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STEROWANIE SILNIKIEM WYPOSAŻONYM W TECHNOLOGIE SPALANIA HCCI

Streszczenie: Obowiązująca europejska norma emisji EURO 6 zostanie wkrótce zastąpiona nową, jeszcze bardziej rygorystyczną normą EURO 7. Powszechnie wiadomo, że nowe regulacje wymagają emisji NOX. Do dyspozycji jest jednak odpowiednie rozwiązanie techniczne, a mianowicie innowacyjna technologia silnika, zwana HCCI. Zasada tej technologii polega na samozapłonie jednorodnej mieszanki paliwowo-powietrznej z wykorzystaniem procesu sprężania. Spalanie mieszaniny odbywa się w całej objętości sprężania bez zapłonu iskrowego, przy czym poziom emisji NOX jest prawie znikomy. Jednak technologia ta charakteryzuje się także kilkoma poważnymi problemami, na przykład występuje komplikacja dotycząca kontroli zjawiska samozapłonu. W prezentowanym artykule przedstawiono oryginalny układ diagnostyczny, który umożliwi sterowanie całym układem samozapłonu, a tym samym zapewni niezawodną pracę silnika HCCI. System ten jest teraz opatentowany, a także przetestowany w eksperymentalnym pojeździe zbudowanym na międzynarodowe zawody „shell eco marathon”.

Słowa kluczowe: sterowanie, silnik, technologia HCCI

THE CONTROL OF ENGINE EQUIPPED WITH THE HCCI COMBUSTION TECHNOLOGY

Summary: The actual European emission standard EURO 6 will be replaced very soon with the new and even stricter standard EURO 7. There is a well-known fact that the new regulations are demanding with regard to the NOX emissions. However, there is at disposal a suitable technical solution, namely in the form of an innovative engine technology, which is called the

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HCCI. A principle of this technology consists in a self-ignition of the homogenous air-fuel mixture using the compression process. Combustion of the mixture is performed in the whole compression volume without a spark ignition, whereby the NO_x emission level is almost negligible. However, this technology is also characterized by several serious problems, for example there is occurring a complication concerning control of the self-ignition phenomenon. The presented article introduces an original diagnostic system, which enables to control the whole self-ignition system and in this way to ensure a reliable operation of the HCCI engine. This system is patented now as well as it was tested in an experimental vehicle built for the international competition “shell eco marathon”.

Keywords: control, engine, HCCI technology

1. Introduction

The automotive industry is permanently facing to the durable challenges that are presented in the form of requirements concerning efficient exploitation of the fuel energy, reduction of the emissions and application of the new technologies. Nowadays there is valid within the European countries the emission standard Euro 6, which should help to eliminate most of the harmful substances that are occurring in the air. The upcoming new emission standard Euro 7 will be even more strict and demanding [1,2].

In the 2015 year occurred information about a fact that in some of the motorcars was installed a software, which enabled to hide the over-limit values of the nitrogen oxides during the emission testing process. This affair is called “dieselgate”. Officially, all the motorcars fulfil limits defined for production of the nitrogen oxides (NO_x). The emission testing process is performed in the laboratory conditions and the above-mentioned “special” software was able to overreach the testing machine. The collusive software cooperated with the engine control unit, identified the measuring process and switched the engine into the operational regime with the reduced emission values [3,4]. It is possible to say that the current emission limits are very demanding.

From this reason there are occurring serious problems for the automobile factories how to meet the emission standards [4]. Technological development of the future and better engines, together with application of the anti-emission actions, requires expensive investments.

However, there is at disposal one possible solution, which consists in application of a new, special technology. This innovative technology is called the “Homogeneous Charge Compression Ignition”, i.e. the HCCI technology, which is based on a specific combination of the gasoline engine (using the spark ignition principle) with the diesel engine (utilizing the compression ignition process). Such combination of two quite different ignition methods in one combustion engine offers the best operational characteristics of both ignition systems. There is applied in this case a gasoline as the engine fuel, but the indicated efficiency of such engine is higher, similarly to the diesel engine [5-10].

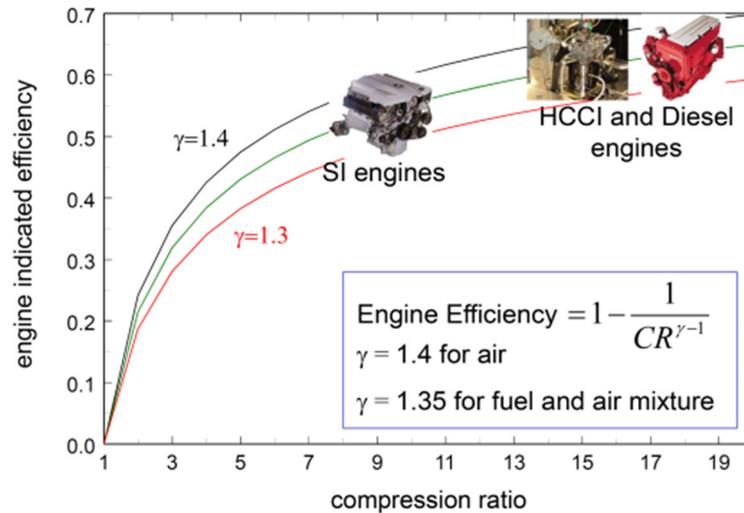


Figure 1. Indicated efficiency of various engine types

The engine indicated efficiency is a function of the compression ratio and specific heats ratio, Fig.1.

The process of the homogenous charge combustion is running at once within the piston combustion volume. Thanks to this fact the whole charge is combusted almost completely. Efficiency level of the gasoline exploitation is very high thanks to application of the progressive and perspective HCCI technology. Another positive result consists in a substantial reduction of the engine fuel consumption, together with reduction of the exhaust gas emissions and what is important the NO_x emission level is almost zero. On the other hand, it is necessary to say that application of the HCCI technology induces some of fundamental problems, for instance a high level of the pressure values, high thermal loading during the compression process, complicated control of the self-ignition process etc. [11].

The worldwide reputable automotive companies are dealing with a development of the HCCI technologies. The contemporary problems concerning the diesel engines emphasize an importance of such development strategy, which is based on the HCCI-engines. The innovative HCCI technology, which is integrated together with the modern motor-management components (e.g. with the direct fuel injection, VVT etc), enables to save the fuel and to fulfil the future emission standards [12, 13]. The global efficiency of the piston combustion engine, which is equipped with the HCCI technology, is close to the diesel engine efficiency, however the HCCI-engine does not require application of an expensive system necessary for elimination of the NO_x emissions. Effectiveness of the HCCI system is based on the fuel combustion at lower temperature levels and on reduction of heat losses, together with the decreased CO₂ emissions [14-16].

The piston combustion engine equipped with the HCCI technology is determined not only as a driving aggregate for the "classic" motorcars, but this kind of engine can be also used as a driving unit of the electric generators installed in the vehicles with the hybrid drives [16].

2. Experimental model and operational conditions

A physical and technical principle of the HCCI-engine operation, which is using combustion of the gasoline-air mixture, is well known among the engine designers already during a longer time. This technology offers a possibility to increase the gasoline engine efficiency so that it could be similar to the diesel engine efficiency. The self-ignition process is running at once in the combustion area. The gasoline-air fuel mixture is ignited as a result of the self-ignition process after compression of the charge. In any case, application of the spark plugs remains still necessary, for example in the case of the cold engine start or during a high-load working regime of the engine. If the engine is operating with a low-level loading, so there is activated the controlled homogenous charge compression ignition process. The specific fuel consumption of the combustion engine equipped with the HCCI technology is similar to the specific fuel consumption of the diesel engine, however it is not necessary in this case to apply an expensive system intended for elimination of the NO_x emissions [16].

The main problem, which is connected with a real application of the HCCI technology, consists in a fact that controlling of the fuel mixture self-ignition process is difficult. The most relevant problem occurs if the engine temperature conditions are variable, because in such a case the HCCI regime is unstable and there is arising in this way a dangerous possibility of engine construction damage. The main task of this article is such conversion or transformation of the standard gasoline engine in order it will be able to operate in the stable regime of HCCI. The experimental engine is a single-cylinder, 4-stroke gasoline engine with the fuel direct injection and with the compression ratio increased up to the value 19:1. The applied fuel injection system is a product of the company Ecotrons. The electronically controlled throttle valve allows regulation of the engine speed using throttling of the air intake [12-16].

There was developed a new heat control system, which is arranged according to Fig.2, in order to perform the above-mentioned conversion of the common gasoline engine so that it can work in the HCCI regime. This system enables to control temperature of the gases, which are entering the cylinder and in this way the given system also controls the self-ignition process. The input air is flowing through the throttle valve. The fuel is injected into the intake air and the fuel-air mixture is passing through the compressor. The compressed fuel mixture is divided into two individual flows: the first one is the "hot flow" and the second is the "cold flow". The hot flow is passing through the heat exchanger and it is warmed-up by the exhaust gases. The cold flow is streaming through the cooler. The both flows (the hot flow and the cold flow) are independent, i.e. they are flowing individually. The engine cylinder is equipped with a mixing valve, which mixes both flows and in this way it regulates the temperature during the suction process. A computer, using the electric servomotor, controls the regulation valve.

The feedback signal is obtained from measuring of the cylinder pressure every 0.5 crank angle degree (CAD). Analysis of the cylinder pressure, which is performed during measuring of the released heat, determines the combustion timing. The combustion timing is defined as such crank angle, by which there is released 50% of the heat (CA₅₀). The calculated combustion timing is applied as the feedback, which enables to realize control of the combustion process by means of the above-mentioned

temperature regulation valve. The installed motor-management software is processing all the sensed data as well as it is managing the whole engine operational system.

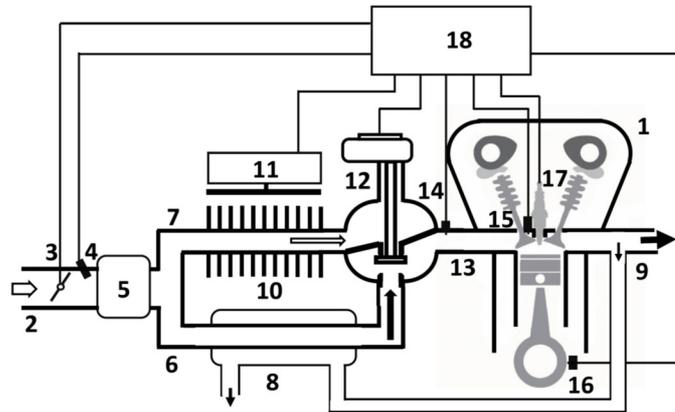


Figure 2. System based on thermal control of the homogenous fuel mixture self-ignition process with compression (1 – combustion engine, 2 - suction pipe, 3 – throttle valve, 4 – fuel injector, 5 – compressor, 6 – heated pipe, 7 – cooled pipe, 8 - heater, 9 – exhaust gas pipe, 10 – cooler, 11 – fan, 12 – mixing valve, 13 – output pipe, 14 – air temperature sensor, 15 – cylinder pressure sensor, 16 – crankshaft speed sensor, 17 – spark ignition, 18 – computer with s ECU

3. Results and discussion

A specific time moment of ignition with the minimal fuel consumption can be defined for the given operational point, which is characterised by the values of engine speed and engine torque. However, this optimal timing is always a compromise among the effective engine work obtained from combustion of the fuel mixture, the heat transfer losses and the combustion process efficiency. If the process of fuel mixture combustion is starting before the top dead centre (TDC) position of the engine piston, thus expansion of hot gases, as well as the reduced cylinder volume, rapidly increases the cylinder pressure and temperature. In this way there is braked the piston movement. Moreover, increasing of the temperature values causes a raising amount of the NO-emissions, whereby a too-high in-cylinder pressure is able to damage the engine, as well.

Furthermore, if the pre-ignition value is rising, there is also at disposal a longer time interval for heat transfer. Additionally, if the ignition moment is closer to the TDC, the in-cylinder pressure and the cylinder temperature are reduced and from this reason the active or positive work of the expanding gas is lower. There is defined an optimal combustion timing for every engine operational point as a compromise among all the above-mentioned influences. Prediction of the optimal combustion timing is a complicated task because it is necessary to take into consideration various contradictory processes and therefore it must be determined experimentally. A possible solution of this task is application of the extreme-seeking control (ES), which can be used as a helpful tool in order to make this process easier. The ES

is a very useful procedure, which is determined for selecting of the unknown and required values in order to optimise the non-linear performance indicator. There is used within this article just the fuel consumption as the performance indicator and the ES serves for determination of the required combustion timing, which minimises this indicator. The ES is utilized for minimisation of the HCCI engine fuel consumption by tuning of the combustion timing value according to Fig. 3. The combustion timing value is the output value, which is very sensitive to the intake temperature. There is applied in this case the discrete ES version determined for minimisation of the cost function, which is able to quantify performance of the controller. The costs depend on differences between the actual and the required combustion timing. The controller parameters are actualised in the online regime using the optimisation process. There is an important and a positive fact that this method does not need additional calculations and therefore it reduces significantly the time, which is required for selection of the optimised controller parameters by means of the proportional-integral-derivative (PID) controller. The PID controller compares the value of the required combustion timing with the value of the measured combustion time in the HCCI engine. There is generated in this way a control signal, which is necessary for reduction of a difference between the above-mentioned time values. Reduction of this difference is made possible by a position of the valve, which is determined for regulation of the intake air temperature. The physically-technical principle of the given procedure consists in analysis of the in-pressure values, whereby it is performed during measurement of the released heat.

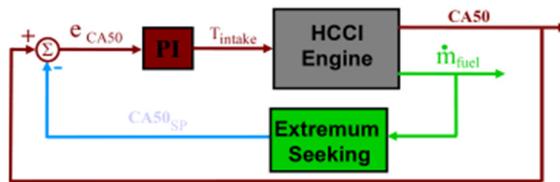


Figure 3. Utilisation of the ES in the HCCI engine determined for minimisation of the fuel consumption

Application of the cost function in the ES enables to minimise the fuel consumption. The cost function is given by the average fuel consumption is relating to one hundred of the engine working cycles:

$$J_{fuel}(\theta) \doteq \frac{1}{n_f - n_0} \left[\sum_{n=n_0}^{n_f} \dot{m}_{fuel}(n, \theta) \right] \quad (1)$$

where n is the number of engine working cycles, $\dot{m}_{fuel}(n, \theta)$ is the value of fuel mass flow through the engine (in grams during 1 second) and θ is the correct value of combustion timing. It is possible to say with regard to the above-mentioned facts that the input parameter, which is determined for the cost function (as well as the parameter, which is adjusted by means of the ES), is defined as 50% of the set-point released heat value $\theta \doteq CA50_{setpoint}$. The cost function is related to the engine fuel consumption in the interval $[n_0, n_f]$ after the delay of 200 engine working cycles.

Therefore the ES is evaluated every 300 of the engine working cycles and the costs are calculated for the last 100 cycles.

The ES was applied in the case of a special HCCI engine, which is determined for the testing or experimental purposes and the utilized engine speed was determined at the level 1500 rpm (Fig.4).

Fig.4 demonstrates an important fact that the ES decelerates the combustion timing up to the value 8 CAD after TDC (ATDC) in comparison with the original combustion timing 3 CAD ATDC. Such modification of the combustion timing reduces the fuel consumption. The time interval of the optimisation process lasted 30 minutes, i.e. about 50 repeats along the horizontal axis in Fig.4.

The analogical experiment was performed using the same methodology, but with a higher value of the adaptation benefit. In this case the ES determined the same minimum level, however far more quickly (Fig.5).

It is possible to say according to the obtained results as well as with regard to the performed analysis that the ES shifts the ignition time about 6 CAD later and thanks to this phenomenon it reduces the engine fuel consumption by more than 10%.

These conclusions were practically tested in the case of a real vehicle, which was designed for the international competition shell eco marathon in London.

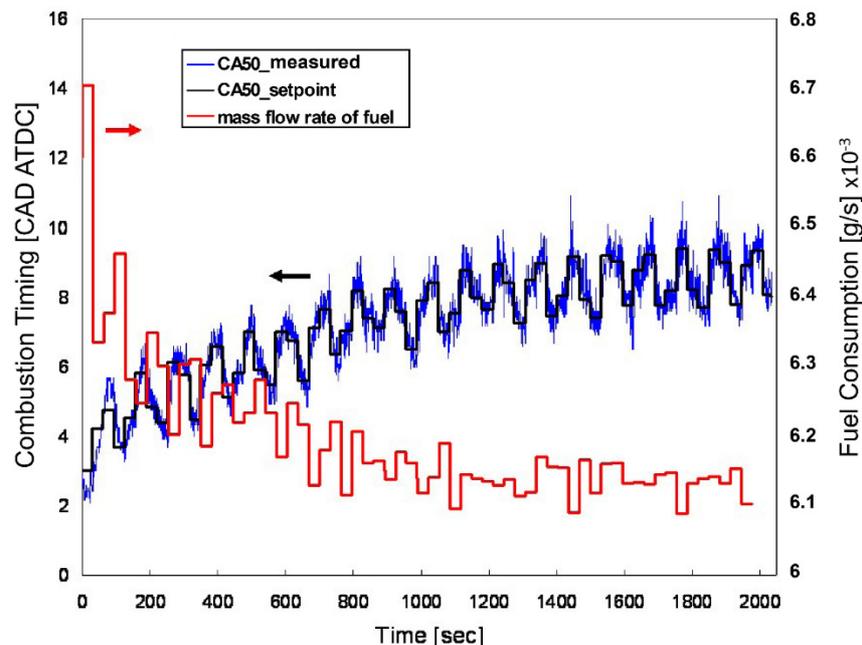


Figure 4. Minimisation of the fuel consumption by the ES using modification of the combustion timing from 3 to 8 CAD ATDC with more conservative parameters

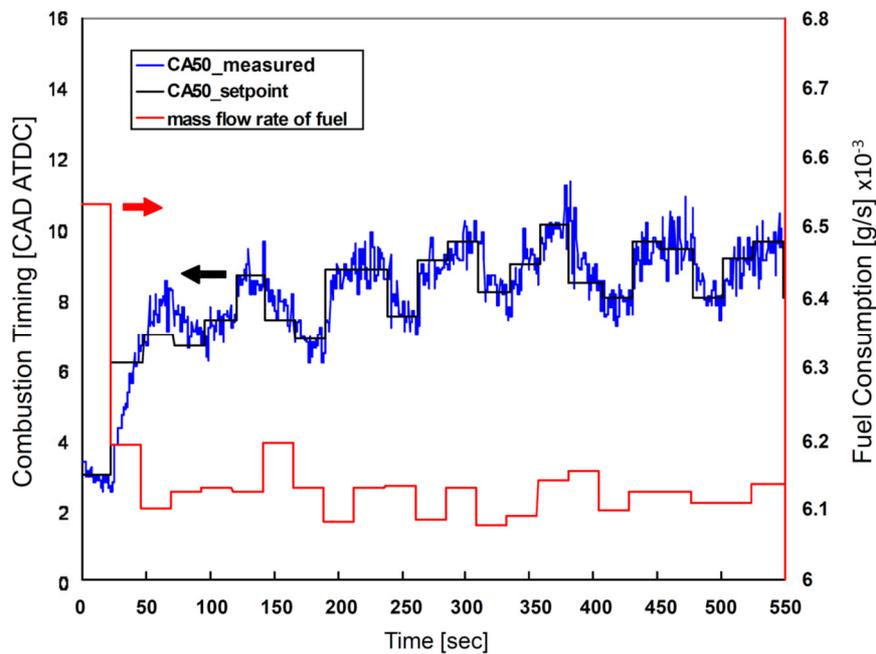


Figure 5. Minimisation of the fuel consumption by the ES using modification of the combustion timing from 3 to 8 CAD ATDC with more aggressive parameters

4. Conclusions

The research and development, which was performed, resulted in a significant reduction of the fuel consumption compared to the standard engine. Optimisation of the driving unit improved the combustion process in order to reach higher level of the fuel consumption efficiency with a positive influence on the environment due to reduction of the carbon oxide emissions. The results of our research work are presented periodically at the international competition Shell Eco-marathon in London. The system, which is based on thermal control of the HCCI technology developed for reduction of the vehicle NOX emissions in order to fulfil the future standard Euro 7, is applied in the experimental vehicle designed for participation at the international competition shell eco marathon 2018.

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