Research on cylinder processes of gasoline homogenous charge compression ignition (HCCI) engine

Corneliu Cofaru

Transilvania University of Brasov, 29, Eroilor Blvd. 500036 Romania

Abstract. This paper is designed to develop a HCCI engine starting from a spark ignition engine platform. The engine test was a single cylinder, four strokes provided with carburetor. The results of experimental research on this version were used as a baseline for the next phase of the work. After that, the engine was modified for a HCCI configuration, the carburetor was replaced by a direct fuel injection system in order to control precisely the fuel mass per cycle taking into account the measured intake air-mass. To ensure that the air – fuel mixture auto ignite, the compression ratio was increased from 9.7 to 11.5. The combustion process in HCCI regime is governed by chemical kinetics of mixture of air-fuel, rein ducted or trapped exhaust gases and fresh charge. To modify the quantities of trapped burnt gases, the exchange gas system was changed from fixed timing to variable valve timing. To analyze the processes taking place in the HCCI engine and synthesizing a control system, a model of the system which takes into account the engine configuration and operational parameters are needed. The cylinder processes were simulated on virtual model. The experimental research works were focused on determining the parameters which control the combustion timing of HCCI engine to obtain the best energetic and ecologic parameters.

1. Introduction

World urban areas face a number of major environmental challenges regarding the transport sector, their scale and intensity can vary, thus, in this case, a common set of issues can be identified. They are related to poor air quality, traffic volumes and congestion, high levels of ambient noise, lack of recreational areas and other factors of this kind. In the same time, these environmental challenges constitute a major problem and have significant impacts on human health, environment and economic performance.

Transport sector is important for the wealth of human societies and quality of life, providing access to jobs, services, education and leisure while creating the conditions to support economic growth, moving goods and people. This is why transport is an instrument in achieving some of the sustainable development goals, such as improving urban and rural access, improving safety and reducing air pollution.

Transport has also negative effects, such as pollution, including carbon dioxide emissions and accidents. In addition, transport with conventional power trains is also responsible for small amounts of other GHG emissions including methane, nitrous oxide and fluorinated gases , as well as acoustic noise and significant local air pollution from SOx, NOx, carbon monoxide, volatile organic compounds (VOC), unburnt hydrocarbons and particulates, all of them affecting human health and environment. The emissions' increasing was observed for both categories: passenger transport and freight transport. The values of this phenomenon are mainly due to an ever growing transport demands, characterized by large increases in passenger kilometers and tone kilometers. As for the passenger road transport, a relative decrease in the use of public transport is also noteworthy, even if the high level of efficiency on the passenger cars has not been sufficient to counteract this trend. As for the freight road transport, an increased share of road freight transport as opposed to other transport modes supplements the increased transport demand for goods.

There are some ways to achieve the tasks regarding diminishing fuel consumption, pollutants and CO_2 emissions by: homogenous charge compression ignition engine (HCCI) represents a recent combustion technology that combines the main advantages of the gasoline engines (the homogeneous charge) with the main advantages of the diesel engines (higher compression ratios which determinate higher efficiency) determining the potential to reduce emissions while increasing fuel economy. HCCI could give 50% improvement in engine efficiency at part-load compared to spark ignition engines and 30% compared to compression ignition engines.

An important advantage is the low temperature combustion that offers higher thermal efficiency and lower emissions of Nitrogen Oxides (NOx) and Particulate Matter (PM) in comparison with spark ignition and diesel engines. For such engines, a major problem is to control the start of the combustion because the air and fuel need to be mixed homogeneously before the starts of combustion and, the air-fuel mixture auto ignites due to the temperature increasing at the end of compression stroke.

2. Experimental setup

A single cylinder four-stroke engine was used to collect the experimental data in this research. The engine having the specifications presented in Table 1 was connected to a SIEMENS 1PH6167 4NG00 dynamometer, Figure 1.

Table 1. Engine's specifications

Engine type	SI	HCCI	[-]
No.of cylinders	1	1	[-]
Fuel	Gasoline	Gasoline	[-]
Displacement	652	652	[cm³]
Compression Ratio	9.7:1	11.5:1	[-]
Bore	100	100	[mm]
Stroke	83	83	[mm]
Con-rod length	149	149	[mm]
Valve position	DOHC	DOHC -variable	[-]
Intake Valve Opening	17° BTDC	variable	
Intake Valve Closing	45° ABDC	variable	
Exhaust Valve Opening	47° BBDC	variable	
Exhaust Valve Closing	15° ATDC	variable	
No. of valves	4	4	[-]
Fuelling system	Carburettor	Direct injection	[-]
Injection Pressure	-	10	[MPa]
Lubrication	Dry Sump Lubrication by Oil Pump, Replaceable Oil	Dry Sump Lubrication by Oil Pump, Replaceable Oil	[-]
Cooling	Liquid Cooled	Liquid Cooled	[-]

During the tests, one could register data regarding: ambient, intake and exhaust pressures, injection and cylinder pressure, oil pressure, ambient, cylinder, oil, water temperatures, torque, the valves timing and pollutant emissions (HC, CO, NOx).

The standardized equipments were used for tests.[1,2,3,4,5,6,7]. The inlet air has the possibility to be conditioned in conformity with research requirements to obtain the control of combustion timing. The inlet and exhaust pressure was measured through KISTLER 6041A and KISTLER 4075A10 transducers. The fuel consumption was measured by using a fuel mass flow meter and the air flow was measured by using laminar anemometer.

Figure 1. The test engine on the research banch

The cylinder's pressure data were obtained with a KISTLER 6041A piezoelectric transducer. The information regarding crankshaft's position was obtained by using a transducer type ROD 426A.

The engine test incorporated a full electronic and manual control.

The calibration tool was also used to record engine's control parameters such as the intake manifold pressure, air flow rate, injection timing, fuel injection pressure, injection duration, equivalence ratio, etc.

The equipment used for pollutant measurements is presented in Table 2.

Table 2. Equipment for pollutants measurement

Equipment type	*Pollutant*
NDIR Pierburg	O_2/N_2
NDIR Pierburg	CO, CO_2
CLD Pierburg	NO/NO_x
HFID AVL	HC

The HCCI test engine was realized starting from a SI engine equipped with a carburetor as a platform. In order to obtain a HCCI operation cycle some modifications were implemented to the engine. The compression ratio was increased from 9.7:1 to 11.5:1, the fuelling system was changed, replacing the carburetor by direct injection system provided with an electromagnetic actuating injector. The injector was fitted by replacing the spark plug.

To modify the quality of cylinder's mixture in order to control the combustion process, the engine was provided with a variable gas distribution using a camshaft phaser system, as it is shown in Figure 2. The original camshafts were replaced by others camshafts with new cams profile. These cams provide a short valves opening period and a lower valve lifts to offer a safety clearance (valve-piston) when the valve timings are changed during the research work.

The thermodynamic analysis of combustion process was realized using the "BremoXP" soft-ware.

The engine tests matrix is presented in Table 3.

3. Experimental results and discussions

The main problem of the HCCI is to control the start of ignition, for this reason, the cylinder's charge needs to have a high temperature and sufficient dilution at the start of the compression process.

In cylinder, the air fuel mixture temperature must be at a high level to initiate and to sustain the chemical reactions to determine auto-ignition process and combustion process. The air-fuel mixture dilution is necessary to control the rates of heat release reactions.
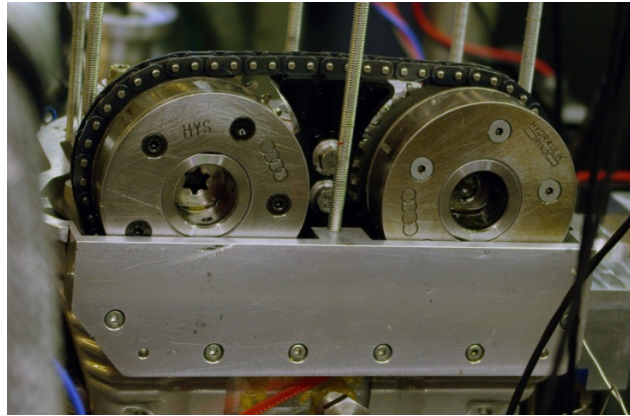

Figure 2. The engine cam phaser

Table 3 Engine testing matrix

Parameter	Values				
EVC (CA)	630	644	646	649	-
IVC (CA)	204	210	215	-	-
IA (CA)	325	335	345	350	-
ID (μs)	2400	2500	2600	2700	-
N (rpm)	1900	2000	2100	2200	2300

For this research, the burnt gases meeting both requirements were used, to rise the mixture temperature and to realize the mixture's dilution, exploiting their effects: heating, dilution, heat capacity and chemical activity..

The analytical and experimental studies showed that in gasoline HCCI engine the ignition is dominated by the charge heating effects instead ,the combustion duration is dominated by the dilution and heat capacity effects of mixtures.

The heat release is influenced by a combination of charge heating effect and by the dilution and heat capacity effects. Taking in account these influences on ignition and combustion processes in gasoline HCCI, it is important to manage the using of burnt gases, because it is advantageous to use burnt gases at as high temperature as possible to determine auto ignition of air fuel mixtures especially at low loads. For this reason residual gas trapping was chosen, by using a negative valve overlap strategy (NVO). The great amount of residual gas is trapped in cylinder when the exhaust valve is closed early during the exhaust stroke. In order to keep the trapped burnt gases in cylinder and to avoid the back flow of these gases into the inlet manifold, the intake valve is opened later, after TDC at the beginning of the inlet stroke. Applying this strategy, a higher charge temperatures are obtained and it made possible to extend the combustion at low loads, but at high speeds and loads, the ignition can be also advanced and the results being a very fast pressure's increase.[8,9,10]

In order to use the trapped residual gas as to obtain a HCCI combustion, the set up of the valves timings was due to realize a negative valve overlap. During the engine test to determine the influence of quantity of burnt gases on combustion process, the engine speed (n), start of injection (IA), fuel injected mass (DI) and the intake valve timing were kept constant. The exhaust valve closing timing varied between 639 and 649 CA, these points are placed during the exhaust stroke. This means that the exhaust valves closes earlier than the piston reaches the TDC, on these conditions, the burnt gases are

compressed after the closing of the exhaust valves, the consequence being the rising in the cylinder's pressures. Note that the exhaust valves open later than on the usual recommended values for the spark ignition engine

In order to avoid the back flow of the burnt gases into the inlet system, the intake valve will be opened later during the inlet stroke.
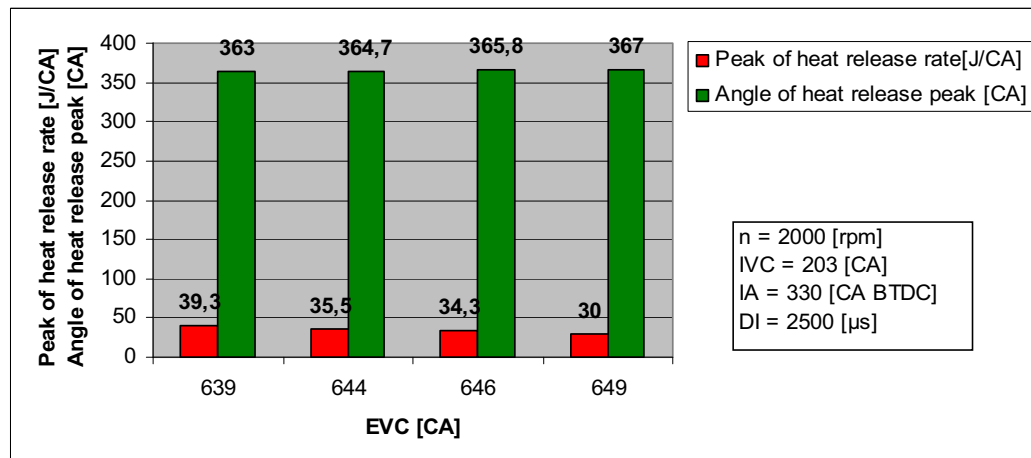

Figure 3. Infuence of exhaust valve closing (EVC) on heat release peak and angle of heat release peak.

Analyzing the cylinder's processes determined by changing the EVO values, the increased amount of burnt gases trapped in cylinder by earlier closing of exhaust valve can be noted and it determines a vigorous combustion which is placed near the TDC, the peak of rate heat release reaches 39,3 [J/CA] at EVO=639 [CA], retarding the closing of the exhaust valve at 649 [CA], the peak of heat release value is 30 [CA], representing a decrease of - 23,7 %. Diminishing the quantity of burnt gases in the cylinder's mixture determinates the moving of combustion in the expansion stroke, The angle of heat release rate peak moves from 363 to 367 [CA] (Figure 3).
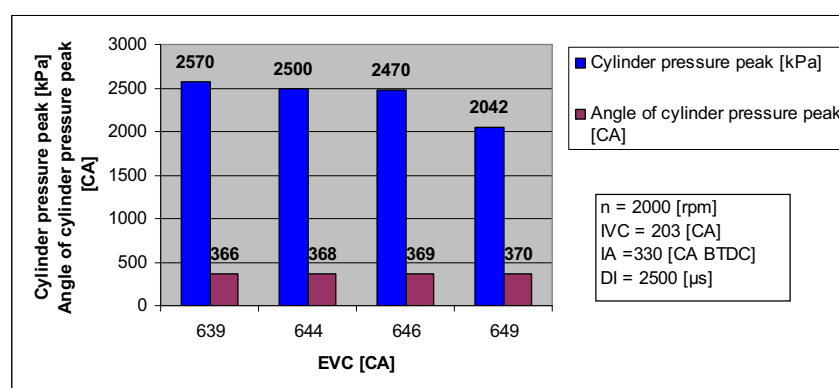

Figure 4 Infuence of exhaust valve's closing (EVC) on cylinder's pressure peak and angle of cylinder's pressure peak.

The improving of combustion process by keeping in cylinder a higher quantities of burnt gases are sustained by the cylinder's pressure and temperatures, the peak values following in the same way the

rate of heat release, decreasing from 2570 [kPa] to 2042 [kPa] for the cylinder's pressure and decreasing from 1462 [K] to 1375[K] for temperatures (Figure 4 and Figure 5).The quantity of burnt gases kept in cylinder determines the oxygen concentration influencing the gaseous pollutants formation, the HC and CO increases with rising of burnt gases quantities, instead the NOx rises with the decreasing of burnt gases quantities because the mixtures is provided with more oxygen contents.
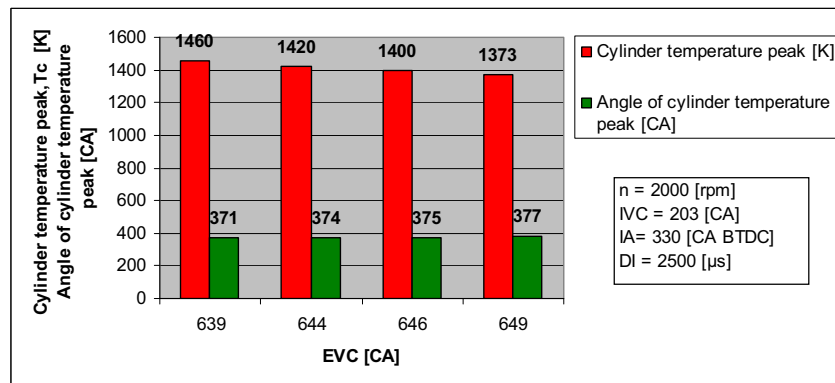

Figure 5. Infuence of exhaust valve's closing (EVC) on cylinder's temperature peak and angle of cylinder's temperature peak.

Regarding the intake process, the inlet valve's opening timing is placed later during the intake stroke to avoid the back flow of the cylinder's burnt gases; there is no influence of mixture compositions. The research was focused on the influences of the intake valve's timings upon cylinder processes: mixture quality and combustion. By the intake valve's closing time, the quality of the cylinder charge can be calibrated, in way of maximization or of reduction. The influence of the intake valve's closing was realized for 204, 210 and 215 [CA], maintaining constant the following parameters: EVC at 649 [CA], the injection advances at 330 [CA], the injection duration ID=2550 [µs] and the engine speed n = 2000 [rpm], in these cases, the quatities of burnt gases and fuel remainig constant in the cylinder.

By changing of values of IVC, the intake valve's opening timing, determining the modification of the fresh air content in the cylinder's mixture was also modified, in fact, the quality of mixtures are changed. Increasing the values of retarding the inlet valve's closing from 204 [CA] to210 and 215 [CA], the data of experimental research show that the peak of heat release rate decreases from 29,8 [J/CA] at IVC = 204 [CA] to 25,1[J/CA] at IVC = 210 [CA] (- 15,8%) and to 23,8 [J/CA] at IVC = 215 [CA] (- 20,1%),

The peaks of heat release rate are placed at the same crank angle. The peak of cylinder's temperature decreases from: 1377 [K] to 1347 [K] and, 1320 [K] for established IVC values. The pollutant emissions follow the values of cylinder's temperatures, HC increases from 650 [ppm] to 681 [ppm] and 775 [ppm], CO increases from 800 [ppm] to 1000 [ppm] and 1445 [ppm], and NOx decreases from 17,5 [ppm] to 15,2 [ppm] and 15,6 [ppm].

During the experimental tests, an important step was to determine the influence of the fuel injection advance to obtain the best point of start of injection (SOI) to have an HCCI engine. For this analyse, an engine operation point characterized by the following parameters was established: engine speed n =2000 [rpm], intake valve's closing timing IVC = 203 [CA], exhaust valve's closing timing EVC = 644 [CA], injection duration ID = 2500 [µs] in order to keep the cylinder's content constant at the moment of the fuel injection. The advance of start of the injection points (SOI) chosen were : 350 [CA], 345 [CA], 334 [CA] and 325 [CA], representing 10 [CA], 15 [CA], 26 [CA] and 35 [CA] on the engine's cycle.

The point (SOI) was placed during the intake stroke after the exhaust valve had been closed, but before the intake valve had been opened. The fuel was injected into hot burnt gases where it

evaporated and mixed with them. After the opening of the intake valve, the burnt gases and the evaporated fuel mixed with air, and this mixture was homogenized during the intake and compression strokes. By decreasing of the fuel injection advance from 350 [CA] to 325 [CA] the peak of heat release rate decreased from 31,3 [J/CA] to 25,5 [J/CA], and combustion processes had a light moving in expansion stroke, influencing the peak of cylinder's temperature which decreased from 1373 [K] to 1327 [K]. The level of cylinder's temperature influenced the pollutants emissions , HC and CO emissions increased with decreasing o fuel injection advances, instead NOx decreased from 14,4 [ppm] at IA= 350 [CA] to 8,6 [ppm] at 325 [CA], representing - 40,28%.

The influence of engine's speed on the cylinder's processes was realized for 1900, 2000, 2100, 2200 and 2300 rpm, keeping constant the following parameters: intake valve's closing IVC = 203 [CA], exhaust valve's closing EVC = 644 [CA], fuel injection advance IA = 350 [CA] BTDC, fuel injection duration ID = 2500 [μs] which takes into account the constant content of the cylinder.

Table 4. Influence of engine's speeds on combustion process and emissions

Parameter Engine speed (rpm)	Peak of heat release rate (J/CA)	HC (ppm)	CO (ppm)	NOx (ppm)
1900	23,5	847	1453	5,7
2000	25,0	767	1120	9,0
2100	27,5	727	1027	12,0
2200	29,0	680	907	15,0
2300	31,0	607	1057	17,2

On the one hand, the engine's speeds have an important inflence on the heat exhange process which decreases at the increasing of engine's speed, on the other hand, the homogenization process of cylinder's content is intensified. By increasing of engine's speed,   the combustion process is improved, represented   by an increased of heat release peak from 23,5 [J/CA] to 31,0[J/CA] representing +21,6%.

The influence of fuel quantity injected on cylinder's processes was realised by modyfing the fuel injection duration, the used values being 2400 [μs], 2500 [μs], 2600 [μs] and 2700 [μs], the engine's settings being: n =2000 [rpm], intake valve closing IVC = 203 [CA], exhaust valve's closing EVC = 644 [CA], fuel injection advance IA = 330 [CA] BTDC**.** In fact, by the injected fuel quantity, the energy released by the engine can matching with the demand to overcome the resistance, on this condition, the duration of injection can be considered as the engine's load.

The research regarding the developments of HCCI engine demonstrates the capability of solution regarding lowering the fuel consumption, pollutant emissions, especially that of NOx (Table 5).

Table 5. Comparison between SI and HCCI engines' performances (n=2000 [rpm], iemp=0,2 [MPa])

Parameter Engine type	Specific fuel consumption (g/kWh)	HC (g/kWh)	CO (g/kWh)	NOx (g/kWh)
SI	340	2,9	35	0,84
HCCI	254	3,1	7,5	0,04

4. Conclusions

During the experimental research, the negative overlap strategy to control the engine's processes by residual gas trapped in cylinder was adopted. The amount of trapped burnt gases has a huge influence on the combustion process.The amount of residual gas trapped in the cylinder was changed by

modifying the exhaust valve's closing timing earlier during the exhaust stroke. Closing the exhaust valve earlier during the exhaust strokes, the burnt gases are than compressed and this process determines the increasing of the pumping work.

The intake valve's timings were chosen in order to keep the trapped burnt gases in the cylinder and to avoid the back flow of these gases into inlet manifold; the intake valve is opened later, after the TDC at the beginning of the inlet stroke. The closing of the intake valve was adopted after the TDC to maintain the volumetric efficiency in an acceptable range. For this reason, the intake and exhaust valves timing needs to be tuned and depends on the engine's load and speed. The engine's load was modified by changing the injection duration. The increasing of quantities of injected fuels per engine's cycles determines the rising of the heat release rate.

The obtaining of homogenous mixture in HCCI needs to select carefully the advance of injection (start of injection). Within the experimental tests, the point (SOI) was placed during the intake stroke after the exhaust valve had been closed, but before the intake valve had been opened.

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