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IMPROVEMENT OF DIESEL ENGINE ECOLOGICAL AND ECONOMIC PARAMETERS BY USING HYDROGEN

Summary. Exhaustion and rising cost of fossil energy resources stimulates the search of ways to minimize their consumption. In the transport sector the main energy source is liquid fuel. Due to combustion of that fuel noxious gas is being emitted to atmosphere and creates the "greenhouse" effect, as well, as smog. Reduction of oil reserves increases the price of fuel as well, therefore the search for various alternatives is being made. One of them is usage of hydrogen as a supplement to the traditional fuel. During combustion of hydrogen toxic gases are not emitted. For obtaining hydrogen in a car a hydrogen generator which extracts it from water by electrolysis usually is used. The benefit of using hydrogen is better efficiency of an internal combustion engine. Hydrogen helps to reduce fuel consumption and emission of noxious gas as well. Research of efficiency and emissions of an internal combustion engine using hydrogen as an additive to the traditional fuel has been carried out, computational model to determine fuel costs and exhaust gas emissions under different working conditions has been developed.

УЛУЧШЕНИЕ ЭКОЛОГИЧЕСКИХ И ЭКОНОМИЧЕСКИХ ПАРАМЕТРОВ ДИЗЕЛЬНОГО ДВИГАТЕЛЯ ПРИ ИСПОЛЬЗОВАНИИ ВОДОРОДА

Резюме. Истощение и повышение стоимости ископаемых энергетических ресурсов заставляет искать способы уменьшения их потребления. В транспортном секторе в качестве основного источника энергии используется топливо. При сжигании топлива в окружающей среде образуются вредные газы, приводящие к появлению «парникового эффекта» и смога. Сокращение запасов нефти повышает цены на топливо, поэтому ищутся различные альтернативы. Одним из вариантов является использование водорода в качестве дополнения к традиционным видам топлива. При горении водорода не выделяются токсичные газы. В автомобиле используется водородный генератор, который выделяет водород из воды. Водородное топливо повышает эффективность двигателя внутреннего сгорания. Использование водорода в качестве дополнения традиционных видов топлива улучшает характеристики двигателя внутреннего сгорания, таким образом, уменьшая расходы топлива, уменьшая концентрацию вредных примесей в выхлопных газах. Выполнены экологические и экономические исследования, разработана расчетная модель расходов топлива и количество выбросов выхлопных газов при установке различных режимах работы двигателя.

1. INTRODUCTION

Each year the problem of energy resources is becoming more and more important in the world.

The crisis raging across the planet's economy encourages further look into the problems of energy resources. Car manufacturers are increasingly talking about alternative energy resources and alternative vehicles: electro-mobiles, bio-fuel-powered engines, and hydrogen internal combustion units.

Fuel for alternative vehicles includes fuel that is a non-oil product. According to the current classification the alternative fuel includes:

- Alcohol-based fuel such as methanol, ethanol without sodium and other alcohols in pure form or mixtures of 85% blended with gasoline unleaded to 15 – M85 and E85 and more;
- Compressed natural gas CNG;
- Liquefied natural gas LNG;
- Liquefied petroleum gas LPG;
- Liquid fuels obtained from coal;
- Other fuels derived from biological materials: such as soybeans, rapeseeds or other oil-based fuels;
- Hydrogen.

Need for alternative fuels raises two main issues:

- The limited volume of oil products and consequent rise in prices;
- Chemical structure characteristics of gasoline and diesel fuel. Petrol and diesel contain particles of unstable state of molecular weight, hydrocarbons, that is why fuel does not burn completely and high levels of CO, HC and NO_x occur in exhaust gases [1].

Burning of fossil fuels causes serious environmental problems. The car exhaust gases, i.e. NOx, CO, CO_2 and unburned hydrocarbons have the main negative environmental impact.

Level of engine emissions is determined by an engine operating conditions. The main engine emissions oxidize the nitrogen, carbon oxides and unburned hydrocarbons.

NOx - nitrogen oxides usually form at high temperatures.

CO and CO_2 are produced by burning fuel. If there is enough oxygen, then CO oxidizes into CO_2. Carbon monoxide is formed mainly with rich mixture.

Unburned hydrocarbons form due to incomplete combustion of fuel. Combustion chamber heat is lost at the chamber walls, so combustible mixture at the walls fails to burn completely. The combustion chamber is often with gaps and cracks, which prevent spread of flame. These areas increase the amount of unburned hydrocarbons. As the burn rate is too low, the unburned hydrocarbons are emitted through the opened exhaust valve. In order to burn the fuel completely, it is necessary to increase the combustion rate. This can be done supplying in addition hydrogen to the combustible mixture [2-5].

Hydrogen is prominent as an additional fuel, by using it the fuel burns down better, combustion rate is higher, and exhaust gases are cleaner. The hydrogen flame speed is higher than one of other fuel types, and therefore potentially less heat is emitted to the environment. This improves thermal efficiency.

Hydrogen can be used as an additive in gasoline, diesel and gas engines. Hydrogen can be fed in different ways. In the study carried out hydrogen has been produced by the hydrogen generator or simply comes with the intake air.

With addition of hydrogen the engine can operate with cleaner mixture, so you burn less fuel producing less carbon monoxide. Incomplete combustion is a major cause of CO, HC, NOx emissions in gasoline and diesel engines. Less pollution is achieved when the fuel burns completely [7].

Table 1

Fuel combustion characteristics

Properties/Fuel	Hydrogen	Gasoline	Diesel fuel
Auto-ignition temperature (C)	585	440	280
Flammability limit	4-75	1,3-7,6	0,7-5
The stoichiometric mix (% of weight)	34,7	15	14,55
The laminar flame speed (cm/s)	270	33	33
Lower calorific value (Kcal/kg)	28,673	10,5	10,3
Released heat amount (Kcal/ m^3)	707	860	845
Flame temperature (C) in the air	2045	2300	2290
Octane number	>126	87-98	none

2. EXPERIMENT CREATION

The experiment was aimed to determine economy and environmental parameters of a diesel engine. Exhaust gas NOx, HC and smoke have been measured. Fuel costs at different engine modes have been measured as well.

For the experiment a car of 1997 with the 1.7-liter inline diesel engine has been chosen Tab. 2. For research the car was equipped with a hydrogen generator. The hydrogen generator produces hydrogen gas, which the engine sucks with the air. Then this mixture gets into one chamber with fuel and reaches the right mixture richness. Hydrogen in the combustion chamber explodes faster than fuel ignites, so at that time the amount of energy releases, while fuel is becoming a "sort of" fuel mist, yet increasing the combustion efficiency.

Table 2

Car technical data

Title	Vectra B
Total weight	1790 kg
Length	4495 mm
Width	1710 mm
Height	1420 mm
Acceleration to 100km/h	15.5s
Maximum speed	175 km/h
Fuel consumption:	
Urban	7.1 l/100km
Highway	5.1 l/100km
Mixed	5.9 l/100km
Fuel type	Diesel fuel
Compression ratio	22.0:1
Maximum power	60kW at 4400rpm

The hydrogen generator is filled with electrolyte, which contains distilled water and potassium hydroxide. The hydrogen generator operation principle is electrolysis. This requires 12 volts and 25 amps. The hydrogen generator produces to 130 liters per hour of gas. When the generator operates electrolyte temperature rises and with increasing temperature the generator uses an increasing current. Efficiency of hydrogen gas separation depends on current strength. Tests showed that starting from 28 amps current hydrogen together with water vapor begins to release. Consequently the equipment for stabilizing electric current is needed. The use of DC for electrolysis reaction is not the most efficient way to extract oxygen and hydrogen gas from electrolyte. In order to achieve maximum efficiency of the hydrogen generator and control electrolysis current, which due to the heat released during electrolysis there is not constant, current pulse generator (CPG) is connected.

CPG operation principle is frequent circuit interruption which is characterized by frequency (Hz), i.e. the number of times per second the circuit was interrupted (switched on and off). So the direct current is converted to alternating current of certain frequency, leaving the same voltage. This allows the economical use of the car power. We can also change the amount of gas separation by changing the power, which depends on the current. A review of literature shows the most advantageous rate is about 70%. The exhaust gas was measured by the smoke analyzer Testo 350s. The diesel vehicle emissions were measured with this device. The measurements have been made with the engine running on diesel fuel and with additional hydrogen. Gas emissions were measured at different engine modes. Obtained data are presented in graphs.

NO_x emission. NO_x is odorless, colorless gas, a natural byproduct of combustion. At 1260 ^{0}C nitrogen becomes an oxidant, and this means, now it has the natural tendency to connect with oxygen atoms. NO_x is a nitrogen atom and the unknown (or "x") number of oxygen atoms. When the intake valve opens, the low pressure area formed in the cylinder quickly is filled by an air of an atmospheric pressure 14.7 psi. This compressed air connects with the fuel hydrocarbons (HC) and forms the basis for combustion, pushing a piston and creating power of the engine. During compression when the piston begins to rise, air and fuel molecules due to inter-friction heats up.

Absorbing heat the molecules expand. With further piston rising, the pressure in cylinder keeps increasing, so the friction between the molecules is also increasing, causing further increase of temperature and the molecules are expanding more . When absorbing heat, hydrocarbon molecules are broken down into hydrogen and carbon; and oxygen molecules (O_2) break down into two separate oxygen atoms. Because the ignition spark one oxygen atom oxidizes (combines with them) two hydrogen atoms and creates water, and two oxygen atoms with one carbon atom forms carbon dioxide. With increasing oxidation, the newly formed water and carbon dioxide creates an additional pressure, which is turned by the engine into a useful power helping to rotate the crankshaft driving a car. While the combustion chamber temperature remains below 1260^{0}C degrees, nitrogen molecules remain inert, this means, they do not split into separate nitrogen atoms and do not connect with other gases. However, reaching 1260^{0}C degrees, bad things occur to a broadly beneficial gas. Nitrogen molecules split and bind with oxygen forming NO_x compounds.

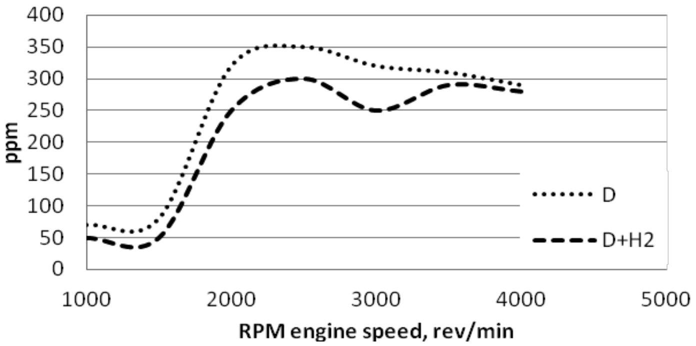

Fig. 1. NO_x amount. D – diesel fuel; D+H2 – diesel fuel and hydrogen
Rys. 1. Emisji NO_x. D - olej napędowy D + H2 - Diesel paliwowe i wodór

Using hydrogen amount of NO_x reduces approximately by 20 percent Fig. 1. NO_x decreases, since burning fuel with hydrogen combustion temperature is less. During compression the piston begins to rise, the molecules of air and fuel due to their mutual friction heat up. Absorbing heat, molecules of hydrocarbon break down into hydrogen and carbon, and oxygen molecules decompose into two separate oxygen atoms. When the fuel is ignited one atom of the oxygen two hydrogen atoms and creates water and two oxygen atoms with one carbon atom create carbon dioxide. With increasing oxidation, the newly formed water and carbon dioxide creates an additional pressure, which the engine turns into useful power that allows rotating crankshaft to drive a vehicle.

Unburned hydrocarbons (HC) emission into the environment is less when the engine is working with leaner combustible mixtures. When the engine is not fully loaded due to lower temperature in combustion chamber amount of carbon monoxide is larger, and the HC concentration in the exhaust gas directly depends on qualitative parameters of the spray. Usage the additional hydrogen results in a higher flame speed. The flame quickly spreads throughout the cylinder. Fuel is burned even in gaps or cracks in cylinder or cylinder head. It will significantly reduce hydrocarbon emissions in the exhaust gas. Using hydrogen results in reduction of HC in the exhaust gas by 20 ppm at an average. The figure shows that the hydrocarbon concentration in the exhaust gases lower is at higher engine speeds. One possible reason is the oxidation of hydrocarbons. Flame extinction at a short distance from the cylinder walls determines the balance between the hot zone and the flame heat released during flame reaction. Usage hydrogen helps fuel to burn better. Hydrocarbon content is presented in Fig. 2.

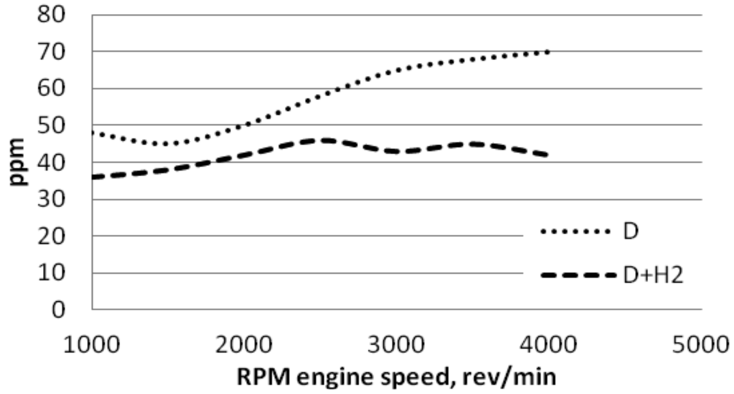

Fig. 2. The content of hydrocarbons
Rys. 2. Zawartość węglowodorów

The biggest problem of diesel engine is its smokiness. Reduction of the amount of soot in the exhaust gases to an acceptable level can be achieved using a whole set of measures, that optimizes combustion process. The smaller fuel droplets are, the better the fuel evaporates and mixes with air, therefore burns better. To reduce amount of soot we will use hydrogen as an additive to diesel fuel. The engine can run with leaner fuel-air ratio, without any loss of an engine power. The smokiness is presented in Fig. 3.

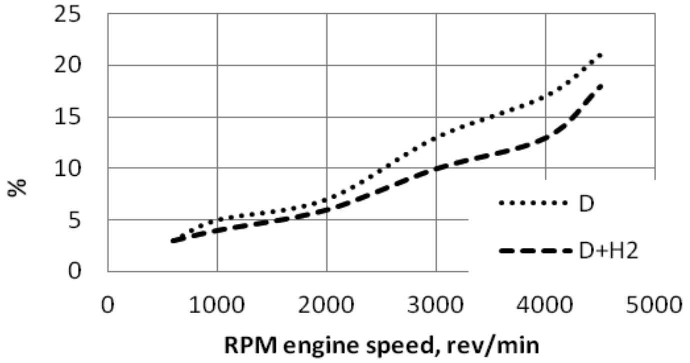

Fig. 3. Amount of soot
Rys. 3. Ilość sadzy

After measuring the soot content in the exhaust gas, as we see from the curve, the engine smokiness decreased by 23%. Additionally fed hydrogen allows the engine to run with lean mixture. In the diesel engine soot level here increases with engine speed, since the fuel is becoming richer. A small hydrogen additive to the engine air fuel intake portion allows the engine to operate with a leaner air-fuel mixture. In the case of most charges of internal combustion engines for normal acceleration almost stoichiometric air-fuel mixtures are needed, but at idling speed, at reduced loads or moderate acceleration, the hydrogen additive in lean combustion mixture ensures normal operation of the engine, at the same time reducing exhaust emissions and fuel consumption. The increase in engine efficiency exceeds energy costs to produce hydrogen. Fuel costs are presented in Fig. 4.

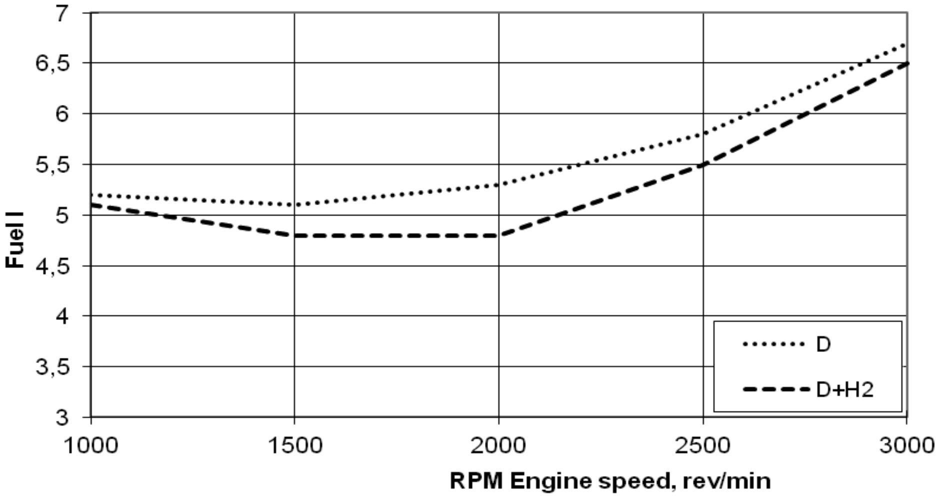

Fig. 4. Fuel consumption
Rys. 4. Zużycie paliwa

By using hydrogen fuel economy makes up to 9%. Since hydrogen-fuel-air mixture is highly flammable, it is possible to delay ignition by few degrees. Fuel will be ignited at the highest dead point. The engine works smoother, and there is no engine piston breaking.

3. COMPUTER SIMULATION

For theoretical research of the hydrogen-fuel-air mixture the computer program for simulation of diesel engine working processes developed by scientists of the Bauman Moscow State Technical University has been used. This model is the simulation software of work processes of the engine and all thermodynamic engine cycles, designed to simulate and optimize work processes, for two-and four-stroke internal combustion engines with various types of extra-supercharged engines. It is also the thermodynamic software, characterized by the fact that the engine cylinders are considered an open thermodynamic system.

Modeling of formation of nitric oxides was carried out by dividing the cylinder into two zones, i.e., new gas-filled area and the area of combustion products gas. The new gas-filled area consists of air, fuel and residual gas. Before ignition of the combustible mixture is just a new gas-filled area. During combustion the volume of the burning gas increases. Combustion calculation assumes that the air-fuel ratio varies linearly from the initial value $AF_{ini} < 1$ to 1. Value of the air-fuel ratio of combustion AF_c is a function of the crank φ

$$AF_c = AF_{ini} + \frac{1 - AF_{ini}}{\varphi_z}\varphi \tag{1}$$

Here: φ_z – combustion duration

When calculating NO formation in the combustion zone, the average NO concentration in the whole combustion chamber is fixed. NO concentration is calculated:

$$\frac{dr_{NO}}{d\varphi}=\frac{p\cdot 2.333\cdot 10^{7}\cdot e^{\frac{38020}{Tc_z}}\cdot r_{N_2}\cdot r_{Oeq}\cdot\left[1-\left(\frac{r_{NO}}{r_{NOeq}}\right)^{2}\right]}{R\cdot T_{az}\left(1+\frac{2346}{T_{C_z}}\cdot e^{\frac{3365}{T_{az}}}\cdot\frac{r_{NO}}{r_{O_2eq}}\right)}-\frac{1}{\omega} \tag{2}$$

Here: p – pressure in cylinder, Pa; T_{cz} – temperature in the combustion zone, K; R – the gas constant J/molK; ω – angular velocity of the crank 1/s; r_{NOeq}, r_{N_2eq}, r_{Oeq}, r_{O_2eq}- equilibrium concentration of nitrogen oxides.

NO concentration in the cylinder $r_{NOc}=r_{NO}\cdot r_{bc'}$

r_{bc} – the combusted gas fraction in the cylinder

NO concentration in the cylinder of the „dry“ combusted gas

$$e_{NO}=\frac{30r_{NO}M_{bg}}{L_c\cdot\eta_m}\cdot 3600000 \tag{3}$$

Here: M_{bg} – gas weight in the cylinder at the end of the combustion, kmol; L_c – work done per cycle, kJ; η_m – mechanical efficiency of the engine.

Soot formation has been simulated according to the mathematical model developed by Dr. Prof. Razleitsev. Soot forms due to high temperature thermal polymerization and dehydration vapour-liquid hardcore vaporization drops. Soot formation in the combustion zone

$$\left(\frac{d[C]}{d\tau}\right)_K=0.004\frac{q_c}{V}\cdot\frac{dx}{d\tau} \tag{4}$$

Here: V – cylinder capacity; q_c –fuel weight cycle; $\frac{dx}{d\tau}$ - heat release rate.

Soot formation becomes faster due to the high temperature thermal polymerization, i.e. incomplete drops turning into vapour. Soot amount during injection is calculated:

$$\left(\frac{d[C]}{d\tau}\right)_n=1.7\frac{q_c}{V}\cdot\frac{1-\exp\left[-\left(\frac{\sqrt{K\cdot t}}{d32}\right)^{n}\right]}{\tau_{enp}} \tag{5}$$

Here: τ – current time since an injection start; τ – injection duration; n – distribution factor; K – vaporization constant; d32 – an average diameter of drops.

After the injection soot content is calculated:

$$\left(\frac{d[C]}{d\tau}\right)_n=0.0028(1-X_{knbp})\frac{n'q_c}{2\cdot V\cdot\tau_2}\left(\frac{\sqrt{K\cdot\tau}}{d32}\right)^{n'}\exp-\left(\sqrt{\frac{K\cdot\tau}{d32}}\right)^{n'} \tag{6}$$

Here: τ_2 – current time after stopping the injection; X_{knbp} – heat amount after the injection

Soot evaluation during combustion

$$\left(\frac{d[C]}{d\tau}\right)_B=3.1\cdot 10^{-6}n^{0.5}p\cdot[C] \tag{7}$$

Here: p – pressure in the cylinder MPa; $[C]=\frac{C}{V}$ - soot concentration in the cylinder.

Soot concentration is evaluated for expansion

$$\frac{d[C]}{d\tau}=B\left(\frac{d[C]}{d\tau}\right)_K+B\left(\frac{d[C]}{d\tau}\right)_n-\frac{1}{B}\left(\frac{d[C]}{d\tau}\right)_B-\left(\frac{d[C]}{d\tau}\right)_V \qquad (8)$$

Here: $B=A\left(\frac{n_{nor}}{n}\right)^m$ - empiric factor; n – engine speed; n_{nor} – speed at maximum power; A – factor.

The soot concentration in exhaust gas is associated with normal combustion conditions

$$[C]_H=\int_{\varphi_n}^{480}\frac{d[C]}{d\tau}\cdot\frac{d\varphi}{6n}\left(\frac{0.1}{p_{480}}\right)^{\frac{1}{k}} \qquad (9)$$

Here: p_{480} – pressure in the cylinder before 60^0 to upper dead point; k – adiabatic exponent of exhaust gas

Smokiness equation

$$Hardrige=100\cdot[1-0.9545\exp(-2.4226[C])] \qquad (10)$$

The numerical model of the diesel engine has been created for the engine working with diesel fuel and with additional hydrogen. The engine load is determined. Four simulation cases were performed, when the engine is unloaded, loaded with 25%, 50% and 70% of load Tab. 3. The ecological parameters are presented in the Table.

Table 3

The ecological parameters

	Diesel fuel	Diesel fuel + hydrogen	Diesel fuel + hydrogen	Diesel fuel + hydrogen	Diesel fuel + hydrogen
Load	0%	0%	25%	50%	75%
Hardrige smoke level	4,765	2,937	3,218	4,652	6,216
Bosch smoke number	0,522	0,321	0,352	0,496	0,822
Factor of absolute light absorption	0,114 (1/m)	0,069 (1/m)	0,095(1/m)	0,457(1/m)	0,194(1/m)
Specific particulate matter	0,095 (pm)	0,052 (pm)	0,068(pm)	0,075(pm)	0,154(pm)
Specific carbon dioxide emission	793,80 (g/kWh)	769,32 (g/kWh)	780,62 (g/kWh)	790,30 (g/kWh)	870,60 (g/kWh)
Fraction of wet NO_x in exhaust gas	1087,4 (ppm)	617,53 (ppm)	700,41(ppm)	905,8(ppm)	1200,6(ppm)
Specif. NO_x emiss. reduc. to NO	7,37 (g/kWh)	4,19 (g/kWh)	4,01 (g/kWh)	6,52 (g/kWh)	8,02 (g/kWh)

The ecological parameters of the engine are improved but any excess over 50 percent of the load increases quite significantly emissions in the exhaust gas.

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