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EVALUATION OF THE IMPACT OF COMBUSTION HYDROGEN ADDITION ON OPERATING PROPERTIES OF SELF-IGNITION ENGINE

OCENA WPŁYWU SPALANIA DODATKU WODORU NA WŁASNOŚCI EKSPLOATACYJNE SILNIKA O ZAPŁONIE SAMOCZYNNYM*

The work presents the results of effect of the addition of hydrogen in an amount up to 9% of mass of diesel oil into the intake system of Perkins1104C-E44TA engine. The impact of hydrogen addition on process heat release in the combustion chamber and the concentration of CO, THC, NOX and PM in the exhaust at predetermined engine operating conditions. It was summarised that the analysis of the results does not justify the use of hydrogen as a fuel additive in self-ignition engines.

***Keywords**: IC engines, hydrogen, diesel, heat emission.*

W pracy przedstawiono wyniki badań wpływu dodatku wodoru w ilości do 9% masy oleju napędowego do układu dolotowego silnika Perkins1104C-E44T. Oceniono wpływ dodatku na proces wydzielania ciepła w komorze spalanie i stężenia CO, THC, NOX i PM w spalinach w ustalonych warunkach pracy silnika. W podsumowaniu stwierdzono iż analiza wyników badań nie uzasadnia stosowania wodoru jako dodatku do paliwa w silnikach o zapłonie samoczynnym.

***Słowa kluczowe**: silniki spalinowe, wodór, olej napędowy, wydzielanie się ciepła.*

1. Introduction

Fuelling hydrogen internal combustion engines (HYICE) with hydrogen is presently the subject matter of numerous research & development works. According to paper [5] it is a temporary solution before projected fuel cells are implemented, which aims to prepare for and put into operation hydrogen storage and distribution infrastructure. Mainly spark-ignition engines are adapted for hydrogen fuelling but it is also possible to adjust self-ignition engines for hydrogen fuelling.

Hydrogen supply IC 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.

1.1. Hydrogen in spark-ignition engines.

An analysis of the impact of hydrogen used as basic fuel [3, 4] proved that:

- it is possible to achieve efficiency at a level similar or higher than in case of a conventional engine fuelled with gasoline with limited engine power;
- high emission of nitrogen oxides in exhaust (fuel contains no carbon compounds producing toxic substances).

An analysis of impact of use of hydrogen as an addition to hydrocarbon fuel [1, 8, 13, 15] proved that:

- it is possible to achieve efficiency similar to that of a conventional engine fuelled with gasoline with slightly limited engine power,
- CO and HC emissions decrease, whereas the emission of NO_X increases and thermal efficiency grows when poor mixtures are used.

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 [5].

In the papers [3, 4], 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 pre-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.

As regards the effects of pre-ignition the authors point to:

- lower efficiency of engine,
- engine roughness work,
- possibility that flame moves to the inlet duct.

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 [8].

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

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%.

In paper [15] 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 [13] 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 $\lambda = 1 - 1{,}4$,
- with quality adjustment of the engine power, the emission of NO_X can be lowered.

Paper [10] 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 [12] 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 can 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. Effective combustion of poor mixtures requires – however – optimisation of compression ratio and charging of the engine, the angle of ignition advance and the share of hydrogen in the mixture mainly because of decreased engine power due to lower content of energy in the volume of HCNG mixture (11% in case of a mixture with 15% of hydrogen in its volume).

Summarising, the analysis of results of studies justifies the use of hydrogen as a fuel addition in spark-ignition engines provided that significant changes in the engine construction are introduced, mainly by using hydrogen injection to the combustion chamber while at the same time combusting poor mixtures at low engine load and stoichiometric mixtures with full engine load. It is necessary to introduce a system eliminating NO_X in combustion gases, e.g. SCR system.

1.2. Hydrogen in self-ignition engines.

Hydrogen in a self-ignition engine may be used only as an addition to diesel oil or biodiesel [8] as it has poor self-ignition properties and as such cannot be used alone in this type of engine. Studies conducted at the Poznań University of Technology in the Institute of IC Engines and Transport [2] show that hydrogen addition of 5% ÷ 7% m/m to the combustion chamber has no greater impact on engine performance but is does result in increased CO and PM emissions.

According to a study conducted in Vilnius Gediminas Technical University (VGTU) stated that smokiness decreases with the additional deployment of hydrogen. Other indicators of the exhaust gas using the hydrogen in case of the rig tests are worse [7]. Similar opinions contained in [6, 11, 14].

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 [17]. 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. Table 1 presents a comparison of chosen properties of diesel oil and hydrogen.

Table 1. Comparison of properties of diesel oil and hydrogen [9]

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
Carbonisation residue	-	0,1	0,0

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 [9] 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.

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/dα 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%.

The aim of this work was to evaluate – through tests – the impact of hydrogen addition in diesel oil on the process of heat release and concentration of harmful substances in self-ignition engines.

2. Test stand

Tests were carried out on Perkins 1104C-E44T engine with eddy current brakes Schenck WM 400 controlled with controller Schenck X-ACT. The apparatus for measuring indicated pressure and analysing thermal emission consisted of AVL INDISMART system for engine indication and a position sensor for crankshaft AVL 365C01. Data had been sent to a PC in real time. With IndiCom software it was possible to view incoming data (also in real time), to record a cycle of 50 measurements and to save the files together with parameters of the tested engine.

Thereafter, the resulting data had been subject to processing with the use of AVL Concerto. The said programme averaged changes of pressure in the cylinder and calculated the rate heat release without taking into account heat loss to cylinder walls (net heat emission). Moreover, during the tests CO, THC and NO_X concentration were recorded with the use of AVL CEB2 combustion gases analyser, equipped with PROVIT 5600 control panel. Measurements of the concentration PM had been estimated with AVL 415. The engine was fuelled with diesel oil (PKN Orlen) and hydrogen addition under pressur 150 bar in cylinder.

Diesel oil consumption was measured with a volume method, whereas the quantity of hydrogen after the reduction of its pressure was gauged with a specially marked rotameter. Hydrogen was delivered before the turbine to the engine's inlet system. Technical data of the engine are presented in table 2 and the test stand overview is shown (Fig. 1).

Table 2. Technical parameters of Perkins 1104C-E44T engine

Parameter	Unit	Value
Effective power	kW	74,5
Compression ratio	[-]	18,2
Cylinder diameter	mm	105
Piston stroke	mm	127
Engine displacement	dm^3	4,4
Number and cylinders, system	[-]	4, stroke
Fuelling system	[-]	Direct injection
Recharge	[-]	Yes; turbocharger

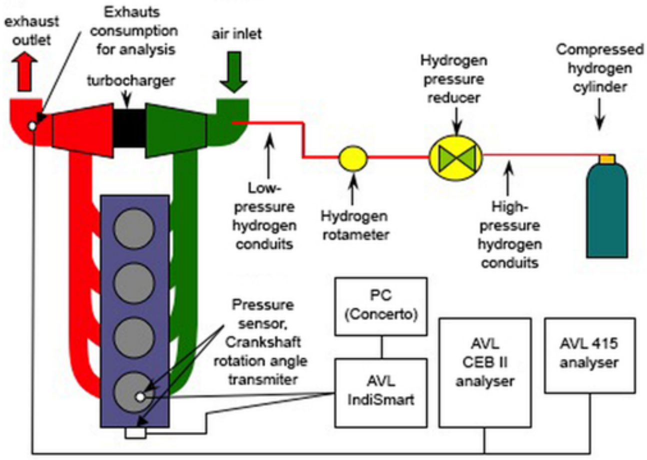

Fig. 1. Diagram of bench with diagram of engine Perkins 1104C-E44TA

3. Results of studies

The studies were conducted with a fixed rotational engine speed of n = 1100 rotations per minute and diesel oil in a quantity equal to torque developed by the engine at the level of M = 165 Nm. Hydrogen was equal to 8.9% of the mass of diesel oil by decreasing the quantity of diesel oil gradually together with the increase of hydrogen addition in order to achieve torque of approx. 165 Nm. The results of pressure measurement in the combustion chamber and the results of calculations of rate of heat release in an engine fuelled with diesel oil only and diesel oil and a hydrogen addition of 5.5% and 8.9% are presented (Fig. 2, Fig. 3) respectively.

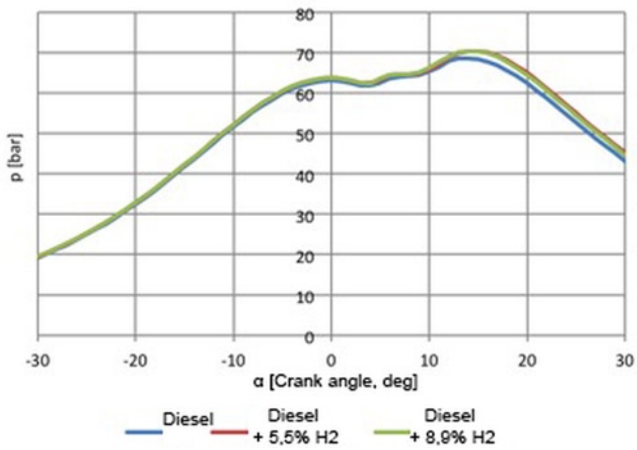

Fig. 2. An indicator diagram p = f (α) with the engine in the conditions of n = 1100 r / min, M = 164 Nm powered diesel and diesel with the addition of 5.5% H_2 and 8.9% H_2

Then again, the results of measurements of CO concentration using method NDIR, THC with FID method and NO_X with CL method and PM mass concentration with the filter method in an engine fuelled with diesel oil and diesel oil with hydrogen addition are presented below (Fig. 4, Fig. 5).

4. Analysis of results of tests and conclusions

Hydrogen addition did not influence definitely essential differences in the combustion process. A slight change in the character of pressure curves in the combustion chamber was noted (increase of maximum combustion pressure by approx. 2%). The curves of rate of heat release show a classic kinetic and diffusion phase depending on fuel type. The kinetic phase remained almost identical, whereas

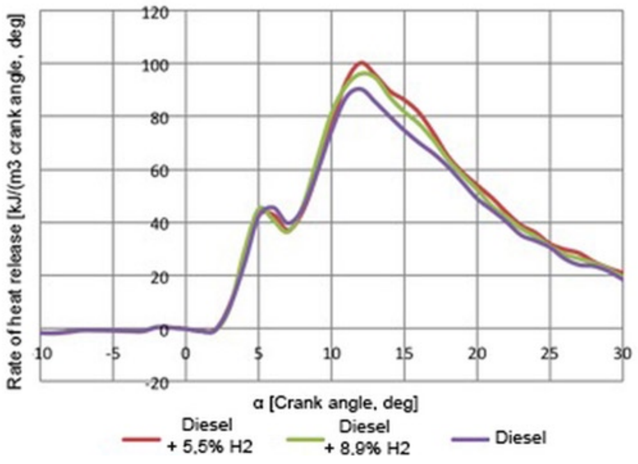

Fig 3. *The rate of heat release as a function ºOWK with engine operating conditions of n = 1100 r / min, M = 164 Nm powered diesel and diesel with the addition of 5.5% H_2 and 8.9% H_2*

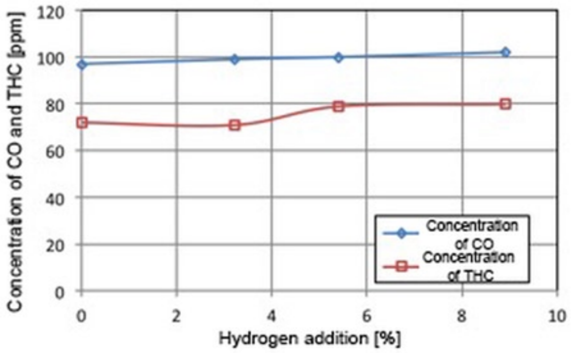

Fig 4. *The results of the measurement of concentrations of CO and THC depending on the hydrogen addition with the engine supplied with diesel oil with additions of hydrogen*

during the diffusion phase of rate of heat release increased by approx. 10%, most likely due to hydrogen combustion. Key parameters of the combustion process (self-ignition knock, character of respective combustion phases) remained unchanged after hydrogen addition was applied.

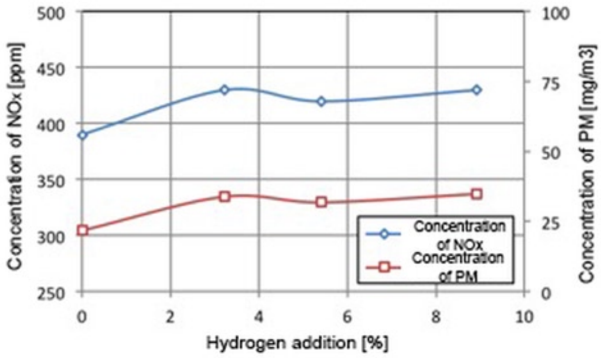

Fig 5. *The results of measurements of concentrations of NO_x and PM depending on the compactness of hydrogen addition measured when the engine supplied with diesel oil with additions of hydrogen.*

The results of measurements of concentration of toxic substances did not prove theories regarding the improvement of those indicators. The analysis of the impact of hydrogen addition in the inlet system of a self-ignition engine proved slight increase in the levels of all analysed constituents of exhaust (i.e. carbon oxide, hydrocarbons, nitrogen oxides and PM). Increase in CO and THC levels may stem from high reactivity of hydrogen inhibiting the oxidation of hydrocarbons as a result of which THC and PM levels increase. The increase in NO_X levels may result from increased temperature in the combustion chamber due to hydrogen addition.

The basic importance to sensible operation of technical object is the knowledge of its failures. Failure, understood as a limiting state of object can be dangerous for human life or/and does financial losses [16]. The ability of object to fulfil required function is called dependability. It covers some features of object as follows: availability, reliability, maintainability, safety, service and durability. The durability is an important tie in dependability chain [16].

Durability prediction of engine is done for example of piston rings for hydrogen fuelling engine [16]. According to [16] for hydrogen fuelling engine it can be expected faster wearing of piston rings than for petrol. The importanse of fuel effect on endine durability belongs to calorific value and elementary composition of fuel first of all [16], in diesel engines too.

Summarising, the analysis of results of the studies does not justify the use of hydrogen as a fuel addition in self-ignition engines.

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