditions that led to spontaneous ignition of charge they obtained significant reduction in emissions and an improvement in fuel economy. Not long after Onishi presentation the same combustion process was demonstrated at Toyota [2]. The spectroscopic analysis of HCCI combustion process was performed in opposed piston two stroke engine. It was discovered that HCCI combustion is well suited to two stroke engines at part load conditions, and the overall burn rates are very fast. It was noticed that combustion in HCCI engines is extremely smooth and the engine had excellent low fuel consumption together with low exhaust emissions in the HCCI mode operation. In 1983 the first four stroke engine in HCCI mode was tested [3]. Experiments were performed with blends of paraffinic and aromatic fuels over a range of engine speed and dilution levels. The process was analyzed, considering that HCCI is mainly controlled by chemical kinetics excepting negligible influence from physical effects, first of all turbulence and mixing. During the researches, a simplified kinetics model was used to predict heat release as a function of pressure, temperature, and species concentration in the combustion chamber. This assumption permitted to show that the HCCI combustion could be divided into two semi independent processes: ignition and bulk energy release. It was concluded that HCCI self ignition is controlled by the same low temperature (below 1000K) chemistry leading to knock in SI engines, and that the bulk energy release is controlled by the high temperature (above 1000K) chemistry, dominated by CO oxidation. Based on these results and previous investigations it was concluded that HCCI combustion is a chemical kinetic combustion process controlled by the temperature, pressure and composition of charge. That research has been further extended in 1989 [4]. Experiments were performed on the engine using the conventional SI operation at high loads and HCCI at part loads. Experiments were made also on four stroke engine. The performance of the HCCI engine operated with fully blended gasoline and diesel fuel with possible combinations of λ and EGR were examined. During research it was found that a low compression ratio was necessary to use a diesel fuel [5]. Otherwise, selfignition occurred too early during the compression stroke. Also studies of the HCCI combustion with diesel fuel, shown successful operation with EGR rates in the range from 0 to 50 %. The experiments with prechambered ceramic-heat isolating combustion chamber have been also performed. For the first time to test HCCI combustion process a standard 1.6 litre VW engine have been used, converted and adopted to HCCI mode in 1992. Measured part load efficiency was higher from 14 to 34 % [6]. In 1994 experiments showed that the possible operating conditions for stable two stroke HCCI combustion could be significantly expanded by using methanol as a fuel [7]. Very interesting experiments were made in 1996 [8]. The investigated combustion process was called PCCI (Premixed Charge Compression Ignition).

The PCCI, diesel and GDI (Gasoline Direct Injection) engines were compared. All experiments were made at optimum λ. The surprising fact was noticed that, in spite of using high technology – GDI engine, the PCCI had the lowest fuel consumption and NO_x emissions. The HC emissions were however higher. Supercharging was also used to increase the engine output, and actually, from the fact that the pressure was low any unambiguous conclusion could not be drawn. At the same time other researches were performed [9].There was an attempt to optimize HCCI combustion process, and especially the time of ignition by means of throttling either the exhaust or inlet transfer duct. In 1997 similar effect of intake and exhaust throttling on HCCI combustion in a production engine was investigated [10]. It have been affirmed that the combustion timing was advanced and the burn duration decreased when the engine was operated with the orifice plates on the transfer ports. In 2000 direct observation of HCCI combustion was made in a four stroke single cylinder indirect fuel injection engine using a primary reference fuel mixture with octane rating of 35 [11]. To investigate the effect of fuel preparation to combustion, experiments were performed with premixed pre-vaporized fuel. The effects of residual gas and fuel distribution on HCCI combustion were also investigated [12]. Measurement of the fuel distribution in a single-cylinder engine operated with a PRF 50 fuel mixture have been made by the use of a planar laser-induced fluorescence (PLIF) imagining. The cylinder head had intake ports with high swirl ratio and correspondingly large gradients were observed in the fuel distribution inside the cylinder. The conclusion drawn from those experiments was that the main effect of residual gas on HCCI selfignition was thermal, and that the primary influence of charge dilution was on the bulk burn. Also the impact of residual gas and inhomogeneity of charge on HCCI combustion process of natural gas was precisely investigated [13]. Researches were made in a single cylinder diesel engine with $\varepsilon = 17$, and with externally cooled exhaust gas before entering the engine. It was affirmed that the mixture inhomogeneity could be successfully used for HCCI combustion control. The investigations of the influence of fuel inhomogeneity on HCCI combustion control and exhaust gas emissions were also made [14]. It performed series of experiments as a conclusion of previous researches [13] i.e. influences EGR inhomogeneity on combustion control. All experiments were performed on a single cylinder engine with compression ratio $\varepsilon = 16$ supplied by means of methane and propane as a fuel. The experiments rely on comparison between engine performances when the engine was supplied by fuel injected upstream homogeneously and by the fuel injected closer to the intake port – heterogeneously. After many series of experiments and engine model simulations it was concluded that the combustion phasing was insensitive to inhomogeneity, but the emissions of NO_x rapidly increase with increasing unmixedness. In 2002 experiments were performed in order to study the effect of turbulence on HCCI combustion process [15, 16 and 17]. Different turbulence levels were created by changing the detachable piston crown thereby combustion chamber geometry and swirl ratios. The experiments in a Volvo TD100 engine series have been performed together with the comparison between a Disc and a Mexican Hat combustion chamber. The compression ratio in both cases was $\varepsilon = 15$. It was concluded that influence of mixture motion and turbulence on HCCI selfignition and combustion is low as compared to SI and CI combustion because HCCI combustion process is a reaction zone where the entire charge is gradually consumed almost at the same time. However turbulence and combustion chamber geometry for HCCI have proved to be important.

In the midst of many names on attention deserve: Li (2001) [18], Kaahaaina (2001) [19], Law (2000) [20÷30] and many others, whose names for the sake of extensive issue cannot be here described.

The advantages of HCCI engines

Apart from that the up to date spark ignition engines fitted with a three way catalyst can be regarded as a very clean engines, problem appears during part load conditions. Low efficiency at partial load results from pumping losses. It follows from specific SI engine load control. SI engine is controlled by changing air flow rate. The air flow through venturi throat is throttled by reducing the flow area. Suffering the consequence of throttling, pumping losses increase during the gas exchange and considerable amount of work produced by the engine must be used for scavenging. As a result engine's efficiency decrease. Besides SI engines are producing large amount of CO_2 which is responsible for a greenhouse effect. In other terms, low efficiency means high fuel consumption especially at part loads and high emissions of CO_2 in the atmosphere. It is a very important to add that engines mainly in cities are solely running at part loads, what signify that the overall efficiency at normal driving conditions is very poor.

Second transport driving power represents Diesel engines, called compression ignition engines, widely used in small displacement passenger cars, bigger trucks and trains, as well as large high power marine and power-generation station applications. CI engine in opposite to SI engine has no pumping losses and thereby has higher part load efficiency. Load control is achieved by changing the amount of fuel. Air alone is induced into the cylinder and this is the reason that for naturally aspirated CI engines, the air flow rate is almost the same for all load conditions or, in the case of turbocharged engines the air mass flow increases with engine load. Naturally aspirated or supercharged engines operation in combination with high compression ratio caused that the part load efficiency is higher for Diesel than for SI engine. But the Diesel engine struggle with smoke and NO_x problems. CI engines are the important source of particulate emission – (0.2 – 0.5)% of the fuel mass is emitted as small (~ 0.1μm diameter) particles which consist primarily of soot with some additional absorber hydrocarbon material [31].Smoke is mainly formed in the rich region of combustion area and NO_x - in the hot temperature burned gas regions. Due to formation mechanisms, it is very difficulty to reduce smoke and NO_x simultaneously through combustion improvement only. Currently used exhaust gas aftertreatment systems are very complex and expensive owing to higher price for consumer.

According to the environmental protection, market requirements and from the reason that the global oil reserves will not last forever it is desirable to create an engine with Diesel efficiency or higher and with SI engine emission characteristics or less.

In comparison with SI and CI, HCCI engine has much higher part load efficiency, zero particular matters and very low NO_x emissions (less than 10 ppm – compared to >500 ppm for diesel engines) [35], as a result of use dilute air fuel mixture. In HCCI engine there is no problem with soot formation due to the use of homogeneous charge. HCCI engines can be operating on gasoline, diesel fuel and, what is very important, on most alternative fuels. If the control issues are successfully addressed, HCCI would combine low fuel consumption, comparable (or better) to the best Diesel Engines, with exhaust emissions similar to the best SI engines fitted with three-way catalysts. HCCI engines representing high efficiency are the next major step as driven propulsion in transportation vehicles. Besides HCCI have potential to be less expensive than CI and SI engines because of they simplified construction.

The HCCI engines do not require (in the contrary to currently used engines):

- sophisticated shapes of inlet duct (cylinder head) to generate specified turbulence in combustion chamber;
- high pressure injection system;
- very complex aftertreatment exhaust gas systems.

In the HCCI engines ignition is determined by the chemical kinetic reaction rates of the mixture, which is controlled by time, temperature and mixture composition.

It seems that Diesel engines are unlikely to achieve NO_x and PM emission levels required by future legislation. The same situation is with SI engines, they can not reach higher load parts efficiency for the sake of construction and working principle. The HCCI engine therefore can be regarded as a hybrid of both above mentioned types of engines, connecting all their attractive properties becoming the future driving propulsion for all vehicles. Hence, the reasons standing behind HCCI are: higher specific heat ratio of very lean mixture; higher cycle efficiency caused by using higher compression ratio; closer to ideal cycle due to faster combustion.

From these reasons there is a strong interest in HCCI worldwide. Japan and several European countries have aggressive research programs in HCCI including public and private sector components. It is announced that: Ford, Nissan, Toyota, Caterpillar, Volvo, VW, General Motors Daimler-Chrysler and Cummins Engine Company have been performing research on HCCI combustion.

Recent research has greatly expanded toward understanding of HCCI, but additional research will be required to resolve the technical barriers, including: control of combustion timing across the load speed map; controlling the heat release for high load operation; cold-start and control during rapid transient states; unburned hydrocarbon emissions.

Working principle of the HCCI engine

The HCCI concept, which is proposed as an ultimate method of lean burn, is completely different from other conventional combustion concepts like spark or compression ignition. In the HCCI engine homogeneous mixture is created and it depends on solution in the intake system or inside the cylinder. Homogeneous charge or air is drawn into the cylinder during suction stroke and compressed to high enough temperature and pressure. To achieve homogeneous spontaneous ignition of the charge preferable near TDC, high intake temperature and the high compression ratio are required. In contrast to SI and CI engines HCCI combustion lacks from the flame propagation. Combustion initiation occurs simultaneously at whole volume of combustion chamber and burns at the same time (see figure 1) [33].

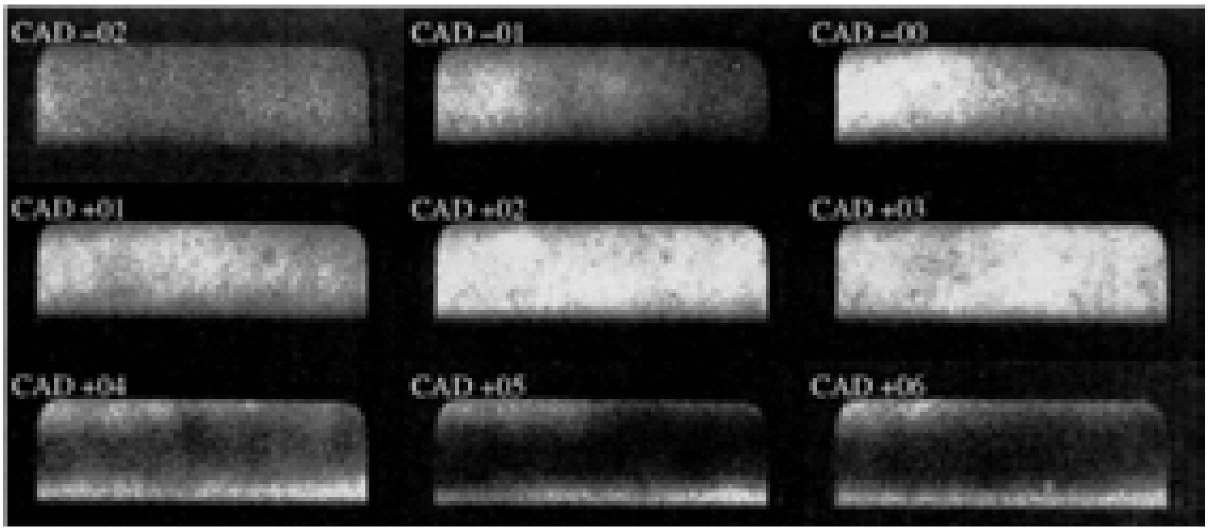

Figure 1. Photo sequence of HCCI combustion, based on 20 images per degree CA [33]

In the figure 1 it can be seen that the combustion starts in almost whole volume of combustion chamber two Crank Angle Degrees before TDC (CAD-02). After combustion initiation the temperature and pressure rapidly increase and whole bulk of fuel burns simultaneously within a few crank angles (CAD-00 to CAD+03). Because the whole mixture burns almost homogeneously unstable flame propagation is avoided. The HCCI non flame combustion process can be described as a ”premixed distributed reaction zone”. On the contrary to the SI engines where large cycle to cycle variation occur, since the early flame development varies considerably due to mixture inhomogeneity in the vicinity of the spark plug, HCCI cycle to cycle variations of combustion are very small. Also in contrast to contemporary engines HCCI fast combustion causes very high and fast heat and pressure release. Under some conditions where enough power was generated p_{max} exceeded 200 bar what is considered to be the critical limit for engine mechanisms [36]. To avoid so fast combustion highly diluted mixture must be used. It is well known that the flame propagation limit is practically about λ=1.7 in SI engines. In comparison with HCCI combustion, the rich limit caused by strong knock intensity – high pressure – is λ=2.9. The case of highest intake air temperature and pressure, up to λ=6.2 can still have stable operation [34]. They are both leaner than λ in conventional engines, so operation of HCCI is possible only using very lean mixture with which conventional combustion is not possible.

Although stable HCCI operation and its substantial benefits have been demonstrated at selected steady-state conditions, several barriers must be overcome before HCCI engine can be widely applied to production automobile and heavy-truck vehicles. A critical limitation of HCCI is that the engine is prone to misfire and knock unless maintained within a certain operating window which makes control over a range of operating conditions challenging. From the reason following research is required in several areas, including: controlling ignition timing over a wide range of speeds and loads; extending the operating range to high loads; limiting the rate of combustion heat release at high load condition; providing smooth operation through rapid transient; achieving cold start; meeting emissions standards especially hydrocarbons HC and carbon monoxide CO.

As was mentioned above for HCCI engine, the critical problems are the control of ignition timing and combustion rate especially for variable load conditions. From a control standpoint, opposite to the SI engine where combustion is controlled by spark timing or CI engine where moment of ignition controlled is by the injection time one of the most striking features of HCCI is that in this engine there is no actuating mechanism directly controlling start of combustion. From this reason combustion control first of all under variable load conditions is the biggest challenge for HCCI engine.

In spite of the problems resulting from very complex combustion control systems HCCI provide huge benefits as a future driving propulsion unit to both light and heavy duty engines. HCCI is also applicable to be used outside the transportation sector such as those used for electrical power generation. Recapitulating HCCI technology can be scaled to virtually every size-class of engine from small motorcycle to large ship engines. From the reason that natural gas has an extremely high octane rating (more than 110), HCCI must be operated at very high compression ratios resulting in high efficiency and clean exhaust gases.

Current application of HCCI technology [32]

At present two engines run in HCCI mode are commercially available in the world. First of them is delivered by Nissan fitted with new technology combustion called MK Combustion System, second is developed by Honda called AR Combustion System.

The ”*MODULATED KINETICS*” – *MK* – system, developed by Nissan [38] (see figure 2), incorporated in a regular CIDI engine using diesel fuel. At light load, the engine operates with high swirl ratio, high EGR quantity and retarded injection timing.

Under this condition, the time required to achieve nearly complete mixing is shorter than the time required for fuel autoignition. Therefore, near-homogeneous combustion occurs. At these low load conditions, the equivalence ratio is low and therefore the homogeneous combustion result in extremely low NO_x and PM emissions. The MK 2.5 and 3.0 ccm engines are commercially available in Japan since 1998. Very important is that in compare with original CIDI engine new technology is more efficiency and less pollutant.

Honda has recently demonstrated a concept for HCCI combustion for a production two stroke engine [39] and proved the reliability of this concept by competing in the Granada – Dakar desert race with a pre-production motorcycle. A scooter, Honda Pantheon 125 ccm, two stroke, single cylinder equipped with HCCI engine is now commercially available on the market.

The *AR – ”ACTIVE RADICAL”* engine is also a dual-mode engine. It operates as a spark ignition engine at high loads, at idle, and for cold starts, in range of part loads working in HCCI mode. The engine has low compression ratio ε=6.1:1 trapped compression ratio, HCCI operation is obtained by throttling the exhaust. With such solution, engine operates with high fraction of hot residual gases, which is enough to obtain HCCI combustion, even at a very low compression ratio. The AR engine has demonstrated considerable advantages in fuel economy, which is 27 percent better than a normal two stroke engine. Hydrocarbon emissions are reduced by 50% in comparison with an original engine. However, without emission controls, hydrocarbon emissions are still very high as compared to current automotive emissions standards.

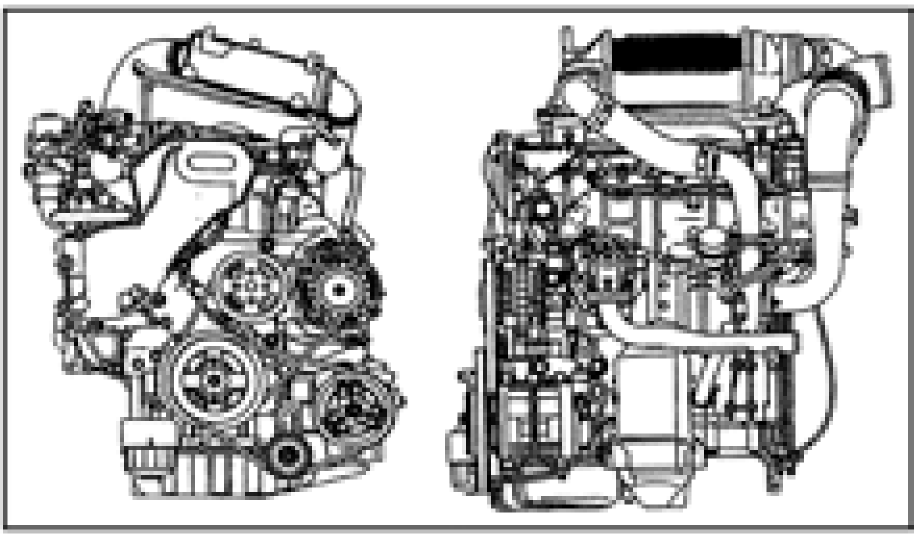

Figure 2. Side and Frontal views of the Nissan MK 2.5 liter Engine [32]

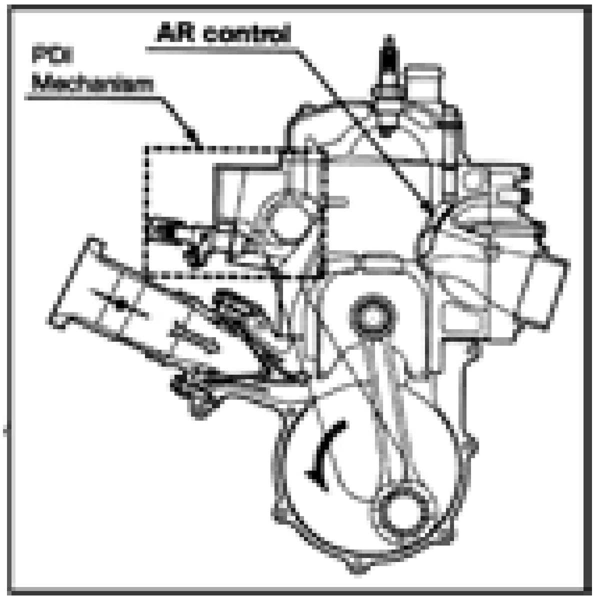

Figure 3. Cut-away of the Honda Active Radical Cycle Engine [32].

Summary

HCCI combustion process is highly different from the combustion processes in the SI and CI engines. The reason is that HCCI lacks flame propagation. Hence this new engine concept has a superior potential for achieving high thermal efficiency when compared to the diesel engine having the efficiency which exceeds 40%. HCCI engine is an alternative strategy when CI engines cannot achieve future NO_x and PM emissions standards. NO_x emission is at ultra low level of ~ 10 ppm in comparison to 600 – 3000 ppm for diesel engines. Also, HCCI engines will be cheaper than presently used engines because of their simplified construction. Currently, the only problem to be solved in future work is the balance improvement between load control strategies and HCCI engine exhaust gas emissions.

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