HCCI ENGINE - IDEA AND EXPECTATIONS, CASE STUDY

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Abstract

Internal combustion engines yet have not exhausted their development possibilities in the range of economy and ecology demands. Development of SI and CI engines, which several years ago proceeded individually in-parallel, now becomes likely in common: one type of engine shares some features with the other one, e.g. direct injection, electronically controlled injectors, electronic control unit etc. However, type of ignition and mixture formation are still different (spark assisted ignition versus auto ignition and homogeneous mixture versus heterogeneous). HCCI engine overcomes this difference. At present HCCI engine uses both type of ignition modes and both types of mixture in different ranges of operational parameters. Direct injection during compression stroke and stratified charge are characteristics for low and mild power resulting in low emission of CO and HC as well as NO_x. Combustion is initiated by spark when mixture is very poor. For maximum load and speed, auto-ignition of homogeneous stoichiometric mixture takes place in the whole volume of combustion chamber. Due to the absence of flame and low temperature, nitrogen oxides, of which molecules arise in post flame zone, are low. Also emission of CO and HC are low due to stoichiometry of the mixture. The key problem is controlled auto-ignition as a function of speed and load (fully HCCI engine). Several methods of auto-ignition control (CAI) are discussed in this paper.

Keywords: *HCCI engine, auto-ignition control*

1. Introduction

The history of HCCI engine began from the moment, when Onishi and co-workers published the basic paper on new combustion process in heat engines, called ATAC - Active Thermo-Atmosphere Combustion [1]. This process depends on heating fuel and air mixed together, what results in faster combustion, better efficiency and lower emission. This process was very attractive for two-stroke engines, thanks to very fast combustion and low NO_x emission.

The system of thermal activation of the mixture was adapted in several other experimental applications to two-stroke engines, as IAPAC[1] [2, 3], AVL - DMI[2] [4] and Orbital Engine Company - OCP[3] [5] etc. Also the author of this paper applied thermal activation of mixture in order to burn lean mixture [6]. These activities were analysed in [7]. These and other not mentioned works gave a base, on which HCCI engine is being developed. Homogeneous Charge Compression Ignition (HCCI) process known also as Controlled Auto-Ignition (CAI), may be applied in any combustion engine, which combines features of both spark ignition (SI) and compression ignition (CI) engines. Auto-ignition of premixed mixture takes place when the temperature rise due to compression reaches higher value than auto-ignition temperature (~1200°C) and when residence time of the mixture is longer then ignition time lag (~3 ms) [8]. Instead of flame propagation from the spark (radially) as in conventional SI engine, there is no flame, auto-ignition appears in the whole volume of the homogeneous mixture, Fig. 1.

Typically in HCCI engine direct injection during intake stroke is applied [9].

[1] Injection Assistée par Air Comprime
[2] Direct Mixture Injection
[3] Orbital Combustion Process

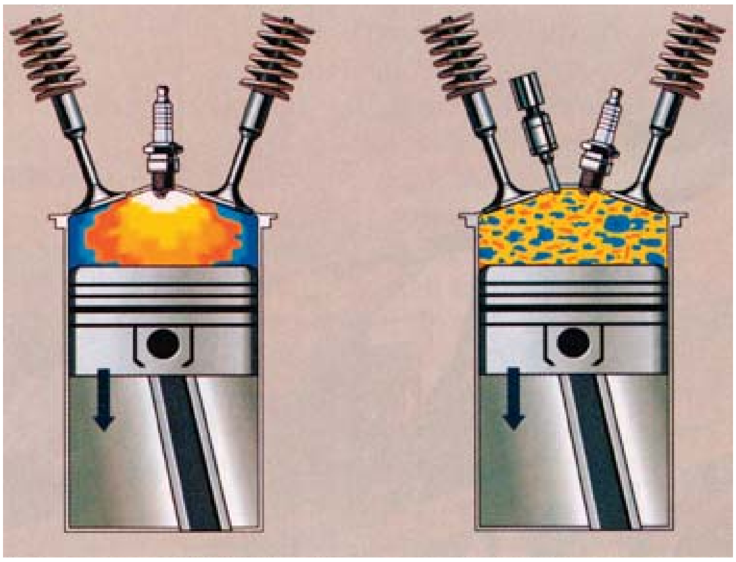

Fig. 1. Comparison of combustion processes in SI engine and HCCI engine [10]

Contemporary HCCI engine operates in two modes:
- at part load as stratified charge SI engine,
- at full load and speed as fully HCCI (homogeneous mixture auto-ignition).

Attempts are made to apply CAI in the wider range of load and speed.

2. How does HCCI engine work?

There are two different trends to evaluate so called HCCI engine. The first one is based on SI engine and developed by General Motors and the second one based on CI engine - developed by Mercedes-Benz and Volkswagen [10]. Contemporary HCCI engines don't work in whole range of load and speed according to HCCI process.

General Motors provided the first public presentation of automobiles driven by HCCI engines: a Saturn Aura (Fig. 2) and Opel Vectra equipped with 2.2 dm^3 Ecotec four cylinder engines [10]. Both engines are fuelled with gasoline (or bioethanol) injected directly into the cylinders and have lower compression ratio (CR) than CI engines. The fuel sensor, like in flex-fuel engines, enables application of different fuels, like gasoline and ethanol.

Fig. 2. GM Saturn Aura HCCI demonstration car [10]

Why so called „HCCI engine?" The engine named HCCI operate either as SI engine or according to HCCI process. The engine works in the whole range of speed and load in two different modes [10]: at low load and speed up to 1000 rpm as SI engine and at high load and higher speed then 1000 rpm as CI engine with homogeneous charge. In the first mode engine operates as typical SI engine fuelled with lean stratified mixture.

In the second mode, mixture auto-ignites in the whole volume, there is no flame, what a results in low NO_x emission, which is formed in high temperature post flame zone. Spontaneous uniform and very fast combustion is localised near TDC, as in Otto cycle, due to that brake fuel conversion efficiency (bfce) is about 15% better than gasoline engine. In the area of homogeneous charge mode, engine works with wholly open throttle, as CI engine, so there are no throttle loses. Auto-ignition controlled with changing speed and load is a key problem. The initiation of combustion depends mainly on temperature of the gases in the cylinder and features of the fuel and its chemistry [8]. The control process involves three steps: signal sensing, signal processing and actuation of the parameters initiating auto-ignition. Pressure sensor mounted in combustion chamber gives signals from prior cycle to very fast computer, which evaluates them and makes adjustment to the current cycle (closed loop control). Instead of pressure sensor, ion-sensor [8] may by used. Combustion in HCCI engine is extremely sensitive to ambient temperature and pressure changes, because they have influence on auto-ignition. Strong influence has also mixture strength and fuel quality, mainly volatility and octane/cetane number [9]. In order to control the intake temperature, variable valve timing (valve overlap) is used. Closing the exhaust valve earlier and opening the inlet valve later (negative valve overlap), hot combustion gases retained in the cylinder heat the intake air to required temperature. This phenomenon acts as internal exhaust gas recirculation (EGR). Also external hot and isothermal EGR may be applied. The problem of auto-ignition control (CAI) lies in the very fast response of the moment of the start of auto-ignition for changing operational engine parameters set on by operator.

GM Co. uses SI engine as a base one, because it is cost-effective: SI engine parts are much cheaper than diesel one.

The second approach, represented by Volkswagen and Mercedes-Benz [9] is based rather on CI engine than SI gasoline. Example of this trend is realised in Volkswagen 2.0-L14 HCCI engine and Mercedes-Benz 1.8 L DiesOtto engine applied to hybrid electric assist motor of Mercedes-Benz F700 concept car, shown at the 2007 Frankfurt Auto Show, Fig. 3. It is direct injection, four cylinder engine with two-stage turbocharging and controlled auto-ignition.

Fig. 3. Mercedes-Benz F700 concept car combining HCCI engine with hybrid-electric drivertain [10]

VW Company uses retardation of recirculated hot gases to control charge auto-ignition and the pressure monitoring of the preceding cycle to adjust the next one. These processes require very fast and accurate valve timing. The Volkswagen's combined combustion system engine is fuelled with synthetic fuel of sophisticated features.

Mercedes-Benz hybrid drivetrain combines HCCI engine working in optimum working conditions (constant speed and load) with electric motor that provides required torque and high efficiency. HCCI engine has direct injection system and is fuelled with gasoline.

However, contemporary authentic HCCI engines can operate only in strictly defined speed and load.

Intensive work is now focussed on extension of the area of homogeneous mixture compression ignition process in wide range of speed and load. This target may be reached with application of sophisticated methods and special fuels. This problem will be discussed below.

3. Control methods of HCCI engine

3.1. Hot gases assisted auto-ignition

When high octane number fuel such as to SI engines, e.g. gasoline and bioethanol, are considered, different methods should be applied than in the case of high cetane number fuels, like diesel oil. Several potential control methods are being proposed to control HCCI/CAI processes [11, 12]:

- heating the intake charge,
- variable compression ratio,
- exhaust gas recirculation EGR,
- variable valve timing (negative overlap).

In the case, when gasoline is used as the fuel, heating inlet charge and increased CR are the potential methods to promote auto-ignition. However, heating the charge is very difficult due to high thermal inertia of heating system. The increased CR may lead to knocking combustion, when engine operates at high load. The application of EGR and/or variable valve timing offer better perspectives to control CAI.

Effects of EGR on CAI process was investigated in [13]. There are the following effects of hot EGR:

- heating effect of the inlet charge, especially for high octane fuels to promote auto-ignition,
- dilution effect of the charge: burnet gases replace air resulting in reduction of air-fuel ratio,
- heat capacity effect, due to higher specific heat of CO_2 and H_2O contained in burnt gases,
- chemical effect, due to promoting auto-ignition of fresh mixture.

In the case of isothermal EGR cumulative effect is as follows: auto-ignition is retarded (mainly due to predominant heat capacity effect), combustion is slower, heat release rate and NO_x emission are lower. In the case of hot EGR auto-ignition is advanced and combustion duration is shortened (but excessive EGR decelerate combustion). Auto-ignition is controlled by charge heating effect, but combustion duration is dominated by dilution and heat capacity effect. EGR (hot and isothermal) may be external, controlled by ECU, or internal by variable valve timing [14].

Summing up: hot EGR controls auto-ignition timing by charge heating effect and combustion duration by dilution effect and capacity effect. The use of recycled hot burnt gases seems to be the most effective means to control auto-ignition. The strategy of valve timing depends on trapping residual gas by early exhaust valve closing, known as negative valve overlap, with the use of electrohydraulic valve actuation system or mechanical variable camshaft timing system [14]. Retarded inlet valve opening (IVO) and early exhaust valve closing (EVC) results in faster mixing of burnt and fresh gases, more homogeneous mixture and uniform temperature distribution. Retarded inlet valve closing (IVC) reduces effective CR and also retards auto-ignition. Schematic of the controlled auto-ignition in the HCCI engine based on SI engine is shown in Fig. 4.

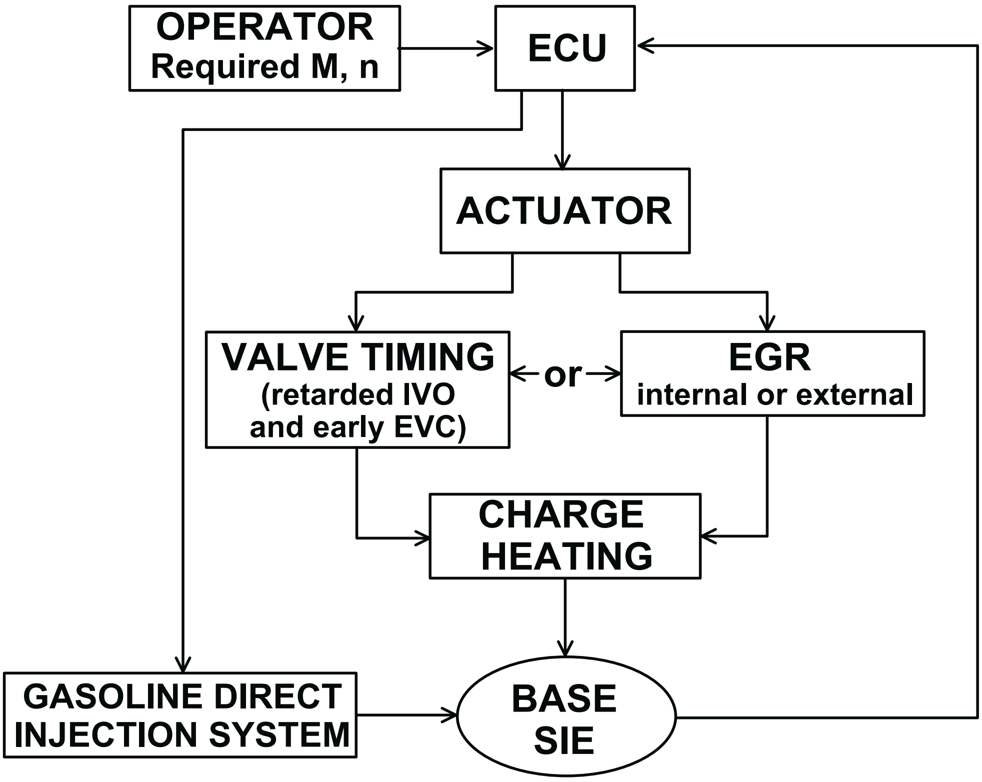

Fig. 4. Controlled auto-ignition in the HCCI engine based on SI engine (SIE). Closed loop control system

3.2. Mixture of fuels having different volatility characteristics

When CAI process in diesel type engine is considered, fuels having high cetane (and low octane) number should be applied. In HCCI engines, auto-ignition and the rate of combustion are mainly controlled by the fuel chemical kinetics [15]. Therefore fuel volatility characteristics play a main role in CAI process. Not all fuels having high CN, such as diesel oil, may be applied to HCCI engine, because their volatility is low and homogeneous mixture cannot be formed. High volatility high CN fuels prone to auto-ignition, e.g. toluene (CN = 56, as diesel fuel) may by used to promote CAI in HCCI engine [16]. On the other hand, in order to avoid very high heat release rate retarding combustion fuel should be used. These two fuels (parent fuel), constitute a blend of an appropriate proportion. These fuels, having different volatility characteristics according to the combustion phasing, control auto-ignition and combustion. E.g. in [16] diesel oil surrogate for CAI control under HCCI engine conditions consisted with 50% n-heptane and 50% toluene mixture. Also other experiments showed that ignition delay and burning rate can be independently controlled using different fuel mixtures [17]. Study on primary reference fuels showed that:

- with decreased ON (increase of CN) of the fuel auto-ignition advances, peak heat released increases and combustion duration gets longer [18],
- fuel with low ON can operate at low load and with high ON - at high load [18],
- ethanol addition to n-heptane retarded auto-ignition [19].

Instead of parent fuel mixing, they may by injected separately by the use of separate fuel systems or sequentially by two-stage injection [20]. The first method demands an extra injection system. Port fuel injection provides a premixed charge in the cylinder and pilot direct injection fuel (having high CN) controls the ignition and combustion of premixed (homogeneous) mixture. The second method depends on two-stage injection of over mentioned fuels, gives good results and don’t require additional injection system [20].

Schematic of the controlled auto-ignition in HCCI engine based on CI engine is shown in Fig. 5.

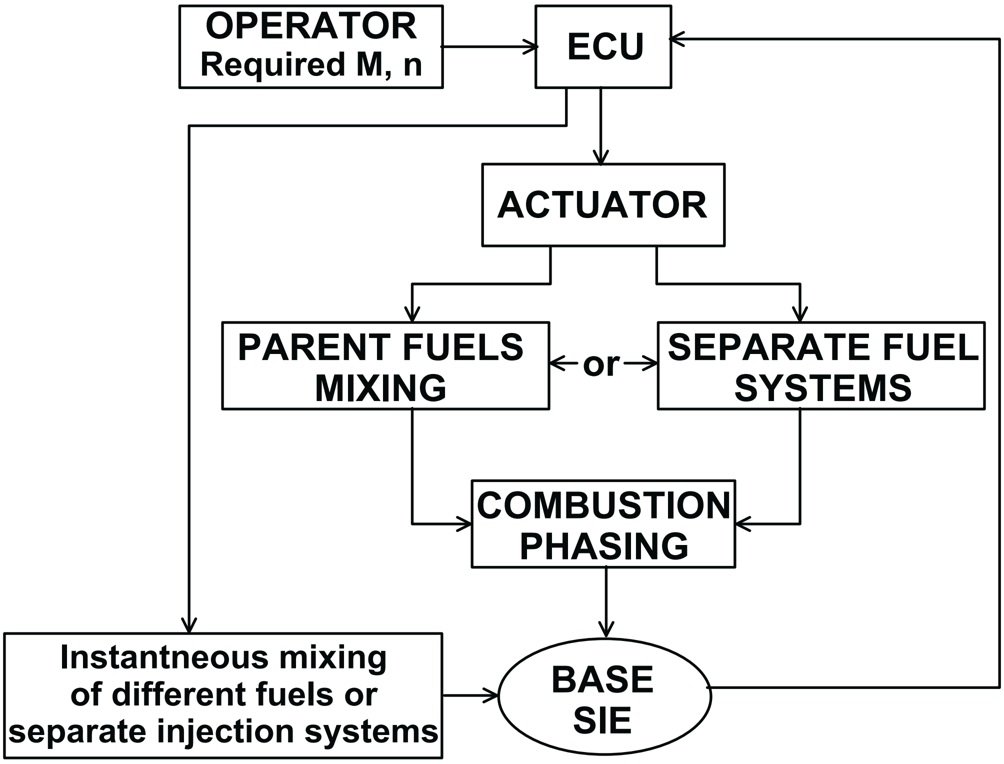

Fig. 5. Controlled auto-ignition in the HCCI engine based on CI engine (CIE). Closed loop control system

Natural gas (NG) may be also used as a main fuel in HCCI engine. Natural gas is an alternative fuel and is used to CI engines after conversion to SI operation or to dual fuel, which is necessary to ignition. NG may be also used as a fuel to HCCI engine, after addition any ignition improver, due to its accessibility to mixing with air - to create homogeneous mixture. In [21] such ignition improver is hydrogen, which advances the auto-ignition and combustion. Hydrogen was obtained in reforming process of NG with the use of exhaust gas (REGR-process). Addition of hydrogen (up to 15%) to NG lowers its auto-ignition temperature and facilitate charge ignition. Due to hydrogen content in the charge, stable operation of HCCI engine was obtained. Instantaneous change of hydrogen fraction is the potential possibility of the control of the moment of auto-ignition.

Another possibility of the enhancement of auto-ignition of NG is addition of dimethyl ester (DME) to NG. Due to high cetane number and high volatility, DME added to NG can ensure successful auto-ignition and combustion [22].

Influence of DME on combustion is a follows:

- majority of DME combustion is consumed before the majority of oxidation of NG,
- as DME fraction increases, the low temperature heat release of DME becomes significant and drives auto-ignition of the charge,
- as NG fraction increases, the operating range of the engine becomes lower and the engine is unstable in the range of $\lambda < 2$.

Also as in the case of hydrogen, changing instantaneously DME content in the inlet charge, is the possible potential way to control auto-ignition in HCCI engine.

4. Conclusions

From above analysis the following results may be drawn:

- HCCI engine yet is not in the phase of mass production. Even only few demonstration cars driven with „HCCI engine" were shown at motor-shows.
- HCCI/CAI process is well realised in the stable conditions of engine operation.
- Auto-ignition of the charge has a potential to be accomplished/controlled by:

- trapping of the exhaust gas in the cylinder with the use of negative valve overlap,
- variable compression ratio,
- exhaust gas recirculation,
- special composition of the fuel,
- addition an ignition improver to the inlet charge.

Intensive work is being carried out on CAI process, which is a key problem of HCCI engine development and application.

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