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Possible applications of prechambers in hydrogen internal combustion engines

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In order to ensure better control of the combustion process in a internal combustion engine powered by hydrogen, it has been proposed to use a split combustion chamber solution. Following paper contains a description of a hydrogen combustion system that includes an analysis of possible technical solutions. The considerations take into account the issues of the dual nature of hydrogen knocking and the problem of burning a stratified charge of a hydrogen-air mixture in a cylinder.

Key words: *hydrogen combustion, hydrogen knock, prechamber, H2ICE, combustion engine*

1. Introduction

In theory, internal combustion engines powered by hydrogen fuels, being less efficient than fuel cells, are an attractive alternative for them. The reasons for this state are mainly their high production potential and well-developed production technologies. The relatively simple structure and low cost of recycling compared to fuel cells allow to conclude with a high probability that hydrogen-powered combustion engines will be the main source of power in electricity and heat generation, as well as marine propulsion source in the near future [5, 15, 25]. The main advantage of using hydrogen as a fuel is its presence in most organic substances, which makes it an open source of power based on renewable technologies. Another advantage of hydrogen combustion in an internal combustion engine is almost complete elimination of carbon from the combustion process, which significantly improves the composition of the exhaust gases in terms of ecology. Complete elimination of carbon from the combustion process seems to be impossible at the moment due to technological limitations and its penetration through the piston rings gaps into the combustion chamber. Considering its negligible amount in relation to its content in commonly used fossil fuels, this issue is not considered in this paper. Aspects in favor of hydrogen fuels are also their high resistance to autoignition from compression and a higher auto-ignition temperature than in the case of petrol resulting from its high octane number (Table 1).

Table 1. Selected parameters of hydrogen and other fuels [16]

	Hydrogen	Methane	Methanol	Ethanol	Gasoline	Unit
Chemical formula	H_2	CH_4	CH_3OH	C_2H_5OH	C_4H_{12}	–
Molecular weight	2.02	16.04	32.04	46.07	100–105	u
Density	0.0838	0.668	791	789	751	kg/m^3
Air flammability range	4.0–75.0	5.0–15.0	6.7–36.0	4.3–19.0	1.4–7.6	vol%
Autoignition temperature	585	540	385	423	230–480	°C
RON	> 130	120	109	109	88–108	–

Despite the aforementioned advantages of hydrogen fuels, their combustion in internal combustion engines is sometimes quite problematic, mainly because of the low ignition energy, which is lower by an order of magnitude compared to gasoline. The low value of the ignition energy of hydrogen makes it easier to start a cold engine significantly, but it also causes a high sensitivity to the formation of spontaneous self-ignition regions resulting in knocking combustion of the air-fuel mixture. Hydrogen knock is a highly undesirable phenomenon, mainly due to the durability aspect. Knocking combustion that generates pressure pulsations in the main combustion chamber leads to excessive wear of the crankshaft bearings and is an additional source of thermal loads. In addition to affecting durability, the phenomenon of hydrogen knock also contributes to a significant reduction in engine performance [29].

Following article presents the results of the considerations on the use of split combustion chambers in hydrogen-powered combustion engines. These considerations take into account aspects related to, inter alia, the dual nature of hydrogen combustion, the combustion of a stratified charge and their influence on the emissivity of harmful substances, with main focus on nitrogen oxides.

2. Hydrogen combustion

Hydrogen, as an alternative source of power for commonly used combustion engines, has many advantages, the most important of which is the absence of carbon-based compounds in the exhaust gases. Currently, mainly due to costs, the most popular form of hydrogen storage and transport in vehicle fuel systems is the gas form [14].

2.1. Hydrogen knock

According to the definition, knocking combustion of the air-fuel mixture in an internal combustion engine is a typical example of an incorrectly performed combustion process [6]. Self-ignition of the air-fuel mixture resulting from increased pressure and temperature in the combustion chamber is assumed to be the main cause of knocking in a spark ignition engine. Hot spots, which are the ignition point of the mixture, are also a factor contributing to knocking combustion. The pressure wave from uncontrolled ignition and the accompanying characteristic sound have an adverse effect on the engine for several reasons. Firstly, a rapid increase of pressure in the combustion chamber causes expeditious wear of the crank system bearings, secondly, this phenomenon significantly contributes to the increase in thermal loads, mainly in the area of the piston crown, and thirdly, overlapping pressure waves having different sources of formation cause significant lowering of the indicated pressure, which in turn contributes to a decrease in its overall efficiency.

In theory, hydrogen as a fuel is characterized by a high compression ignition resistance, which is indicated by the octane number (ON). It describes the resistance of the fuel to knocking combustion, and in the case of hydrogen, its research value (RON) is 130 [23]. On the other hand, practice shows that hydrogen combustion promotes the formation of pressure waves much higher than in the case of gasoline combustion with a research octane number close to 100 [26]. The index used in that case called the motorized octane number (MON) is at level of 60 [32]. Large discrepancies between the values of the RON and MON indexes indicate that they should not be used in relation to hydrogen. A better choice for the evaluation of knock resistance is the methane number (LM) proposed by Ryan et al. used to determine the parameters of gaseous fuels commonly used to express the probability of engine heavy run [20]. Methane number describes the percentage of methane in the reference mixture consisting of hydrogen and methane. Taking into account the methane number equal to 0 in the case of hydrogen, it can be concluded that it is the fuel with the most favorable properties for the occurrence of the knocking combustion phenomenon resulting from unstable course of combustion process.

Table 2. Methane number of selected gaseous fuels [11, 12]

Fuel	Hydrogen	Coal gas	Propane	Natural gas	Methane
Methane number	0	24–30	34	75–95	100

As research shows, the hydrogen knock phenomenon may have two mechanisms of formation, thus we are talking about its dual nature. The first cause, as in the case of a conventional gasoline-air mixture, is the spontaneous combustion of hydrogen as a result of the excessively elevated temperature and pressure at the end of the power stroke. This type of hydrogen knock is defined as heavy and causes a noticeable increase in pressure in the combustion chamber up to several MPa. Its formation also closely correlates with the engine compression ratio [31]. The second mechanism of hydrogen knock generation is the so called light knock, whose cause is claimed to be the unstable combustion process initiated by the spark plug. Although the limit of light knock cannot be clearly established, the pressure pulsations caused by this phenomenon are in the range of 20–100 kPa. It is not as harmful to the engine as heavy knock, but it is also an undesirable phenomenon, therefore it is justified to improve the control of the combustion process in the area of its occurrence.

An important factor influencing the occurrence of hydrogen knock is also the composition of the fuel-air mixture (Fig. 1). Due to the fact that the lean mixture contributes to a decrease in the speed of flame propagation, it reduces the risk of knocking. Research has shown that the intensity of hydrogen knock is the highest for a stoichiometric mixture [11, 12], and therefore it is aimed to deplete the mixture.

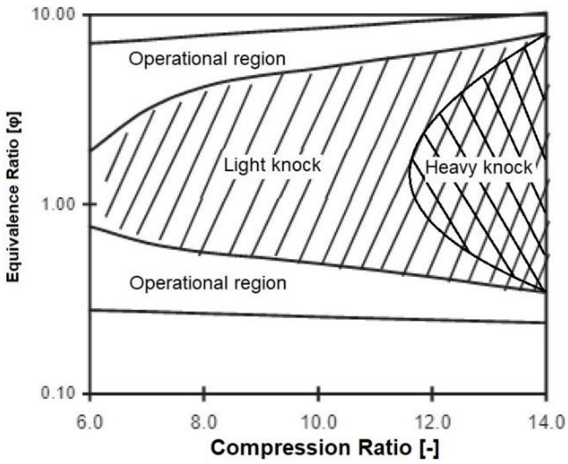

Fig. 1. Regions of hydrogen combustion in SI engines with the heavy knock distinction introduced by the author [11, 28]

Other solutions to impede the occurrence of knock are also changes in the engine operation cycle [33], water injection [3] or exhaust gas recirculation [27], although they usually decrease the overall efficiency of the engine. The location of the self-ignition occurrence is also important, therefore combustion chambers have been developed to prevent knocking through their geometrical features [34].

2.2. Compression ratio

The compression ratio is one of the most important parameters that describe an internal combustion engine mainly due to its direct impact on engine efficiency. According to the equation for ideal gas, an increase of the compression ratio is accompanied by the temperature elevation of the mixture in the combustion chamber. In the case of a mixture of hydrogen and air, this is not considered a disadvantage at first glance, because of its higher autoignition temperature than in the case of gasoline. However, an increase in the temperature of the mixture at the moment of ignition has a significant impact on shortening the delay of its self-ignition. As a result, the speed of the combustion process increases, which can be observed by rapid pressure pulsation. The generated high-amplitude pressure waves are, in turn, the main cause of the hydrogen knock phenomenon.

The second, but not less important, factor in the influence of the compression ratio on the occurrence of the knock phenomenon is the increase in the energy density of the charge in the combustion chamber resulting from the decreasing volume of the chamber during the compression stroke. A higher concentration of chemical compounds involved in the combustion reaction increases the amount of heat released in its course, which, in turn, increases the temperature of the entire process. The increased substrate concentration results in a consequent higher combustion rate, causing the pressure in the combustion chamber to rise rapidly. As research shows, an important factor influencing the formation of the combustion process is also the temperature stratification inside the combustion chamber, therefore it is reasonable to take into account the temperature inhomogeneities responsible for the formation of the so-called hot spots. The limit value indicated by the research teams is 30 K [21, 22]. When this value is exceeded, a high probability of knocking occurs.

It seems reasonable to say that an increase in pressure may cause a decrease in the speed of the combustion process [19], however due to the relatively small influence of this phenomenon compared to the increase in temperature, this was not taken into account in further considerations.

Influence of the compression ratio on the ignition of a mixture with the excess air coefficient λ = 1, investigated in details by Szwaja et al. [13, 24] and Karim et al. [14, 16], shows a clear increase in pressure pulsation intensity for compression ratio values greater than 11 (Fig. 2). After exceeding this value, the hydrogen combustion mechanism of the mixture was described as a heavy knock, resulting from self-ignition in the final phase of combustion process [8].

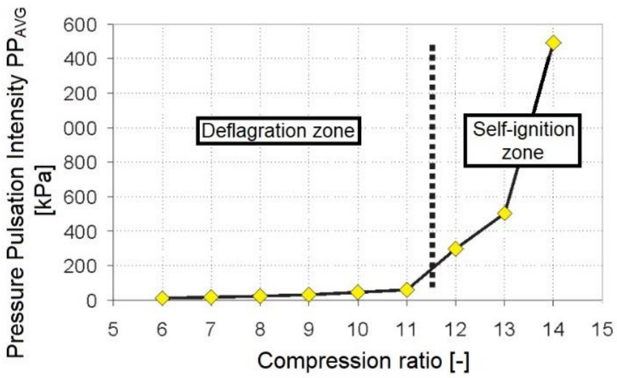

Fig. 2. Compression ratio influence on pressure pulsation intensity of CFR engine [28]

In the range of compression ratios 6–11, combustion of the mixture was described as deflagration with no signs of heavy knock. Deeper analysis showed pressure pulsations with a much smaller amplitude in the range from 20 kPa to 100 kPa caused by the unstable combustion process. This process, called light knock, is also an undesirable phenomenon, despite its less destructive effect on engine components than in the case of heavy knock. As a result of the vibrations of the piston rings, it can cause their accelerated wear, therefore it is reasonable to improve the combustion process in this area.

For compression ratio values below 7, the pressure pulsation amplitudes are so low that they do not have a significant effect on engine operation. It should be mentioned that all ranges for the occurrence of the hydrogen knock phenomenon for the stoichiometric mixture are arbitrary, therefore special attention should be paid to the interpretation of the results of tests carried out especially in the areas of these contractual limit values.

2.3. Lean combustion of hydrogen

The strategy of combustion of the mixture with excess air is a solution commonly used in internal combustion engines for many years. Its general purpose is to improve the economy by reducing fuel consumption and improving the emissivity of the engine.

Currently, lean mixture combustion in conventional spark ignition engines reduces pumping losses in the intake manifold by keeping the throttle valve open at low loads. Furthermore, the higher specific heat of the lean mixture increases the efficiency of the Otto cycle, thus increasing the overall efficiency of the engine [2]. The main factor that limits the excess air coefficient is the exhaust gas temperature, which decreases along with the depletion of the mixture. This phenomenon is important from the point of view of the efficiency of the three-way catalytic converter, which operation depends on the process temperature and the oxygen content in the exhaust gases. In the context of hydrogen combustion, the depletion of the air-fuel mixture slows down the combustion process. As noted by Szwaja, along with the increase of the excess air coefficient, the intensity of pulsation of the combustion pressure decreases linearly (Fig. 3). This phenomenon can be used to increase the efficiency of the engine by increasing its compression ratio.

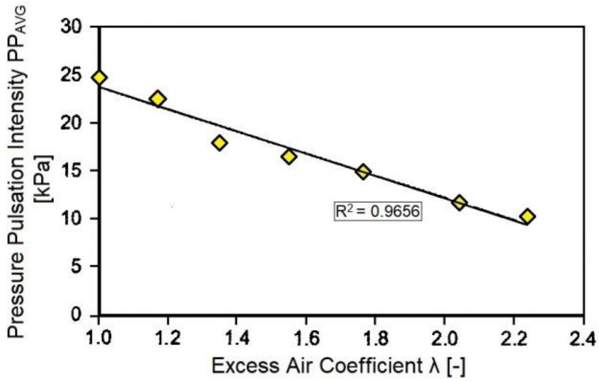

Fig. 3. Excess air influence on pressure pulsation intensity [25]

Lowering the temperature of the combustion process closely correlates with the self-ignition delay, which decreases with temperature deterioration (Fig. 4). Excessive shortening of the self-ignition delay increases the probability of self-ignition, which directly translates into the occurrence of the hydrogen knock phenomenon.

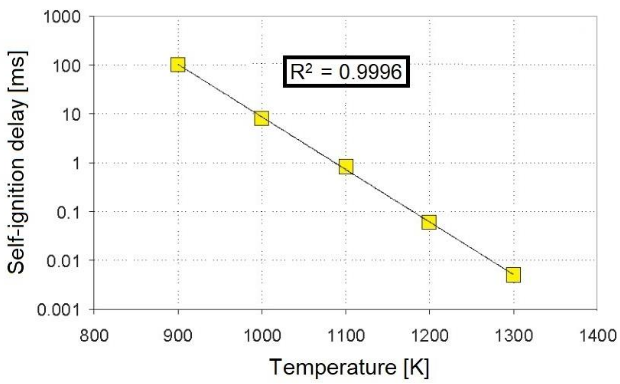

Fig. 4. Combustion process temperature influence on self-ignition delay for stoichiometric air-hydrogen mixture [29]

The results of the research indicate the optimal value of excess air coefficient (λ) at the level of 2.2 [24, 25], whose exceeded value does not have significant effects in terms of emissivity and efficiency. Research by Lee et al. [10] shows that the next step to increase the overall efficiency of a hydrogen-powered internal combustion engine is to burn a stratified charge. This strategy allows for the attainment of better stability of the combustion process by increasing the time of mixture formation and allows for its further depletion in order to increase engine overall efficiency.

3. Prechambers

One of the methods of increasing the control of mixture formation is the implementation of a split combustion chamber. It is a solution based on the concept of dividing the combustion chamber into the main and preliminary space, showing a different structure depending on the fuel used. In compression ignition engines (Fig. 5b), the prechamber is classified as active, which means that the fuel is injected directly into it and its volume is usually from 25% to 40% of of the main chamber volume [17]. The shape of the prechamber separated from the main chamber by a necking enables the creation of controlled conditions for the self-ignition of the mixture by generating a sufficiently high temperature in it and reducing the excess air coefficient. The swirl chambers (Fig. 5a) also allow for the creation of a turbulence that allows for better mixing of the load. In the next phase of the combustion process, the high-speed ignition of the rich mixture in the prechamber at its exit allows for quick mixing with the excessive air in the main space, creating a lean mixture, the combustion of which is initiated by the ignition of the rich mixture.

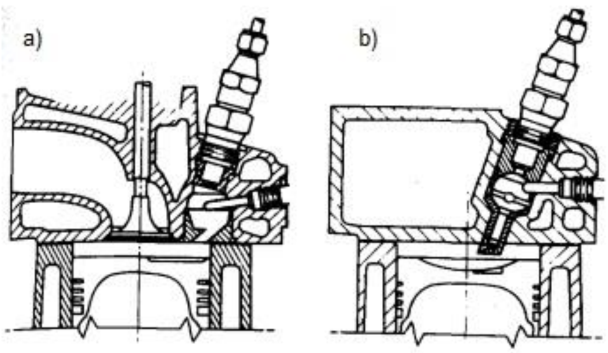

Fig. 5. Splitted chamber systems of CI engines: a) swirl chamber, b) prechamber [6]

In the case of spark ignition internal combustion engines, except some special cases, the prechambers are not a commonly used solution. The reasons for this state of matter can be found in the physicochemical properties of liquid fuels. Due to the smaller volume of the prechamber compared to compression ignition engines amounting only up to a few percent of the main chamber volume, phenomenon of fuel deposition on the walls of the chamber occurs, so that part of it does not participate in the combustion process, resulting in an increase in hydrocarbons emissions. The prechambers, on the other hand, exhibit promising results in the context of engines powered by gaseous fuels [31, 32]. As the research shows, the best results are obtained when an active chamber is used, which allows to obtain a stratified charge through an additional injector installed in it (Fig. 6b). This solution allows for the formation of an ultra-lean mixture with an excess air ratio above 3 in the main combustion chamber.

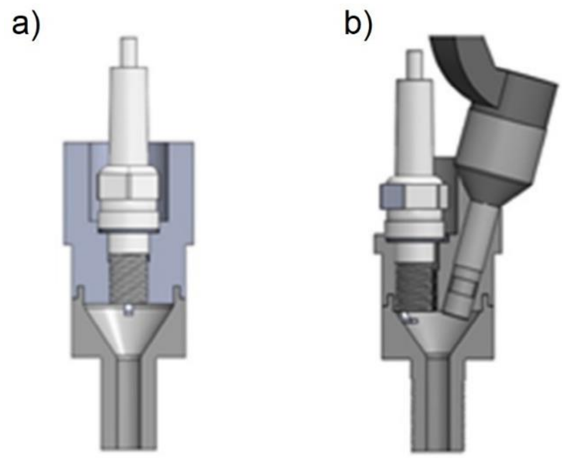

Fig. 6. Prechambers used in SI engines: a) passive prechamber; b) active prechamber [1]

4. Proposed system description

The preliminary function of a system proposed by the author is to improve the combustion parameters of the hydrogen-air mixture in the area of light knock. The use of an active prechamber integrated with the head should enable the use of a greater degree of mixture depletion than in the case of chambers screwed into the spark plug seating. This solution should ensure better heat transmission from the combustion process and allow for even flame propagation due to orifices installed in the prechamber necking area. The main advantage of the discussed system should be a higher compression ratio while maintaining pressure pulsation below the light knock limit.

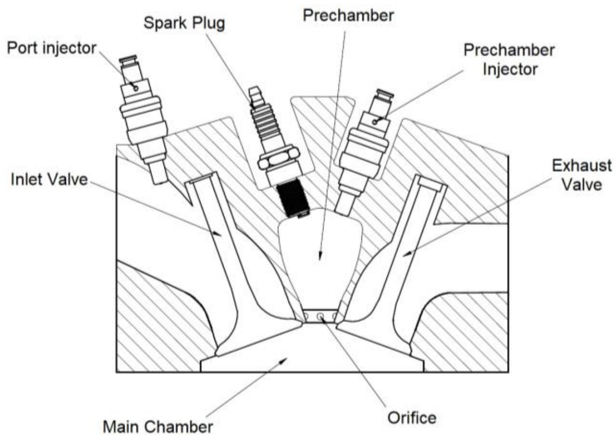

Fig. 7. Simplified scheme of hydrogen combustion prechamber system

The presented system (Fig. 7) assumes the formation of a lean or ultra-lean mixture in the space of the main combustion chamber by means of indirect hydrogen injection. It is also considered to apply direct injection system in the future as it gives better results in real conditions tests [4]. In the space of the preliminary chamber, the volume of which is assumed to be a few percent of the volume of the main chamber, integrated with the cylinder head, the ignition of the stoichiometric or lean mixture is initiated. The mixture then ignites in the main chamber, creating a stratified charge combustion mechanism. The geometry of the pre-chamber and the detailed parameters of the optimal excess air coefficients will be the subject of further research by the author.

5. Summary

Taking into account the factors mentioned in the previous chapters, it seems justified to conduct research aimed at examining the effect of using split combustion chambers in hydrogen powered combustion engines. Further research in this direction could contribute to the popularization of hydrogen as a fuel, and thus increase the share of fuels from renewable sources.

Combustion of hydrogen in internal combustion engines generates a number of problems, mainly due to the complicated mechanism of combustion. In the course of the analysis, it was found that the compression ratio and the degree of mixture depletion are the factors that have the greatest impact on the hydrogen combustion process. On the basis of the literature review, their impact on the generation of hydrogen knock was determined, which, depending on the intensity of pressure pulsation in the combustion chamber, can be divided into heavy knock, which is a highly undesirable phenomenon, and light knock, in the area of which, according to the author, it is possible to improve the combustion process.

Based on the analysis of the issues discussed in the following article, the author presents a preliminary proposal for a hydrogen combustion system in an internal combustion engine, the operation of which should be verified in further research. In principle, this system is to be characterized by efficiency higher than that of any previously known solution.

Nomenclature

CFR	cooperative fuel research
CI	compression ignition
CR	compression ratio
MN	methane number
MON	motorized octane number
ON	octane number
PP_{AVG}	average pressure pulsation intensity
RON	research octane number
SI	spark ignition
λ	excess air coefficient
φ	equivalence ratio ($1/\lambda$)

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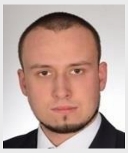

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