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Advanced technology of combustion engines and their emissions

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Abstract The internal combustion engine, which is operating with compression ignition of the homogeneous fuel-air mixture, i.e. using the Homogeneous Charge Compression Igni-tion (HCCI) process, utilizes a relatively new method of ignition technology. On prin-ciple, there is installed in this case neither the spark plug in the engine or injector helping to combustion. Therefore, the combustion occurs due to a self-ignition in sev-eral places at such a time when the fuel mixture reaches its chemical activating energy. This process is significantly faster than the process of Compression Ignition (CI) or Spark Ignition (SI). The HCCI combustion regime is working with a better thermal ef-ficiency while keeping low level of the gaseous emissions thanks to modifications of the CI engines (diesel engines) and SI engines (petrol engines). This technology enables to use a wide range of the fuels, fuel combinations or alternative fuels.

Keywords advanced, technology, engines, emissions

1. INTRODUCTION

The internal combustion engines have become very popular and widely used, however the gaseous emissions produced by these engines no longer reach a satisfactory level. The researchers are looking for new combustion methods in order to reduce the engine emissions. It is possible to state that just the self-ignition of a homogeneous fuel mixture by means of the compression has a considerable potential. The HCCI combustion is defined as such process, by which a homogeneous fuel-air mixture is compressed until the point of self-ignition is reached at the end of the compression stroke. This kind of combustion is a significantly faster process than the conventional combustion in the diesel engines (CI) and petrol engines (SI) [1]. A mutual comparison of various parameters influencing the combustion processes in the case of SI, CI and HCCl engines is presented in Table 1 [2]. The HCCI combustion is able to improve the engine thermal efficiency and to keep low level of emissions what can also be reached by a suitable modification of the petrol engines and diesel engines. There can be used in this case a wide range of the fuels, fuel combinations and alternative fuels. The HCCI engines are mostly operating with a lean fuel-air mixture, which ignites automatically in several places inside of the compression volume, without a visible flame spread area [3]. After the self-ignition phase, the combustion is running very rapidly and is fully controlled by the chemical kinetics instead of spark timing or ignition timing [4]. However, it is very difficult in this case to control the important operational phenomena, such as: the self-ignition of the mixture, the rate of heat release during high-load operation, the extent of emission standards fulfilling and knocking of the engine [5].

The main advantages of the HCCI technology are as follows: i) the HCCI engines are combusting a lean fuel-air mixture, therefore they can operate with high compression ratios, similarly to the diesel engines and with higher engine efficiency compared to the conventional engines [6,7]; (ii) these engines can utilise a wide range of the fuels [8,9]; (iii) they are working with cleaner combustion and lower emissions, especially the level of NOx emissions is almost negligible [10].

Type of engine	SI-engine	HCCI-engine	CI-engine
Method of ignition	Spark ignition	Self-ignition	Compression ignition
Mixture	Mixed homogeneous before ignition	Mixed homogeneous before ignition	Heterogeneous with mixing in cylinder
Point of injection	In one point	In several points	In one point
Loss at throttle	Yes	No	-
Compression ratio	Low	High	-
Engine speed	High	-	-
Kind of burning	Spreading flame	Self-ignition in several points	Diffuse flame
Fuel saving	Good	The best	Better
Maximal efficiency	30%	>40%	40%
Engine emissions	HC, CO, NO_x	HC, CO	NO_x, PM, HC
Method of injection	Port	Port, direct injection	Direct injection
Equivalence ratio	1	<1	-

Table 1 Comparison of parameters influencing combustion in the SI, CI and HCCl engines

The HCCI technology has also certain disadvantages, for example high levels of the Unburned Hydrocarbons (UHC) and carbon monoxide (CO), as well as knocking of the engine in certain operational regimes [11]. Concerning the gaseous emissions, it is a well-known fact that the diesel engines produce higher amount of the NOx emissions and Particulate Matter (PM) or soot. This unfavourable situation in the case of diesel engines requires implementation of effective control strategies because these emissions have a negative impact on human health and environment. Application of the HCCI combustion process offers a suitable solution of this situation [10]. With regard to a fact that the HCCI technology operates with a lean mixture, the maximal temperature values are much lower than in the case of the petrol engines and diesel engines. Low levels of the maximal temperatures reduce the NOx emissions. However, on the other side, the low temperatures are the cause of imperfect fuel combustion, especially near the combustion chamber walls. This situation leads to high emissions of the carbon monoxide and hydrocarbons. The oxidation catalyser can remove the controlled emis-sions because the exhaust gas is still rich in oxygen.

2. BASIC PRINCIPLES OF THE HCCI COMBUSTION

2.1 Chemistry of fuel combustion in the HCCI regime

The HCCI combustion process is characterized by a set of several hundred types of complex chemical reactions. This process consists of a two-stage heat release. The first phase of the heat release occurs due to the Low Temperature Reactions (LTR). During this phase only a small part of the total energy is released (7÷10%). The second stage of the heat release occurs due to reactions at high temperature [6], whereby during this phase a large amount of energy is generated (approx. 90% of the total en-ergy) [7]. During LTR, the fuel is consumed through the initial decomposition of the hydrocarbon (HC) fuel molecules, leading to creation of the hydrocarbon radicals. These radicals react with oxygen and they form the alkyl peroxy radicals. The alkyl peroxy radicals are further converted to the hydroperoxy radicals by the isometric process. After then there is occurring a secondary additive reaction of the oxygen mol-ecules, where the oxo-hydroperoxide radicals are formed. These radicals are further isomerised and decomposed to the keto-hydroperoxide species and OH radicals. The alkyl peroxy radicals are backwards decomposed into the initial reactants that enable to form the olefins and hydroperoxyl radicals. All the above mentioned chemical reac-tions start at the temperature level approximately 700 K and they are active at moder-ate reaction rates. Due to heat release at this stage, the fuel mixture temperature rises and when it reaches the value 900K, the High Temperature Reactions (HTR) start.

2.2 Formation of NOx and soot

A brief study, which describes formation of NOx and soot, is important in order to well-understand basic principles of the HCCl combustion process. The areas of NOx and soot production are illustrated in Fig. 1 [4]. NOx is a common name for two gase-ous pollutants, i.e. for the nitric oxide (NO) and nitrogen dioxide (NO_2). The process of NOx formation is a complex process, which includes a reactive combination of nitro-gen originating from the air and from the fuel during combustion of the fuel-air mix-ture. The NOx is a thermally produced gas and therefore its formation is largely de-pendent on control of the combustion temperature [10]. It is evident that NOx for-mation usually occurs at low equivalence ratios and at high flame temperatures. Pro-duction of NOx can be reduced keeping the flame temperature below 2200K [9]. On the other hand, formation of soot occurs in the areas with high equivalence ratio or in mixtures rich in fuel and at moderate temperatures. A strategy, which leads to reduc-tion of the NOx emissions during standard engine operation, usually causes also re-duction of soot emissions and vice versa.

As the NOx and soot emissions are a strong function of the temperature and equivalence ratio, the most direct approach to reduction of these emissions requires a careful control of the flame temperature and equivalence ratio [10]. Accordingly, the main purpose of the HCCI combustion is reduction of the flame temperature using a sufficient supply of the air in order to increase the fuel mixture homogeneity.

It follows from the HCCI concept that when a thoroughly homogeneous fuel-air mix-ture is created in the engine cylinder, the pressure and the temperature are increasing during the piston compression stroke what leads to simultaneous self-ignition in the whole cylinder volume. The local temperatures are kept at low levels without a high-temperature flame area, thus preventing the NOx emissions [2]. Due to homogenized lean mixture, which reduces the local equivalence ratios, the soot formation is also reduced.

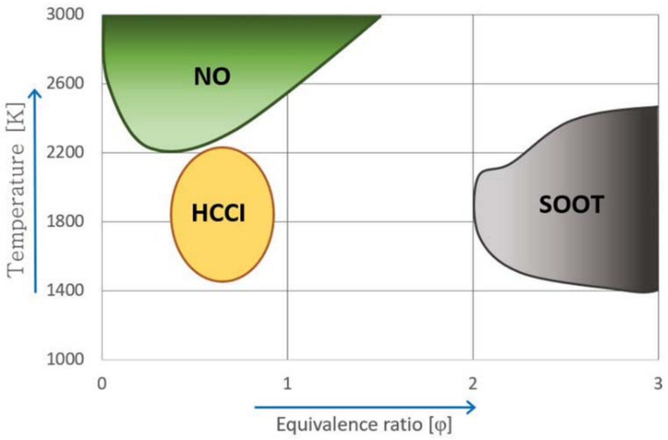

Figure 1 Equivalence ratio dependence on temperature

2.3 Thermal efficiency

According to the results summarised from the presented review, most of the researchers [2-11] observed that the thermal efficiency of the HCCI en-gines is higher compared to the conventional engines (fig.2). A study was realised in order to measure the thermal efficiency of the HCCI engine and the obtained value was compared with a conventional engine using biogas as a fuel. The experiments were realised at different levels of the input temperatures, i.e. at 80°C, 100°C and 135°C. The main component of the fuel was methane (46%) and the fuel-air mixture was based on anaerobic fermentation of the cellulose biomass. They found that at the input temperature 135°C the thermal efficiency was higher compared to conventional engine. According to authors the HCCI engines are able to work with 45% higher efficiency than the conventional engines when the hydrogen is used as the fuel. Other authors investigated combustion characteristics of the HCCI engine at different charging pressures and using petrol as fuel, whereby he obtained the same results as the previous researchers.

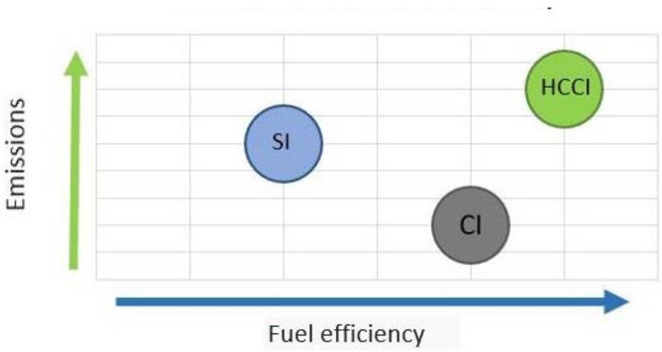

Figure 2 Emissions and fuel efficiency

2.4 Exhaust gas temperature

In the case of the HCCl combustion, the exhaust gas temperature is significantly lower than in the case of conventional combustion due to homogeneous combustion of the mixture. This fact is one of the basic positive circumstances of the HCCI combus-tion, as was stated in the above-described research works [5-10]. Most of the researchers have found that the exhaust gas temperature increases with higher engine load due to richer mixture and decreases with increasing proportion of EGR, causing a leaner mixture. At higher EGR levels, the non-reactive gases (CO_2 and water vapour) have higher heat capacity and, unlike other components of the exhaust gases, they ab-sorb the heat produced by combustion and reduce temperature of the mass in the cylinder.

2.5 Ignition delay

One of the most important parameters influencing the performance characteris-tics of the internal combustion engine is the ignition delay. The delay of ignition usual-ly influences the Start of Combustion (SOC), pressure in cylinder and HRR. The type of applied fuel and its concentration in the cylinder charge has a major impact on the time of ignition delay. In the case of the HCCI engines, the self-ignition should occur near the Top Dead Centre (TDC), in order to reach a better power output. The engine power output has been found to be best when the SOC is between 5 and 15 de-grees of the Crank Angle Degree (CAD) after TDC. For this reason, the ignition delay time should be set according to the requirement of the HCCI combustion. Application of a fast and accurate method for prediction of SOC is necessary for control of the HCCI engine in real time. Many researchers developed various models de-termined for prediction of SOC and ignition delay. Chemical properties of the fuel, en-gine speed and engine load are influencing the ignition delay in the combustion pro-cesses.

3. COMPARISON OF EMISSION

The United States, Europe, Japan and Singapore are introducing different standards valid for the vehicle emissions. Therefore, the emission levels are now considered to be a very important worldwide problem. The gaseous emissions gener-ated by the HCCI engines consist of the hydrocarbons, carbon monoxide, NOx and particulate matter. Various fuels used in the HCCI engines generate evidently low lev-els of NOx and particulate emissions and, on the other side, high levels of the un-burned carbon monoxide and hydrocarbons. However, the emission levels are changing in the case of each engine and they depend on the operational conditions, fuel quality and engine design.

3.1 CO emissions

The emissions of carbon monoxide are mainly produced due to an imperfect fuel combustion, which occurs in such a case when the flame temperature is decreased and the process of chemical transformation to CO_2 remains incomplete. The literature sources [1-11] inform that production of the CO emissions is higher in the HCCI engines than in the conventional engines. This fact is a great challenge for the HCCI engine, which needs to be solved as soon as possible, in order to utilize po-tential of the HCCI technology without restrictions. Authors reported that the CO emissions are higher in the HCCI engines due to nature of this combustion type. They applied various fuels, but the results were the same in terms of the CO emissions. The amount of CO_2 and CO emissions depends on combustion efficiency. The combustion efficiency is defined as the ratio between the CO2 and the total amount of fuel carbon, which is contained in the exhaust gases, including CO, CO_2 and UHC. CO is mainly formed in the cylinder slots, which are too-cold for complete chemical reaction of fuel. The com-plete conversion from CO to CO_2 requires temperatures above 1500 K. However, CO formation occurs in the case of HCCl combustion at low load level, when the high-est combustion temperatures remain below the desired values.

3.2 Hydrocarbon emissions

The hydrocarbons in the exhaust gases are occurring either due to a poor quality of the fuel what causes incomplete combustion or from a semi-product of the second-ary hydrocarbons, which are arising during combustion and are not completely com-busted. Generation of the hydrocarbons is typically caused due to a local extinction of flame as a consequence of ignition failure. The predominant view is that HC emis-sions are increasing in the case of the HCCI combustion and, similarly to the CO emissions, this fact is another serious challenge for the HCCI engines. At low combustion temperatures the insufficient combustion process causes enormous production of the HC emissions. Similar to the CO emissions, the HC emissions are mainly formed in the engine cylinder slots, which are too cold for complete combustion of mixture. It is evident that also this problem requires an effective solution in order to reduce the HC emissions. Higher concentrations of hydrogen and natural gas in the diesel engines decrease the level of UHC and CO emissions, because the gaseous state of the hydrogen and natural gas reduce the wetting effect on the cylinder walls.

3.3 NOx emissions

Since the HCCI engines usually operate with a reduced amount of fuel, i.e. with the lean mixture, the temperature of flame is usually below 2000K. At this low com-bustion temperature, the chemical reactions producing the nitrogen oxides (NOx) are actually inactive. NOx is generally formed during the high temperature reaction, when the atmospheric oxygen dissociates into the nitrogen radicals during chemical reaction and NO is formed. Part of the NO is converted to NO2 during the next chem-ical reactions created in the combustion chamber. The performed study concludes that NOx emissions in the HCCI engines are negligible compared to the conventional engines (fig.3).

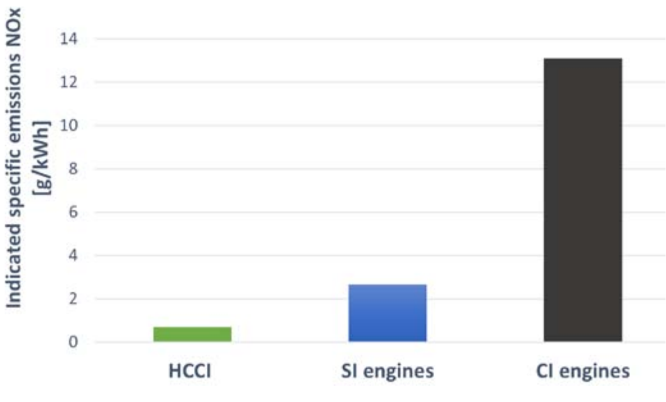

Figure 3 No_x emission

4. CONCLUSIONS

It was concluded finally, according to summary of the above-presented facts and results obtained from the analysed research works performed by many researchers, that the HCCI combustion process can be applied in the existing conventional piston combustion engines after their suitable modification. The most important advantages, resulting from the HCCI combustion regime, are: reduced amounts of the NOx and soot emissions, together with keeping almost the same level of the engine power output compared to the combustion processes in the conventional engines.

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