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PERFORMANCE OF INTERNAL COMBUSTION ENGINE FUELED BY LIQUEFIED PETROLEUM FUEL WITH WATER ADDITION

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Summary

An attempt has been made to analyze water addition in various forms to the operating medium of an LPG fueled engine. The advantages of adding water to the operating medium of an engine has been described, both for spark and compression ignition engines powered with LPG fuel, including the impact on the operational parameters and pollutant emission. It is estimated that the addition of water to the operating medium has a beneficial effect on the thermal efficiency of circulation, at the same time contributing to the reduction of carbon monoxide, hydrocarbons and nitrogen oxides emission. The methodology of empirical research on spark ignited engine fueled with LPG with water addition has been presented: testing was carried out under conditions simulating traction engine usage – under the NEDC approval drive test, consisting of an Urban Driving Cycle – UDC and an Extra Urban Driving Cycle – EUDC. The characteristics of the fuel used in the test has been described, including its composition and selected physical and chemical properties. The results of empirical research have been presented, i.e. the fuel consumption

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and pollutant emission. It was found that the addition of water has an effect on reducing the operational fuel consumption and emission of carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide under engine operating conditions corresponding both to urban and extra-urban driving conditions.

Keywords: internal combustion engines, liquefied petroleum gas, LPG, water addition

1. Introduction

The mixture of liquefied hydrocarbon gases, mainly C3 and C4 (hydrocarbons with 3 and 4 carbon atoms), commonly known as LPG (*Liquefied Petroleum Gas*) is a specific type of fuel. It is widely used for heating and motor purposes, and in English literature is referred to as *autogas*). Its low production costs and – as a consequence – low market price, its high calorific value and the possibility of to obtain low pollutant emission as compared to conventional liquid petroleum fuels have been causing a rapid increase in the use of LPG fuel.

Yet another advantage of LPG fuel – as compared to other gaseous fuels – is the ability to store it in vehicles in a liquid phase at a pressure of approximately (0.3 ÷ 0.5) MPa, which does not require the use of costly and heavy high pressure cylinders [4, 5].

Poland is one of the leading markets for LPG fuel, which is accompanied by the dynamic development of the entire industry associated with the production and maintenance of LPG systems for vehicles. The industry is becoming an important element of the automotive industry, for the most part based on local solutions.

LPG fuel is used mainly for spark-ignition engines, originally fueled by petrol – therefore bifuel engines [4, 5]. Engine start and warm up is fueled by petrol and the basic operation may be either fueled by petrol or LPG with a periodic dosage of petrol in order to cool the combustion chamber and improve the lubricating properties of fuel gas. There is also a possibility to use spark ignition engines fueled by LPG fuel only – such solutions are used primarily for large combustion engines used for the propulsion of heavy vehicles [4, 5]. Originally, these are usually compression ignition engine designs, upgraded to spark-ignition LPG fueled engines. This solution, however, is more often applied to fueling engines with natural gas.

LPG fueled spark ignition engines have favorable emission properties [6, 18, 24, 27, 32]. As in the case of all gaseous fuels, there is a visible reduction in emission of carbon monoxide and – usually – hydrocarbons, which mainly results from the fact that gaseous fuels generate a significantly more uniform combustible mixture than is the case for liquid fuel combustion. The results of nitrogen oxides emission are ambiguous – in some cases, because of the higher combustion temperature of gaseous fuel, the emission of nitrogen oxides is increased. One particularly preferred use of autogas is to fuel spark ignited direct injection engines – engines utilizing the 6th generation autogas systems [5]. In such engines the original injector is used for the injection of petrol or LPG fuel in its liquid phase. Using LPG fuel to power compression ignition engines [18, 27, 32] makes it possible to reduce the emission of particulates (i.e., their mass), as well as the number of emitted particles [18, 27, 32].

There is also the possibility of using LPG fuel to power compression ignition engines [19, 23, 28]. In such a case, a mixed type ignition takes place in the cylinders – compression ignition from the startup injection of heavy fuel, usually diesel, and forced, of fuel mixture with air. In the case of compression-ignition engines, thanks to the application of a LPG fuel system, it is possible to attain a reduction in emission of not only carbon monoxide and hydrocarbons but also nitrogen oxides, and – above all – a sharp reduction in particulate emission. Another environmental benefit is the reduction of noise emission.

However, there are also disadvantages of LPG fuel application to internal combustion engines. Major issues might include a higher thermal load of the combustion chamber due to a higher combustion temperature of light hydrocarbons and virtually no lubricity of gaseous fuels. This may be the cause of increased wear for certain components – exhaust valve plates and exhaust valve seats in particular. One of the possibilities for improvement in this regard is the use of water addition to the cylinder's operating medium.

Water addition to operating medium in internal combustion engines is a solution known from the beginning of the twentieth century. As early as in 1913, P. B. Hopkinson in his publication [13] described the addition of atomized water, supplied to the cylinder of a diesel engine, which facilitated, among others, the reduction of heat load on the piston crown and combustion chamber and the reduction of knock. Initially, the addition of water to the operating medium has been primarily used in internal combustion engines, which require the use of high performance solutions, as is the case of, for instance, aircraft engines [7, 8]. By lowering the combustion chamber and cylinder temperature, the engine's tendency to knock was reduced, making it possible to use a higher compression ratio in spark ignition engines, therefore attaining an increase in effective output. Also, solutions utilizing water addition to operating medium were sporadically used, mainly for reasons related to engine cooling, which also included the solutions used in aircraft engines that involved replacing the traditional engine cooling system with water injection to the operating medium [7, 8].

The operating medium can be fed with water [7, 8, 14–17, 20–23, 25, 26, 29–31]:
- by direct injection into the combustion chamber,
- with inlet air:
  - by water injection into the inlet air,
  - by supplying water vapor into the inlet air,
  - by feeding air-water spray into the inlet air,
- with fuel in the form of fuel-water emulsion.

The use of fuel-water emulsion provides particularly significant advantages. The authors [14, 30] have shown that the use of emulsion significantly reduces the fuel consumption and decreases the temperature of emitted exhaust gases, consequently reducing the emission of nitrogen oxides.

The test results for water addition as a separate stream, fuel-water emulsion and vapor are presented in [1, 12, 15–17]. The study was conducted in relation to reducing the emission of harmful components of exhaust gases and increasing the thermal efficiency of the engine. Adding water to operating medium proved to have a beneficial effect on the tested scope of facets.

J. A. Harrington [12], in his paper, verified a significant effect of the addition of water on the reduction of knock and the emission of nitrogen oxides, with concurrent reduction of carbon monoxide emission and a slight increase in the emission of hydrocarbons.

In addition, the presence of water in the combustion process facilitates certain processes taking place in the combustion chamber, for instance hydrolysis, pyrolysis, reforming, and hydrogenation [1, 14, 29]. As a result of these processes, a substantial acceleration in the oxidation of hydrocarbons is evident, which tends to reduce the emission of partial and incomplete combustion products [1–3, 7–10, 12, 15–17, 25, 26, 32]. During combustion at high temperatures water reacts with, for instance, soot, produced as the result of hydrocarbon disintegration under conditions of local oxygen deficiency, according to the following chemical equation:

$$C + H_2O \rightarrow CO + H_2 \tag{1}$$

producing high-energy gases, which are easily subjected to complete and total combustion.

At the same time the significant heat of water evaporation contributes to reducing the temperature of the medium, which enables the reduction of nitrogen oxide emission – in accordance with the thermal mechanism of nitrogen oxides formation (J. B. Zeldowicz [33]), reducing the combustion temperature of stoichiometric mixture by 100 K causes a respective reduction of the nitric oxide formation rate by 33% [33].

Basic research on the combustion of fuel-water emulsions was presented in the works of M. W. Ivanow and I. P. Nefedova [14], who found that water emulsified in heavy residual oil causes a spontaneous phenomenon of fuel micro explosion in the combustion zone. The phenomenon of micro explosion is caused by a difference in the volatility of water and fuel. It is considered that the phenomenon of micro explosion generally increases the quasi-uniform mixture formation rate and – as a consequence – causes an increase in the oxidation reaction rate, thus reducing the emission of particulates. It was also found that the presence of water vapor has a beneficial effect on the kinetics of combustion processes. Carbon monoxide burns faster than in a wet air than in dry, the same tendency is observed in the case of hydrocarbon-water emulsion droplets.

A model of combustion of emulsion droplets was described in [30], including the micro-explosion phenomenon. The phenomenon reduces the size of droplets, which consequently evaporate faster in the combustion zone. The presence of water vapor in the combustion zone reduces the chemical reactivity of hydrocarbons, thus prolonging the self-ignition delay and improving the flame extinction. The effects of water depends on the physical and chemical properties of hydrocarbons used, and specifically on their volatility and oxidation rate [30].

H. Özcan and S. M. Soylemez [25, 26] conducted testing that aimed at assessing the effect of water addition on the LPG fuel combustion process in spark ignited engines. The testing involved feeding the water addition into the intake manifold. The test results indicated that the addition of water had a cooling effect on the air-fuel mixture and reduced the combustion rate – consequently lowering the peak combustion temperature, which in turn provided a 35% reduction in emission of nitrogen oxides, without any significant change in carbon monoxide and hydrocarbon emission. It was found that the addition of water to the intake manifold reduces the compression effort, due to a reduction in the operating medium temperature. Under the testing conditions, the increase of the water-fuel mass ratio (with constant fuel mass) was accompanied by an increased torque, power output and thermal efficiency of the engine. The average absolute increase in thermal efficiency for the mass-water ratio of 0.5 was approximately 2.4%, as compared to the use of pure LPG fuel for the tested engine RPM range.

In [2, 3, 7–10] the authors described experiments involving feeding water to the engine intake manifold using ultrasonic atomization method. For this purpose, an ultrasonic waveguide at a frequency of approximately 40 kHz was used, as well as a vibrating plate at a frequency of approximately 3 MHz. The diameter of droplets emitted by the waveguide was less than 10 μm on average, which prevented the droplets settling on the intake manifold walls and the cylinder head inlet ports. The megahertz atomizer supplied the intake system with virtually uniform water-air spray jet. In both cases, an increase in the engine power output and thermal efficiency was achieved, whilst harmful emission of carbon monoxide, hydrocarbons and nitrogen oxides (for spark-ignition and compression ignition engines and diesel engine), as well as particulate matter (for compression ignition engine) was decreased. Also, ultrasonic atomizers were used for feeding the operating medium not only with water but also with an aqueous solution of alkali metal salts [2, 3, 10]. Feeding the circuit with alkali metal salts in addition to the water agent caused a reduction of nitrogen oxide and particulate matter emission.

The literature on the specific design solutions for systems supplying water to operating medium is abundant, including, for instance, Patents of the Republic of Poland [20–22].

2. Empirical Research

The aim of the empirical research, the results of which are presented in this article was to evaluate the effect of adding water to the operating medium in a spark ignited, LPG powered engine on fuel consumption and the emission of harmful substances under conditions simulating traction engine usage. The engine operating conditions simulating traction usage were determined based on the engine load during NEDC (New European Driving Cycle), consisting of an Urban Driving Cycle – UDC and an Extra Urban Driving Cycle – EUDC [11].

The testing was carried out using a Daewoo Lanos passenger vehicle manufactured in 2000 equipped with a spark-ignition engine of a 1498 cm^3 cylinder volume and a multifunctional catalytic converter. An indirect multi-point injection fuel system was used.

The vehicle testing was carried out at a Schenk Komeg EMDY 48 chassis dynamometer station, located at the Automotive Industry Institute. The vehicle testing was carried out at an internal combustion engine temperature previously warmed up to a constant level.

The emission testing was carried out using a testing workstation for exhaust gases composition, including a Horiba Mexa 7200 system equipped with Horiba analyzers:

- AIA–721A (carbon monoxide concentration measurement),

- AIA–722 (carbon dioxide concentration measurement),
- MPA–720 (oxygen concentration measurement),
- CLA–755A (nitrogen oxide concentration measurement),
- FIA–725A (hydrocarbon concentration measurement).

The fuel consumption was determined on the basis of the carbon mass balance found in the exhaust gas components.

The engine was fueled with commercial autogas of basic composition which was determined with the use of a gas chromatograph Agilent 6890N:
- ethane – 0.20% m/m,
- propane – 45.93% m/m,
- n-butane – 52.77% m/m,
- isobutane – 0.77% m/m,
- isobutene – 0.19% m/m.

The autogas had a motor octane number of 92 and a calorific value of 45.97 MJ/kg with density amounting to 550.6 kg/m^3 at 15°C.

Water was fed into the cylinder by letting the inlet into the intake system behind the air filter. The intake system was fed with water atomized in the 45 W 1.7 MHz Astoria Boneco 7035 ultrasonic atomizer. The fuel supply was controlled to achieve a proportion of water weight in the total weight of water and fuel amounting to 2.22%.

The testing was conducted for two engine fueling systems:
- autogas – designation: LPG,
- autogas with the addition of water – designation: LPG & H_2O.

3. The pollutant emission and fuel consumption test results

The table shows the results of specific distance pollutant emission testing: carbon monoxide – b_{CO}, hydrocarbons – b_{hc}, nitrogen oxides – b_{NOx} and carbon dioxide – b_{CO2}, as well as operating fuel consumption – Q during drive tests for two engine fuel system types: autogas and autogas with the addition of water. Each test was performed four times – the table presenting the average values of the results.

Table1. The results of specific distance pollutant emission testing and operating fuel consumption during drive tests for two engine fuel system types: autogas and autogas with the addition of water

Physical quantity		Measuring unit	Fuel system type	Test		
Name	Designation			UDC	EUDC	NEDC
Specific distance emission	b_{CO}	g/km	LPG	10.86	1.34	4.86
			LPG & H_2O	7.46	0.63	3.15
	b_{HC}		LPG	3.43	0.24	1.42
			LPG & H_2O	2.88	0.23	1.21
	b_{NOx}		LPG	0.12	0.18	0.16
			LPG & H_2O	0.11	0.17	0.15
	b_{CO2}		LPG	206.8	107.9	144.5
			LPG & H_2O	191.8	104.1	136.4
Operating fuel consumption	Q	$dm^3/100$ km	LPG	15.21	7.21	9.62
			LPG & H_2O	13.81	6.88	8.92

Figures 1–4 present the specific distance emission of pollutants during driving tests for two engine fuel systems.

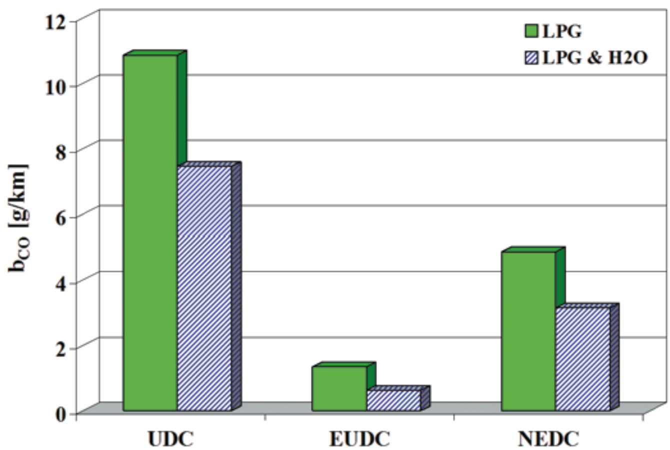

Fig. 1. Specific distance emission of carbon monoxide – b_{CO} during drive testing for two engine fuel systems

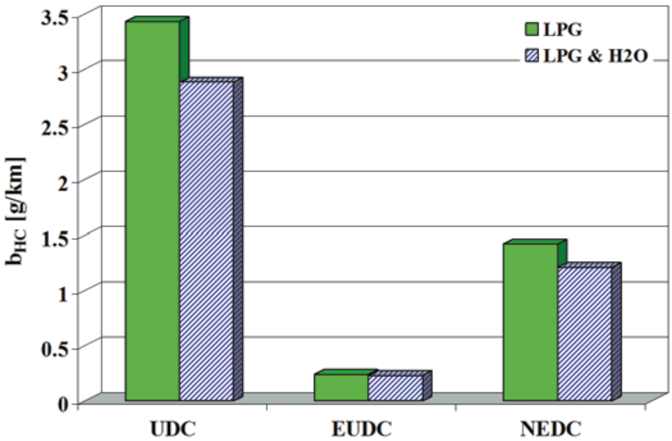

Fig. 2. Specific distance emission of hydrocarbons – b_{HC} during drive testing for two engine fuel systems

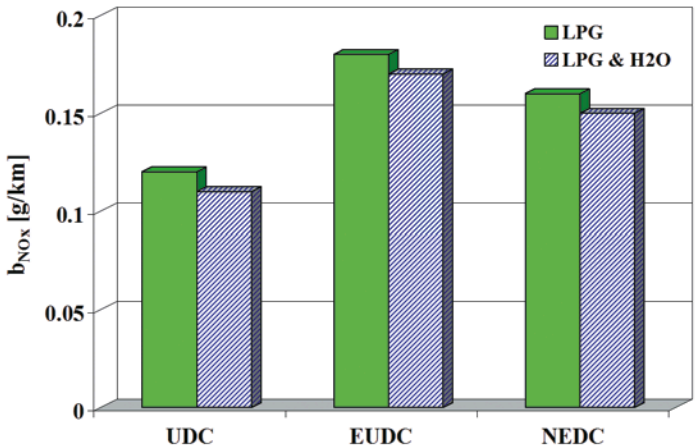

Fig. 3. Specific distance emission of nitrogen oxides – b_{NOx} during drive testing for two engine fuel systems

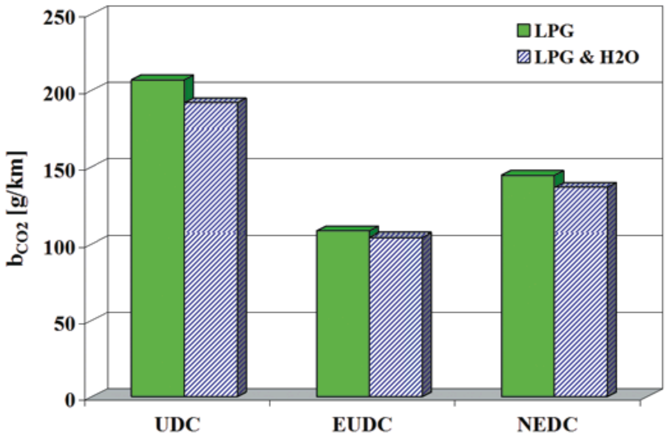

Fig. 4. Specific distance emission of nitrogen dioxide – b_{CO2} during drive testing for two engine fuel systems

There is an evident reduction in specific distance emission of all pollutants due the additional water supply to the operating medium – varying, sometimes significantly, for particular substances and engine operating conditions. Figure 5 shows the operational fuel consumption in drive tests for two engine fuel systems.

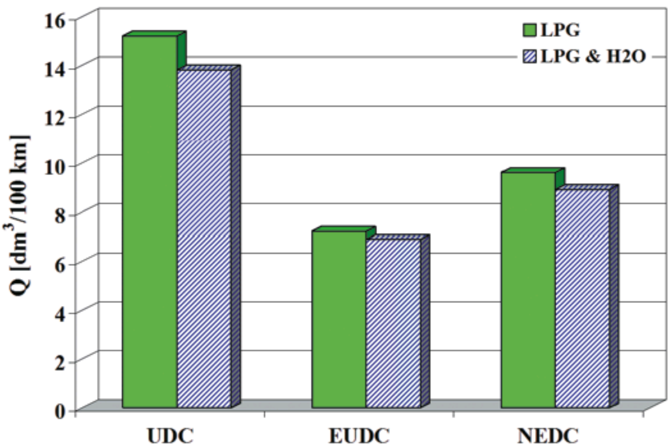

Fig. 5. Operating fuel consumption – Q during drive tests for two engine fuel systems

Also, additional water supply to the operating medium caused a reduction in the operating fuel consumption. Figures 6 and 7 present the relative decrease rate in specific distance emission of pollutants and operating fuel consumption due to additional supply of water to the operating medium:

$$\delta = \frac{x_{LPG} - x_{LPG\&H_2O}}{x_{LPG}} \tag{2}$$

where: $x = b_{CO}; b_{HC}; b_{NOx}, b_{CO2}; Q$,
index: LPG – for engine autogas fuel system,
index: LPG & H_2O – for autogas fuel system with the addition of water.

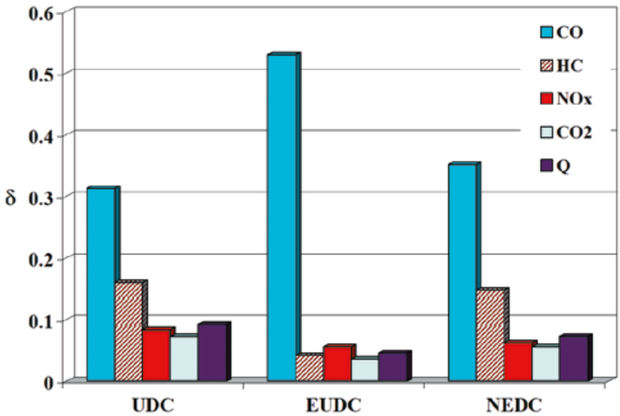

Fig. 6. The relative decrease rate in the specific distance emission of pollutants and operating fuel consumption due to additional supply of water to the operating medium

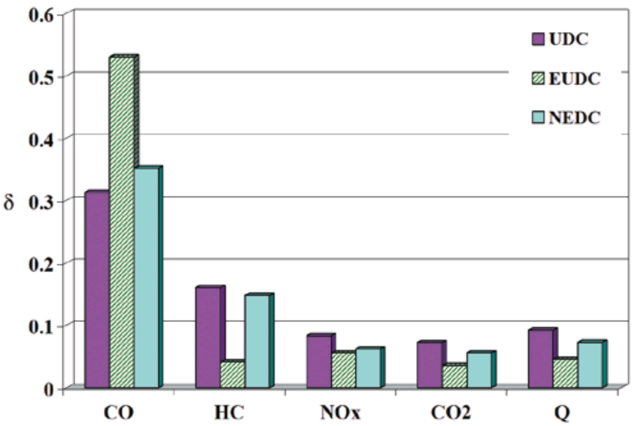

Fig. 7. The relative decrease rate in the specific distance emission of pollutants and operating fuel consumption due to additional supply of water to the operating medium

The greatest relative reduction in the emission of pollutants was for carbon monoxide (about 0.31 ÷ 0.53), followed by hydrocarbon (0.04 ÷ 0.16). In the case of nitrogen oxides and carbon dioxide emission, as well as the operation fuel consumption ratio the relative reduction ratio of the pollutant emission and operational fuel consumption due to additional supply of water to the operating medium had a similar value, within the range of 0.04 ÷ 0.09.

4. Conclusion

Based on the analysis of scientific literature on the additional supply of water to the operating medium in internal combustion engines, as well as the results of own empirical research, it is possible to formulate the following conclusions.

1. Water addition to operating medium of the internal combustion engine is an efficient way to influence the combustion process. According to literature references, water addition can reduce the combustion temperature, which contributes to the reduction of nitrogen oxide and knock tendency. Simultaneously, the products of combustion chamber processes involving water, such as hydrolysis, pyrolysis, reforming and hydrogenation, tend to intensify the oxidation of organic compounds, which consequently allows the reduction of carbon monoxide, hydrocarbons and particulate matter emission. The phenomenon of micro explosion of fuel-water emulsion droplets observed in the combustion chamber helps to improve the quality of fuel atomization.
2. The empirical research on the beneficial effect of adding water to operating medium on the reduction of pollutants emission (carbon monoxide in particular and – subsequently – hydrocarbon, and nitrogen oxides) was confirmed. However, it is significant that – unlike in the majority of literature references– in the case of nitrogen oxides there was a relatively small decrease in emission.
3. Water addition to the operating medium has a positive impact on thermal efficiency of the engine, resulting in a decrease in the operation fuel consumption – this also corresponds to the decrease in the emission of carbon dioxide.
4. The technique of feeding water using ultrasonic atomization turned out to be effective due to the stability of the obtained water spray, which allowed to avoid the deposition of a liquid water layer in the intake manifold.

When summing up the empirical research, it should be noted that the studied subject is not a state-of-the-art-solution, and the results indicate that it does not meet the approval requirements. It is therefore necessary to undertake additional research using a more modern model. On the other hand, the results of empirical research indicate that the addition of water to LPG fueled engines can deliver measurably beneficial effects in the case of old cars, hence the sector in which the use of LPG fuel systems is predominant.

The results of previous empirical studies, regarded as preliminary studies on the modification of LPG combustion in spark ignited engines, fully confirmed the assumptions on improving the engine performance thanks to the addition of water to the operating medium. The authors are aware, that it is necessary to run an extensive research program, including, among others, multidimensional research of a regulatory nature, and above all, research on the combustion process, including determining the heat generation characteristics based on engine indication.

The full text of the article is available in Polish online on the website http://archiwummotoryzacji.pl.

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