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HYDROGEN AS FUEL IN OPERATION OF INTERNAL COMBUSTION ENGINES

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Abstract

Hydrogen internal combustion engines (HICE) are presently the subject of numerous R&D projects. For hydrogen fuelling mainly, spark-ignition engines are adapted but it is also possible to adjust self-ignition engines. Self-ignition engines may be fuelled only with dual-fuels and usually demonstrate an oversized level of compression ratio requiring reduction because of engine knocking, whereas spark-ignition engines – on the contrary feature an undersized level of compression ratio that needs to be increased to ensure an effective combustion process. Hydrogen may be used also for gasoline dual-fuel engines. Hydrogen utilization as diesel engine fuel should be considered depending on the type of diesel cycle:

1. *The use of hydrogen alone or as an addition to gasoline or LPG and methane in spark-ignition engines;*
2. *The use of hydrogen as an addition to diesel oil in self-ignition engines.*

In the paper are presented the review of the literature on the use only of hydrogen as a fuel or only of the addition of hydrogen to hydrocarbon fuels in engines with spark ignition and diesel. Have been studied combustion process, generation of heat and power, and efficiency of the engine. Have been evaluated opportunities to reduce harmful emissions. Have been evaluated possibilities of using hydrogen as a fuel for both type of engines. In the paper are presented the review use hydrogen as a fuel for vehicles with fuel cells too.

Keywords: *Exhaust Emission & Ecology, Hydrogen, Engines, Vehicles*

1. Introduction

For hydrogen fuelling mainly, spark-ignition engines are adapted but it is also possible to adjust self-ignition engines. Self-ignition engines may be fuelled only with dual-fuels and usually demonstrate an oversized level of compression requiring reduction because of engine knocking, whereas spark-ignition engines – on the contrary – have too little of compression ratio that needs to be increased to ensure an effective combustion process. Hydrogen may be used also for gasoline dual-fuel engines.

Hydrogen supply to IC engines should be considered depending on the type of engine cycle:

1. The use of hydrogen alone or as an addition to gasoline or LPG and methane in spark-ignition engines;
2. The use of hydrogen as an addition to diesel oil in self-ignition engines.

2. The use of hydrogen as fuel or addition to gasoline or LPG or methane in spark-ignition engines

It was found in the paper [6-7] that fuelling IC engines of hydrogen (HICE) is a temporary solution before fuel cells are introduced. Hydrogen IC engines are based on the technology of spark ignition piston engines and after some modifications may be used fuelled both with conventional fuels as well as with hydrogen.

Table 1 presents a comparison of chosen parameters of fuels, e.g. hydrogen, methane, gasoline and LPG that may be used for fuelling spark-ignition engines.

Tab. 1. Comparison of parameters of fuels at temperature 25°C and 1 bar pressure [16]

Property	Unit	Hydrogen	Methane	Gasoline	LPG(1)
Density	kg/m^3	0.0824 – 0.0838	0.72 – 0.65	730 – 744	2.25
Octane number (LOM)	-	130	125	86	95
Upper calorific value	MJ/kg	141.7	52.7	48.3	
Lower calorific value	MJ/kg	119.7 – 119.9	42.2 – 46.7	43.0 – 44.8	46.1
Flammability range	% V/V	4 – 75	4.3 – 15	1.4 – 76	1.8 – 9.0
Min. ignition energy	mJ	0.02	0.28 – 0.29	0.24 – 0.25	
Flame rate	m/s	1.85 – 1.90	0.38	0.37 – 0.43	0.39
Self-ignition temperature	°C	585	450 – 540	257 – 277	510 – 490

(1) *with 50% propane and 50% butane*

In the papers [3, 8], authors refer to pre-ignition hydrogen as one of the main problems in applying hydrogen in piston engines with spark ignition.

According to the authors, the basic causes for self-ignition include:
- low energy of hydrogen ignition (0.02 mJ),
- wide range of combustion limits 4%-75% v/v,
- small critical distance for flame propagation.

Because small gasoline engines operate with a slightly richer mixture and do not have a catalytic reactor, their fuel consumption and emissions are very high. When gasoline engines are fuelled with hydrogen only, emission of NO_X increases and the flame often retreats to the inlet system. The results of studies presented in the paper [6] lead to the following conclusions:
- the most appropriate air fuel ratio is $\lambda = 1.5$ because of stable engine work and prevented retreat of flame to the inlet system,
- the retreat of flame to the inlet system can be eliminated by using a poor mixture and delivering hydrogen immediately after the inlet valve,
- it has been found that engine power dropped by approx. 24% in case of hydrogen fuelling compared to gasoline,
- emissions of HC, CO and CO_2 are at minimum levels when engines are fuelled with hydrogen in result of vapouring and combustion of lubricating oil,
- the results of studies proved that fuel consumption rates and CO, HC, NO_X and CO_2 emissions may be improved when hydrogen as a fuel is used in small carburettor engines that do not require any significant changes.

Paper [1] presents results of studies of a 6-cylinder, spark-ignition engine type MAN E2876 LE302 intended for a power generator and as a standard fuelled with natural gas and hydrogen alternatively. The studies were carried out at a fixed rotational speed of 1500 rotations per minute and variable engine load. Those conditions correspond to the work of the engine in a power-generator. Parameters of the engine that had to be adjusted to hydrogen fuelling included in particular the angle of ignition advance and air fuel ratio.

Compared to natural gas fuelling, when fuelling engine with hydrogen the concentration of carbon oxide and hydrocarbons was minor and resulted mainly from the combustion of lubricating oil. However, a small increase concentration of nitrogen oxides was recorded only in conditions of load close to maximum. In both cases, general engine efficiency is high and when fuelled with natural gas its maximum value is approx. 42%, whereas when fuelled with hydrogen it came to c.a. 37%.

2.1. Adding hydrogen to gasoline

Another important feature of hydrogen allowing for its convenient use as a fuel addition is the possibility of its combustion at very low concentration, which in effect expands the flammobility range of the air fuel mixture [16].

Based on data shown in Tab. 1 and earlier findings on the difference in calorific values of hydrogen, CNG and gasoline it can be concluded that hydrogen addition in fuel should decrease the calorific value of the air fuel mixture (stoichiometric hydrogen air mixture has calorific value of 2913 kJ/m^3, which is equal to 3446 kJ/m^3 in case of gasoline & air mixture) [16].

Another aspect of using hydrogen addition to which attention should be given is the combustion rate. In case of hydrogen it is almost 7 times greater than in case of gasoline, thus is very valuable from the point of view of the combustion process. The process is much faster, approx. 13-17% less thermal energy is lost through radiation to the cylinder walls, head, etc. Moreover, because hydrogen as an addition contains no carbon compounds, the emission of carbon compounds (HC and CO) is lesser, thus increasing the emission of NO_X [16]. Thermal efficiency of the engine drops together with the increase of hydrogen addition. The studies presented in [16] concerning the impact of hydrogen addition in gasoline (mixtures up to 60% of volume) prove that:

- hydrogen addition in rich mixtures does not show any greater impact on indicated pressure or combustion time,
- hydrogen addition in poor mixtures causes increase of torque and average effective pressure, whereas combustion time drops. Faster combustion process leads to an increase in NO_X emission,
- together with the increase of hydrogen addition, changes in the studied parameters are more and more important.

In papers [3, 8] the authors point to the following features of combustion of hydrogen with hydrocarbon fuels in spark-ignition engines:

- flammability point of hydrogen several times lower than in case of methane and gasoline, which expands the flammability range of poor mixtures,
- the speed of hydrogen combustion is 7 times greater than the speed of combustion of methane and gasoline, i.e. less heat energy is emitted to the environment by radiation (only 17-25%). In case of methane it comes to 22-33% and to 30-42% in case of gasoline,
- compared to hydrocarbons hydrogen characterises with high diffusion, which has impact on good mixing quality, turbulence and homogeneity of the flammable mixture,
- very low value of the ignition energy facilitates immediate ignition and easy cold start-up of the engine,
- damping port is 3 times smaller than similar parameters for hydrocarbon fuels, which means that the flame shall move closer to the cylinder walls and combustion shall be more effective,
- hydrogen addition causes a decrease of CO and HC emissions and an increase in NO_X emission and thermal efficiency of the engine, especially when fuelled with a poor mixture.

In paper [13] the study addressed the impact of hydrogen addition to gasoline on the value of average effective pressure, engine work efficiency, efficiency filling of cylinders and emission characteristics. The results of the studies proved that fuel consumption and average effective pressure had been decreased through of hydrogen addition. The results of studies also showed that thermal efficiency of the engine was greater than in case of gasoline combustion. Furthermore, HC and CO emissions dropped owing to the use of hydrogen addition.

The results of studies presented in the paper [12] regarding impact of combusting hydrogen addition to gasoline compared to the combustion of gasoline in spark-ignition engines lead to the following conclusions:

- the engine was found working stably on poor mixtures,

- with the hydrogen addition the engine power increased,
- the unit consumption of fuel decreased and the level of HC and CO emissions lowered,
- higher level of NO_X emission was observed, especially when combusting mixtures within the range of $\lambda = 1\text{-}1.4$,
- with quality adjustment of the engine power, the emission of NO_X can be lowered.

2.2. Adding a mixture of hydrogen and oxygen (HHO fuel) to gasoline

HHO stands for a combination of hydrogen and oxygen as a product of electrolyser that may be located on board of the vehicle. In the paper [17] results of studies were presented in the AVL BOOST programme regarding the process of combustion of a mixture of gasoline and HHO in a spark-ignition engine. The engine's model was based on a real, four-cylinder, four-stroke Holden C20LE engine with engine displacement equal to 2.0 dm^3. Subject to analysis was the average indicated pressure, the efficiency in filling cylinders and the rate of heat release for 10 different values of the composition of the flammable mixture. The performance of an engine fuelled with gasoline and fuelled with a mixture of gasoline (90%) and HHO (10%) was compared.

With model studies of the combustion process, it was possible to formulate the following conclusions:

- introducing hydrogen – oxygen mixtures to the combustion chamber has considerable impact on the combustion process,
- a positive impact on the composition of combustion gases was found, in particular the emission of CO_2 and nitrogen oxides dropped when combusting poor mixtures,
- a higher level of hydrogen and oxygen (HHO mixtures) in the combustion chamber has been found to result in a lower average indicated pressure and concurrent decrease in engine performance,
- also noted was a change in the rate of heat release and the velocity of pressure growth and relocation of the occurrence of maximum pressure.

2.3. Adding hydrogen to LPG

The study of the impact of adding hydrogen to LPG on the emission of harmful substances, thermal efficiency and the functionality of the engine allowed for drawing the following conclusions [16]:

- the average effective pressure and thermal efficiency drop together with the increase in the quantity of the added hydrogen. Adding hydrogen to LPG does not affect those parameters of the engine,
- compared to an engine fuelled with LPG only, adding hydrogen in the quantity of 10% v/v and mixture composition of $\lambda = 0.9\text{-}1.15$ results in considerable increase in NO_X emission. Maximum NO_X emission was found at $\lambda = 1.2$. Adding 20% H_2 causes an increase of approx. 20% of NO_X emission.

2.4. Adding hydrogen to methane

Paper [11] addresses the possibility of combusting poor mixtures by adding hydrogen to a spark-ignition engine fuelled with methane. The following hydrogen additions of 10%, 30% and 50% of methane's volume were used. The results of the study show that the limit of combustion of poor mixtures may be moved towards poor mixtures by adding hydrogen, in particular in greater engine load. The impact of engine's rotational speed on the said limits is much lower. The angle of ignition advance also has impact on the limits of combustion of poor mixtures but both excessive delays as well as ignition lead is not recommended.

Paper [5] presents the results of studies of the impact of combustion of gasoline, LPG and CNG and mixtures of methane and hydrogen on pressure in the combustion chamber, the rate of heat release and the length of combustion process in experimental studies on spark-ignition engine with 1.6-dm3 capacity in Opel Astra vehicle and in the EnComTwo simulation programme. In result of the studies it was found that adding 15% of hydrogen to the methane air mixture results with the same combustion process as when combusting gasoline without adjusting the engine's setting.

Paper [4] presents the results of studies conducted in ENEA laboratories, which aimed to identify potential possibilities of using mixtures of natural gas and hydrogen (known as HCNG or Hythane) in the used motor vehicles. The Iveco Daily CNG delivery van was tested, adapted to spark ignition and stoichiometric fuelling of engine with methane in ECE15 cycle, comparing levels of emission when fuelling the engine with methane with the results achieved when fuelling the engine with hydrogen and methane mixtures when combusting mixtures both stoichiometric and poor.

It was found that optimal conditions of HCNG combustion could be achieved by applying – depending on the conditions of engine's operation – both the combustion of poor mixtures in order to reduce fuel consumption and the combustion of stoichiometric mixtures in order to reduce emission of harmful substances.

Papers [14-15] present the results of studies on fuelling spark-ignition engines with various mixtures of methane and hydrogen (Hythane). The fuel system delivers a mixture of natural gas/hydrogen in variable proportions, adjusted independently of the conditions of engine's operation. The impact of the fuel's composition on the engine characteristics and the emission of harmful exhaust substances were studied with content of 10% and 20% of hydrogen in the methane/hydrogen mixture. It was proved that in order to achieve maximum efficiency of the engine across the entire load range with concurrent low level of emission of exhaust substances the composition of the mixture should be varied with regard to engine load factor. For hythane with low hydrogen content (up to 20%) a limited improvement in emission can be obtained.

3. The use of hydrogen as an addition in diesel oil in self-ignition engines

Because of its properties, hydrogen is better predisposed to fuelling of spark-ignition engines than self-ignition engines. However, because of high calorific value, the possibility of limiting the emission of toxic substances, attempts were made to fuelling of self-ignition engines with hydrogen [16]. Those studies focused on hydrogen added to fuel because hydrogen has poor self-ignition properties and as such cannot in this type of engine be used as the only fuel. Tab. 2 presents a comparison of chosen properties of diesel oil and hydrogen.

The impact of hydrogen on the combustion process in self-ignition engines is similar as the impact described earlier on spark-ignition engines (low calorific value vs volume, decrease in the emission of toxic carbon compounds, high flame speed).

Current studies [10] show that depending on the quantity of the added hydrogen thermal efficiency of the engine drops, increases the delay of self-ignition and promptness in increasing pressure in the cylinder (self-ignition of the mixture occurs later while the combustion of the mixture is faster). Increased temperature leads to increase in the concentration of nitrogen oxides, but noticeable is considerable drop in the emission of carbon compounds.

Studies on the impact of hydrogen addition on the combustion process and generation of thermal energy and the concentration of harmful substances were conducted in the Institute of Vehicles of the Warsaw University of Technology on a turbocharged engine Perkins 1104C-44T with engine displacement of 4.4 dm^3 with direct fuel injection with rotational speed of n = 1100 rotations per minute. Hydrogen was delivered to the engine's inlet system upstream the turbocharger in the quantity up to 9% of the mass of diesel oil.

Tab. 2. Comparison of properties of diesel oil and hydrogen [10]

Property	Unit	ON	Hydrogen
Density	kg/m^3	840	0.0824 – 0.0838
Lower calorific value	MJ/kg	42.49	119.81
Flame ratio	m/s	0.3	1.85 – 1.9
Cetane number	-	45 – 55	-
Self-ignition temperature in air	°C	280	585

In result of the aforementioned unpublished studies:

- a noticeable cleare change in the character of the curves (increase of maximum pressure of combustion by approx. 3%) and increase in the rate of heat relaese in the phase of diffusion combustion by approx. 10%), however key parameters for the combustion process (self-ignition delay, share of kinetic phase of combustion in the entire process) remained unchanged after hydrogen was added,
- theoretic deliberations on the decrease of concentration of toxic substances had not been confirmed. The analysis of the impact of hydrogen addition in the inlet system in a self-ignition engine showed an increase in the concentration of all studied constituents of exhaust (i.e. carbon oxide, hydrocarbons, nitrogen oxides and particules).

Studies conducted at the Poznań University of Technology in the IC Engines and Transport Institute prove that hydrogen addition of 5% ÷ 7% m/m to the combustion chamber has no greater impact on the performance of the engine, however it was noticed that of great importance is the method of receiving and controlling the composition of the hydrogen & air mixture.

The subject of the paper [2] comprised an analysis of the possibility of improving environmental friendly indicators in self-ignition engine AVL 5804 bi-fuelled with diesel oil with hydrogen addition). Bi-fuelling provided hydrogen to the inlet channel and a self-ignition dose of the diesel oil was used, each time defined for a particular load and rotational speed as a source of ignition of the hydrogen air mixture.

Fuelling the engine with diesel oil with hydrogen addition delivered to the inlet duct caused an apparent change in thermo-dynamic and ecological indicators, i.e.:

- maximum reduction of the speed in pressure growth $dp/d\alpha$ by approx. 5% and the value of the maximum pressure in the combustion chamber by approx. 6%,
- increase in the concentration of carbon oxide by approx. 150%,
- decrease in the concentration of nitrogen oxides by approx. 25%,
- decrease in the concentration of non-combusted hydrocarbons by approx. 300%,
- increase in the concentration of particles by approx. 150%.

4. Conclusions

The possibilities of using hydrogen as fuel should be considered depending on the type of ignition:

1. The use of hydrogen in spark-ignition engines:

   The analysis of impact of using hydrogen only as the basic fuel proved that:

- efficiency can be achieved on a similar or higher level than in case of a conventional engine fuelled with gasoline with limited engine power,
- high emission in exhaust of nitrogen oxides only (the fuel does not contain any carbon compounds producing toxic substances).

The analysis of the impact of hydrogen used as an addition to hydrocarbon fuel proved that:

- it is possible to achieve efficiency similar to that of a conventional engine fuelled with gasoline

with slight limitation of engine's power,
- decrease in the emissions of CO and HC and increase in the emission of NO_X and increase in the thermal efficiency, especially when a poor mixture is used.

Summarising, it can be stated that the analysis of results of studies justifies the use of hydrogen as an addition to fuels in spark-ignition engines but significant changes in the construction of the engine are necessary, mainly by using a hydrogen injection to the combustion chamber while combusting poor mixtures with low engine load factors and stoichiometric mixtures with full engine load. It is necessary to introduce to the system combustion gases treatment removing NO_X, e.g. SCR system.

2. The use of hydrogen in self-ignition engines

The analysis of the impact of hydrogen addition in the inlet system of the engine proved that:
- the speed in the growth of pressure and the value of maximum pressure in the combustion chamber decreased, which had minor impact on the power and efficiecy of the engine work,
- concentration levels of all components of exhaust analysed increased (i.e. carbon oxide, hydrocarbons, nitrogen oxides and PM).

Summarising, the analysis of results of the studies does not justify the use of hydrogen as a fuel addition in self-ignition engines. It is a temporary solution before fuel cells are introduced.

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