PRELIMINARY INVESTIGATIONS OF THE HCCI COMBUSTION SYSTEM IN A RAPID COMPRESSION MACHINE

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Abstract

The preliminary results of the investigations of the HCCI engine combustion system are presented. The studies were performed with the use of the Rapid Compression Machine converted for HCCI requirements. The instrumentation and the research procedure are also introduced.

The influence of the methane-air mixture initial temperature and the stoichiometry of the mixture on a combustion process were studied in order to establish its impact on selfignition. The results of the performed studies have confirmed that two aforementioned parameters have considerable significance for the whole process and that the effect of initial temperature is almost entirely diminishing in its higher values.

1. Introduction

New type of engine combustion process such as Homogeneous Charge Compression Ignition (HCCI) is considered as one of the most promising ways to meet the market and environmental challenges of the future power unit used in transportation. Additionally, such new engines will have to fulfill strict regulations about CO_2, HC, NO_x emissions, together with increased efficiency which expresses in low fuel consumption. HCCI combustion process is completely different as compared to the diesel (compression ignition) and spark ignition conventional combustion processes. This type of combustion does not involve any flame propagation. Instead of this, the entire charge is burned in non-flame mode almost in the same time. Moreover, this type of the engine operates unthrottled thus pumping loses are significantly reduced. Such arrangement allows for applying high compression ratio similar or even higher than that in Diesel engines. In order to control the energy release and knock intensity the engine must be operated at high level of charge dilution. As a result, the high compression ratio and lean–burn method become an effective way to meet the demand for energy conservation, higher thermal efficiency and less harmful exhaust emissions. Unlike a diesel engine, HCCI combustion takes place homogeneously throughout the whole mixture in combustion chamber. Since the fuel-rich diffusion does not take place, the particular emissions are at the zero level. The reduction in NO_x emissions results from the reduced burned gas temperature. The NO_x emission level is well below of that from spark ignition engines with direct injection and stratified charge equipped with a complex three-way catalyst. Indeed, an HCCI engine offers the fuel economy potential comparable, or better to that offered by diesel engines.

While the potential benefits of HCCI combustion are great, this type of combustion also presents its own set of unique problems, such like high HC emissions, knock intensity during full load and difficulty in controlling phasing combustion especially under variable load. To achieve the ability to control phasing combustion during transient engine operation and to reduce level of unburned hydrocarbons would be the key to successful HCCI engine introduction to the world market.

2. Apparatus

A Rapid Compression Machine (RCM) is a research tool to simulate a single cycle of an internal combustion engine, thus allowing the study of spontaneous ignition under more favorable conditions than those existing in real engines. For this reason, a Rapid Compression Machine (RCM) has been rebuilt and adopted to study the effects of combustion process in a Homogeneous Charge Compression Ignition engine, supplied by means of a natural gas under well determined conditions. The RCM used for this project was originally built in the mid-seventies to investigate impact of combustion chamber geometry on exhaust emissions in the new prototype of diesel engine [1].

The compression ratio has been increased. The volume of combustion chamber has been lessened by the change of the piston crown and the shape of the lower part of the cylinder head. Those modifications allowed to reach the maximum compression pressure up to 30 bar, for the initial conditions specified as normal. The value of maximum compression pressure in the rapid compression machine was chosen in order to refer the real engine conditions present during compression stroke. Except that, the level of compression pressure is comparable with those which occur in currently used diesel engines. That fact in case of conversion of the diesel engine to HCCI mode does not require huge design interferences, changing the production line pattern and increasing production costs as well. Moreover, compared to classical engines working at similar conditions, it is easier and more precise to represent HCCI engine parameters. The parameter which is essential for the selfignition, except high compression ratio, is high initial temperature of the methane–air mixture. Technically this problem in the case of the rapid compression machine has been solved by the use of 3 heaters. The power of heaters was selected to be enough to reach the initial temperature of the mixture about 200^0C. Installed thermal sensors inside the combustion chamber, outside the cylinder liner and also cylinder head, allowed for measuring the temperature with a sufficient accuracy. In order to make the exact adjustment and measurement, thermal sensors type K chrome–nickel–chrome–aluminum with high-speed characteristic has been utilized. Additionally, electronic temperature controller type R 202 K of $0,1^0$C class, has also been applied. Thermal sensors have been installed outside of the heaters for the sake of safety and to control the temperature level in the range suggested by the manufacturer. Because these studies have been carried at the high temperature level, a few modifications of filling and emptying systems had been adopted, i.e. air cooled radiators between cylinder liner and high pressure hoses have been used. Besides, special high temperature and high linear velocity resistant o-rings have been utilized. The cylinder head and the cylinder liner have been covered with special isolating medium as a temperature protection. Rapid compression machine used in this work consists of: slider-crank gear (set), stuffing box separating crankcase from the piston driving chamber, piston with special o-rings, as well as the cylinder head equipped with the pressure and the temperature sensors. The essential feature of the machine is the possibility to obtain high piston velocity level up to10 m/s, through the explosion of flammable mixture under the piston (oxygen–hydrogen mixture in this case). As it was mentioned before, a piezoelectric pressure transducer KISTLER with 0 - 250 bar range has been installed centrally in the cylinder head, together with a thermal sensor for the measurement of high-speed temperature changes in the range of 0 – 1200^0C. The piston had been connected rigidly with the piston rod, working in a stuffing box equipped with a labyrinth sealing. Subsequently, the piston rod has been connected to the engine with the crank mechanism. The working principle of the RCM is as follows: the crank mechanism is blocked in any position between BTC and TDC, in that case 130^0CAD before TDC. The space under the piston is filled with oxygen–hydrogen mixture under the pressure of 10 bar, whilst the main combustion chamber is filled with air – methane mixture under the normal pressure. After the assumed period of time, necessary for the stabilization of the preset initial temperature, the experiment is carried out. A little while after releasing the blockage, the flammable mixture is fired by the electric spark. The pressure, raised because of the combustion process, acts on the lower part of the piston and pushes it rapidly towards of TDC. The selfignition and combustion of the air-methane mixture takes place, assuming that the conditions were sufficient. By the appropriate selection of the initial pressure, mixture composition and the electric spark delay the piston velocity movement can be optionally regulated. Taking into account HCCI process, one can see that it is completely different from well-known piston engine combustion processes.

3. Experimental procedure

The rapid compression machine, adopted for the HCCI requirements, was used for the study of a part of the single engine cycle, i.e. compression and firing stroke. A very important advantage of RCM is that there are no any interferences in the combustion process, being the result of previous cycle. The cylinder chamber before each experiment was almost completely emptied and than filled with clean, fresh charge. This would be not possible to achieve in a research or an actual engine. First, the measurement of the maximum compression pressure was performed, as the reference to next experiments, and also to make easier to define the beginning of the combustion. The latter is especially difficult to determine in case of using highly diluted mixtures. The next step in the study procedure, beginning from the temperature of 30^0C, was to evacuate both chambers by the vacuum pump and filling them with proper charges. The driving chamber has been always filled with the same hydrogen-oxygen stoichiometric mixture under 10 bar pressure. The main combustion chamber, depending on the type of the examined mixture, has been filled with methane-air mixture of various composition. After warming that mixture up to the predetermined level (according to the temperature sensor placed inside the combustion chamber, and after the period of 10 minutes time – necessary for the stabilization of the whole volume temperature) the experiments have been performed. To determine the crankshaft rotational speed and its angular position the crankshaft position marker has been used.

All measurements of the process parameters have been carried out in domain of time. In order to attain comparison between each test, all the values have been presented as the function of crank angle.

For the investigation of the combustion process, following air-methane mixtures have been used: stoichiometric and the 50%, 70% and 100% of the excess air.

The analyzed mixture was prepared in 20 liter bottle, one day before the test, in order to obtain homogenous charge. At first the temperature range in which selfignition of methane occurs was determined experimentally. Next, the effect of the initial mixture temperature on the time where the combustion starts was determined and also its course, type and duration for the mixtures of various stoichiometries. In order to attain real engine conditions, the initial temperature upper limit was 180^0C considering safety reasons and the thermal and mechanical strength of the combustion chamber. Also the fact that temperature of cylinder liner in real engine can not exceed 200^0C in respect of proper lubrication between the engine elements was taken under consideration.

4. Results and discussion

Pressure – time data of the compression and the postcompression period were collected. The pressure was measured by transducer positioned in the center of cylinder head, recorded digitally on PC via an A/D converter at a sampling rate of 200 ms/point. Depending on the initial temperature of mixture, combustion of methane occurred in the late stages of compression stroke or at the beginning of extension stroke. The ignition delay was determined from the pressure record, and defined as the time from the start of compression, where the pressure profile increases almost vertically. Figures (1-4) show a typical measured pressure history for the compression test of air at 30^0C, and combustion characteristics of air-methane mixtures with various strength, at 150^0C and 180^0C.

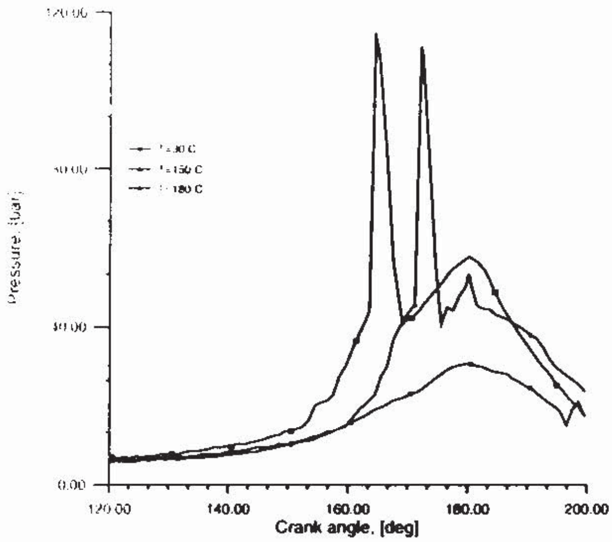

Fig. 1. Cylinder pressure trace for $\lambda = 1$

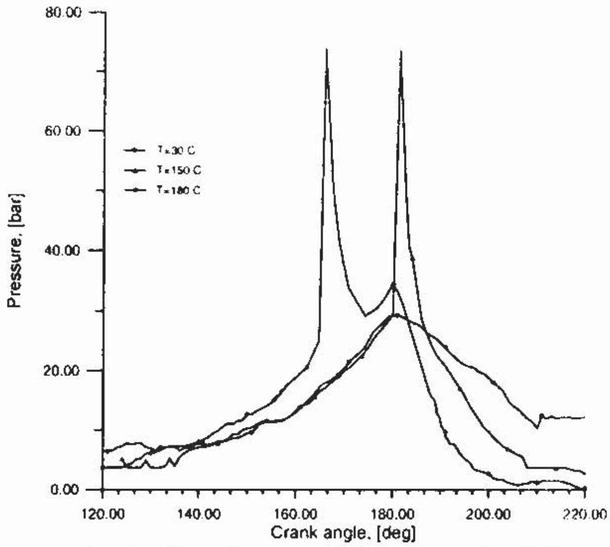

Fig. 2. Cylinder pressure trace for $\lambda = 1{,}5$

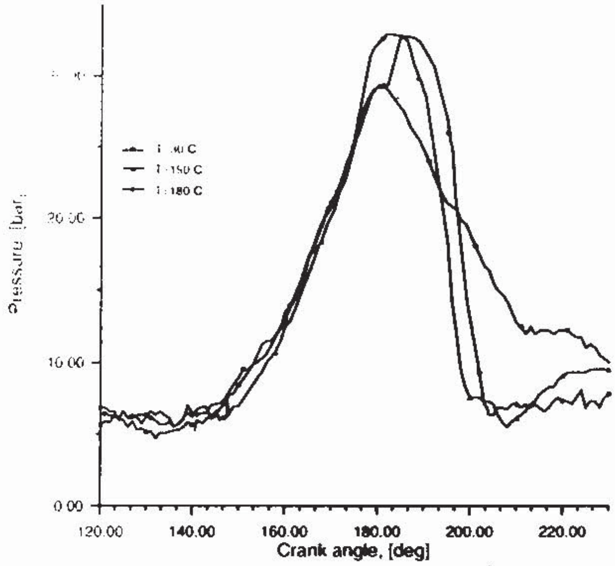

Fig. 3. Cylinder pressure traces for $\lambda = 1{,}7$

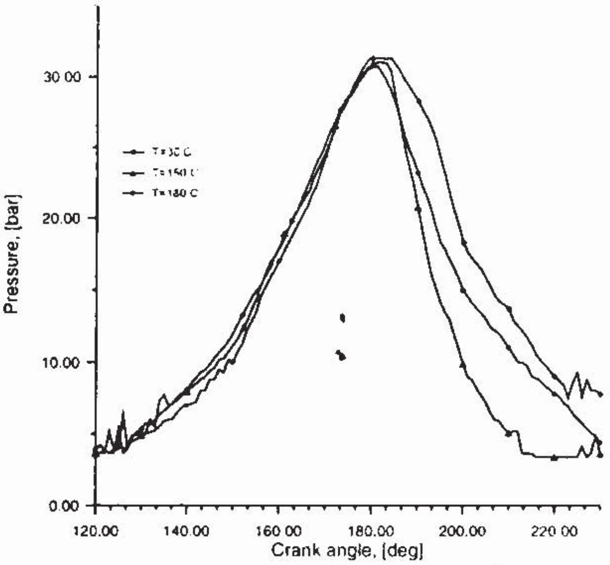

Fig. 4. Cylinder pressure traces for $\lambda = 2$

The investigation of methane – air mixtures of various strength have been carried out in order to determine influence of initial mixture temperature on the combustion process and especially on its beginning, intensity, course, dynamic and duration. The pressure traces shown above consisted the basis for the analyses, which is decisive for the engine efficiency. All the experiments were carried out for one, fixed compression ratio and therefore the pressure profiles were dependent only on the initial mixture temperature.

First, the impact of the initial mixture temperature on the maximum combustion pressure P_{max} was determined. In general the maximum pressure values increase along with the initial temperature at the range of lower temperatures and they basically remain unchanged for the range of higher temperatures (figure 5).

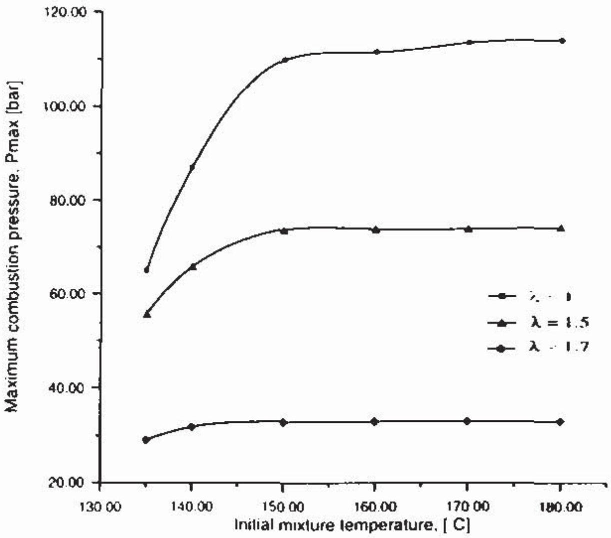

Fig. 5. Maximum pressure versus initial temp.

Regarding the specificity of the studied phenomenon, applied methodology and the manner of result analysis it is not possible to determine exactly the boundary temperature value above which this influence diminishes. The low pressure values recorded in low temperature regions seems to be caused by partial burn-out of the mixture inside the RCM cylinder. This, in turn, comes out from the fact that the initial mixture temperature is too low to allow the selfignition temperature to be high enough for the maximum compression pressure of 30 bar. It has to be remembered that the ratio of the combustion chamber volume to its surface is low due to high compression ratio. This results in the fast heat losses and consequently quick mixture cooling by the combustion chamber walls. At these conditions mixture selfignition occurs only in the zones where temperature and pressure are sufficient. Taking into account the fact, that combustion process in the HCCI engine is characterized by lack of flame propagation and proceeds very rapidly, a part of mixture close to chamber walls is likely not to take a part in reaction, owing to low temperature. This assumption is planned to be confirmed during further experiments with the use of the research engine and measurements of exhaust gas analysis. The plots in the figure 5 indicate that the maximum combustion pressure values for the charge of given strength were the highest in the case of stoichiometric mixture and decreased with the excess of air. It is quite obvious in the light of the fact that for leaner mixtures the smaller amount of the fuel is introduced in the combustion chamber.

Afterwards the influence of initial mixture temperature on the angle of self-ignition advance and maximum combustion pressure (fig 6,7) has been performed. It was observed that along with the increase of initial mixture temperature, the beginning of combustion is also visibly accelerated. In the range of temperature from 135-150 ^{0}C self-ignition was observed at the 4,5-5,5 deg of CA after TDC. In the higher range of temperature, i.e. from 150 up to 180 ^{0}C the initiation of the process occurred at 172 deg before TDC. For instance in the case of stoichiometric mixture and initial temperature 135 ^{0}C, the beginning of combustion occurred at 4.5 deg after TDC, whilst for the initial temperature of 180 ^{0}C the mixture ignites at about 6.5 deg before TDC. It was noticed that in the case of lean mixtures and the same initial conditions, self-ignition occurred with delay, which seems to be quite reasonable, if one takes into account that the mixture contains less fuel. For the initial temperature of 180 ^{0}C self-ignition in stoichiometric mixture was observed at 16.5 deg before TDC, for λ=1,5 at 15.2 deg before TDC, and for λ=1,7 at 5,2 deg before TDC.

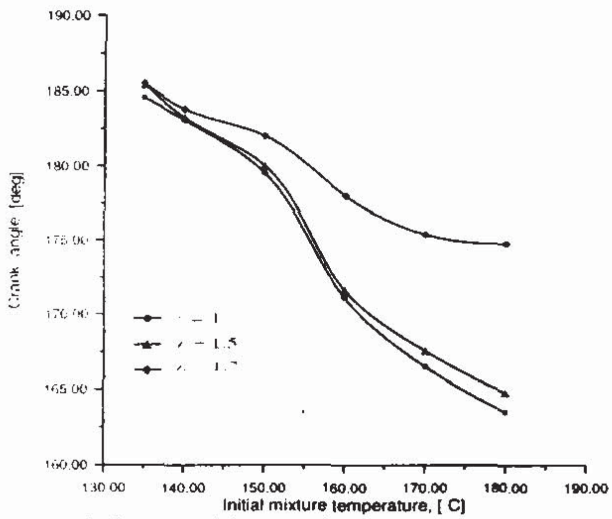

Fig. 6. Influence of the initial mixture temperature on the beginning of combustion (expressed in the crank angle deg)

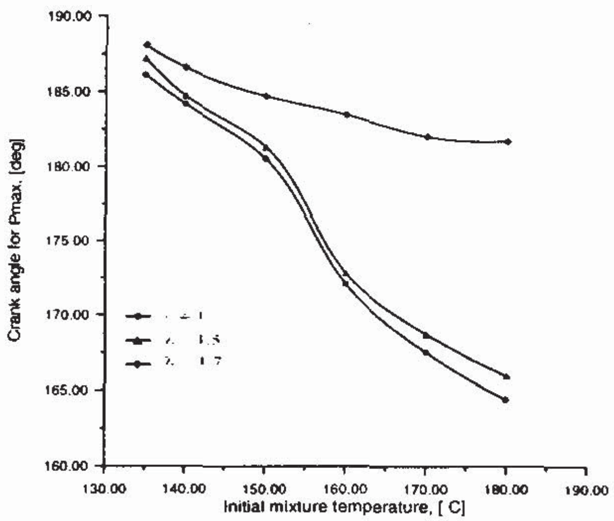

Fig. 7. Influence of the initial mixture temperature on the P_{max} position (expressed in the crank angle deg)

The course of combustion process in HCCI engine is characterised by a very rapid and violent reaction. That is easy to observe from the time of combustion processes presented in the table 1.

Table 1. Combustion process duration

Initial mixture temperature	Combustion process duration		
	λ = 1	λ = 1,5	λ = 1,7
[°C]	*[deg]*	*[deg]*	*[deg]*
135	1,6	1,8	2,6
140	1,1	1,5	2,8
150	1,0	1,3	2,7
160	1,0	1,2	5,5
170	1,0	1,2	6,6
180	0,9	1,2	7,0

The duration time of combustion was counted there from the beginning of ignition till the maximum pressure value in the cylinder, and expressed in crankshaft angle degree. In the case of mixtures with $\lambda = 1$ and $\lambda = 1{,}5$ the combustion duration is close to 1 deg CA, whilst in the case of lean mixtures, i.e. λ 1,7 or 2, the whole process lasts longer. For example in the case of mixture with lambda $\lambda = 1$ and the temperature 180 ^{0}C, the combustion process took about 0,9 deg, and for $\lambda = 1{,}7$ it extended to about 7 deg. The reason for the latter combustion time elongation is not sufficient amount of fuel in the mixture (lean mixture).

The influence of temperature on the pressure raise rate, i.e. its impact on the real combustion rate was also analysed (fig. 8). The pressure increase was expressed as the tangent of the angle of the combustion pressure curve. It results from the chart that the pressure growth in all investigated mixtures had almost the same character. In the initial temperature range up to 145 ^{0}C the pressure increase was relatively low, and above that temperature the pressure was on the same level. It turned out that in this case λ has no effect on the character of combustion velocity changes but it does has effect on the reaction velocity.

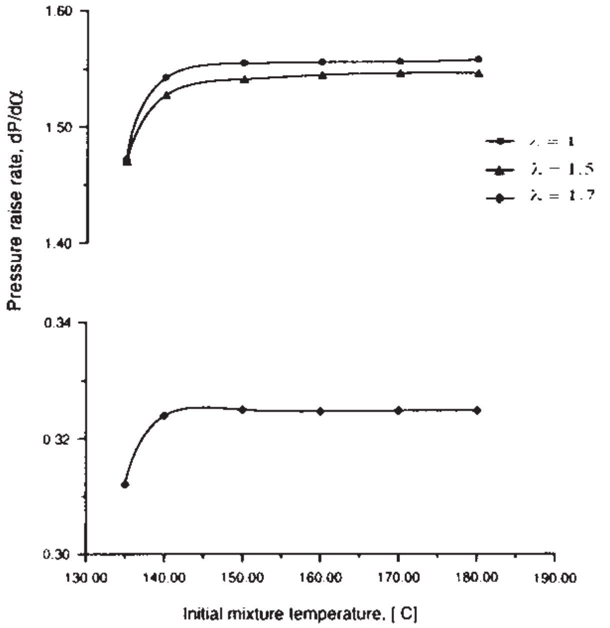

Fig. 8. Pressure raise rate vs. initial mixture temperature

5. Summary

The experiments carried out in the HCCI engine showed unambiguously that the key factor, which is decisive for the whole combustion process, is the initial temperature of the mixture. That parameter determines maximum pressure value, its gradient and time of initiation, which as a result affects engine heat efficiency. The mixture composition is also crucial factor, which has strong influence on the combustion process. It determines the amount of available oxygen in the combustion reaction, i.e. constrains the energy level produced by an engine. The λ value in lean mixtures has almost no effect on pressure raise rate. It is due to the specific type of combustion, which occurs in HCCI engine and is characterised by lack of flame propagation what, on the contrary, is very typical for conventional Diesel or spark ignition engine.

References

[1] Dąbkowski A., Leżański T., Rychter T., Sapiński A.: „Maszyna pojedynczego sprężu o wymuszeniu ruchu tłoka za pomocą spalania". Journal of KONES'97, 1997, pp.41-44

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