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BETTERMENT OF ECOLOGICAL PARAMETERS OF A DIESEL ENGINE USING BROWN‘S GAS

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Abstract. Hydrogen could become an important element, allowing us to accumulate and transfer energy in a clean way. Hydrogen can be used in cars as a fuel additive which increases the combustion efficiency of the fuel-air mixture. A small amount of hydrogen gas could also be produced in a car by decomposing water by means of electrolysis, using for this purpose the energy produced by the car's electric power generator. The hydrogen and oxygen (HHO) mixture obtained, which is also known as Brown's gaseous mixture, is supplied to the engine's intake manifold.

Tests have been performed with 1.6 TD (SB) diesel engine. The automobile was tested on a chassis dynamometer running at a different speed. The engine was tested using fuel-air combustion mixture and fuel-air-HHO gas combustion mixture without additional adjustment of the fuel supply system. The test results have revealed that additional injection of HHO gas into combustion mixture resulted in up increase of fuel consumption, but the CO, the HC, the PM amount has decreased insignificantly. At few engine loads the amount of NO_x decreased, however increasing the engine load resulted in a gradual increase.

Having analysed test results we came to a conclusion that additional supply of HHO gas into combustion mixture resulted in improvement of the combustion quality of fuel-air mixture and ecological performance of the engine. This is especially relevant for the automobiles which are not equipped with a supplementary exhaust gas toxicity decreasing system.

Keywords: ecological parameters; diesel engine; Brown's gas; hydrogen.

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Introduction

Oil reserves on planet Earth are running out. This gives rise to a necessity for finding substitutes for conventional internal combustion engine fuels. Gas and bio-gas are used and future-oriented hydrogen power generation is developed (Mažeika, Matijošius 2010). Hydrogen, the most common element on the planet, is not found as a pure substance, it is rather found in the environment as a chemical compound. The usual method used for obtaining pure hydrogen from water is electrolysis, whereas other chemical reactions are used for obtaining hydrogen from hydrocarbonates or other compounds. Providing that electric power necessary for electrolysis of H_2 is derived from renewable energy sources, the hydrogen obtained could become an important element for clean accumulation and transfer of energy (Matijošius, Sokolovskij 2009).

Hydrogen, as an energy source for automobiles, can be used in the following ways:

- In automobiles with fuel elements, used for obtaining electric power from hydrogen, in which case automobile is driven by an electric motor drive;
- By burning hydrogen as fuel in internal combustion engines.

Decreasing the harmful impact of transport vehicles on the environment is still a very topical issue. The harmful environmental impact of transport vehicles is caused by toxic emissions of internal combustion engines (Juostas, Janulevičius 2009), contamination of roadside soil (Baltrėnas *et al.* 2009), noise and other factors (Baltrėnas *et al.* 2004, 2007; Gražulevičienė, Bendokienė 2009; Paulauskas, Klimas 2011). Many research papers deal with the issues related to production and application of more environmentally friendly fuel types (Bendikienė *et al.* 2011; Baltrėnas, Kvasauskas 2008; Labeckas, Slavinskas 2010; Lebedevas *et al.* 2011; Pukalskas *et al.* 2009; Matijošius, Sokolovskij 2009).

The aim of the research is to study the possibility of additional supply of hydrogen and oxygen (HHO) gas into air-and-fuel mixture and to assess the efficiency of using this gas in a compression ignition internal combustion engine.

Research objectives:

- To explore peculiarities of production of HHO gas in an automobile by means of electrolysis;
- To study the efficiency of using HHO gas in a compression ignition internal combustion engine by employing chassis dynamometer (rolling road) tests.

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Hydrogen has an autoignition temperature of 858K requiring an ignition source to combust in an IC engine (Lambe, Watson 1993). Diesel fuel which has an autoignition temperature of 525K can be used as a pilot to ignite hydrogen. The literature contains a body of work in which hydrogen was used in conjunction with diesel fuel to power CI engines. This dual fuel combustion is often called diesel pilot-ignited hydrogen combustion. Diesel pilot ignited hydrogen combustion at low quantities of hydrogen is beneficial since the diesel fuel is being replaced by hydrogen, which may stretch the supply of hydrocarbon fuels.

Particulate matter (PM), oxides of nitrogen (NO_X), carbon monoxide (CO), and hydrocarbons (HC) are all regulated vehicle emissions. Carbon dioxide (CO_2) is under consideration to be limited in the future, and all of these emissions have been found to be harmful to the environment; thus, their reduction is desirable. Diesel-hydrogen dual-fuel combustion has been reported to yield decreases in all of these emissions, when compared to operation of the compression-ignition engine burning diesel fuel alone.

In one experiment, small amounts of hydro-oxygen ($2H_2$, O_2) were fumigated into the intake of the engine using an electronic injector. The resultant reduced ignition delay was believed to cause a decrease in NO_X in the test engine proportional to the amount of $2H_2$, O_2 fumigated (Gjirja *et al.* 2000). In another experiment by Tomita *et al.* (2001), hydrogen was mixed with the intake air of a direct-injection diesel engine. SOI timing of the diesel fuel was varied across a wide range, holding the overall equivalence ratio equal with and without the addition of hydrogen. Their tests showed very low NO_X emissions when SOI was advanced to or beyond 40° before top-dead-centre (BTDC), with NO_X emissions rising with later injection timing. This was reasoned to have occurred because of the thorough mixing of the hydrogen/air mixture and the diesel fuel before ignition. It was also observed that CO_2 decreased proportionally to the amount of hydrogen substituted for diesel fuel, due to less carbon available in the reactants. At low loads, lower efficiency was achieved running in a dual-fuel mode compared to running with diesel alone. The hydrogen was believed to cause an increased ignition delay due to the large mole fraction of hydrogen in the air displacing oxygen. Efficiency of the engine was affected with the addition of hydrogen, such that typically the brake thermal efficiency of the engine was slightly reduced. It was observed that combustion under dual-fuel operation is controlled by flame propagation rather than autoignition (Tomita *et al.* 2001). A study of lean premixed combustion by Jacobs *et al.* (2005) in a conventional diesel engine fuelled with diesel fuel showed that NO_X was reduced as timing was retarded. This was attributed to the reduced flame temperatures caused by retarded injection (Jacobs *et al.* 2005).

An investigation into the effects of gaseous fuels burned with diesel fuel in a direct injection engine conducted by Varde K. S. and Varde L. K. (1984) used hydrogen to supplement the diesel fuel up to 15% of the total fuel energy in a naturally-aspirated diesel engine. At light loads, the addition of hydrogen reduced soot formation up to 50% over the conventional diesel-fuel mode due to the high equivalence ratio. In their study, NO_X increased as the ratio of H:C was increased by partial fuelling with hydrogen, with greater hydrogen amounts increasing NO_X proportionally (Varde K. S., Varde L. K. 1984). Tsolakis and Megaritis (2004) used a fuel reformer to produce hydrogen-rich gas to be introduced into the combustion process by way of reformed exhaust-gas recirculation (REGR). Their findings showed that this method of achieving partially premixed charge compression ignition (PCCI) yielded the potential for reduced NO_X and PM emissions, and enhanced efficiency.

Homogeneous charge compression ignition (HCCI) has been attempted with hydrogen, and in the regime where it is feasible, an efficiency gain over spark-ignited hydrogen combustion engines was observed (Stenlaas *et al.* 2004). Hydrogen has also been experimented with in the biofuels sector; it was observed in an experiment by Senthil Kumar *et al.* (2002) that hydrogen addition to the intake air of a primarily vegetable-oil fuelled diesel engine can reduce smoke and increase thermal efficiency, addressing two inherent problems with using vegetable oils as fuel. In their study hydrogen was added as a mass fraction of the total fuel, and increasing the 'mass share' of hydrogen had the following effects: decreased CO, increased NO, increased ignition delay, decreased HC, and both increased and decreased efficiency, depending on the amount of hydrogen and type of base fuel used (Senthil Kumar *et al.* 2002).

1. Comparison of the properties of diesel fuel and hydrogen

As compared to diesel fuel, hydrogen is distinguished by nearly three times higher calorific capacity, it requires less energy to ignite, burns faster, has a higher diffusion coefficient and is better mixed with air (see Table 1).

Table 1. Physical and chemical properties of diesel fuel and hydrogen

Physical and chemical properties	*Diesel fuel*	*Hydrogen*
Calorific capacity H_u, MJ/kg	42.5	120
Density ρ, kg/m^3 at $t = 0$ °C and $p = 0.1$ MPa	~850	~0.09
Relative density as compared with air	~654	~0.0695
Composition of the main elements according to their weight, %	86C, 13 H	100 H
Boiling temperature, °C	180–360	–253
Ignition temperature, °C	250	~560
Ignition energy, mJ	–	0.02
Cetane number	45–55	5–10
Research octane number	30	130
Flame propagation velocity, m/s	~0.3	~2.7
Combustion temperature, K	2289	2449
The amount of air needed for burning of 1 kg of material, kg/kg	14.6	34.5
Possible ignition boundaries of the air-and-fuel mixture, λ	0.95–12	0.14–9.85
Possible composition of the air-and-fuel mixture according to the air volume, %	0.6–7.5	4–77
Diffusion coefficient, cm^2/s	–	0.63

When burning hydrogen CO_2 emission is equal to zero. As an inflammable mixture, hydrogen is characterized by wider ignition boundaries. Engine can run on a mixture of diesel fuel, air and hydrogen. This mixture could burn more efficiently, ensuring more complete burning of hydrocarbons contained in fuel.

2. Production of HHO gas and its application in an automobile

Accumulating and storing hydrogen is difficult. Hydrogen can be produced locally in an automobile by means of a water electrolysis device. Hydrogen electrolysis generators are known to be of two types:

- Decomposing water into separate hydrogen H_2 and oxygen O_2 gases. In an electrolysis unit oxygen is disengaged next to anode, while hydrogen is disengaged next to cathode.
- Producing HHO gas (Brown's gas) – an inflammable mixture of hydrogen and oxygen.

Water electrolysis from a chemical perspective is a reaction:

$$2H_2O + 2E = 2H_2 + O_2, \qquad (1)$$

where: E – the amount of energy theoretically necessary to produce one mole (2 g) of hydrogen.

$E = 240$ kJ. The same amount of energy is theoretically released upon burning one mole of hydrogen (Yilmaz *et al.* 2010).

Brown's gas generator is filled with electrolytic solution, composed of 97% distilled water and 3% KOH solution. Using an electric current of $U = 12$ V voltage and $I = 25$ A strength the generator produces $Q_{HHO} \approx 1.5\ l$ HHO gas in $t = 60$ sec. The volume ratio of hydrogen and oxygen gas in Brown's gas is 2:1. A gas mixture consisting of 1240 l of hydrogen and 620 l of oxygen, the total volume of which constitutes 1860 l, is produced from 1 kg of water. At 0°C temperature and $\rho = 0.1$ MPa pressure the density of oxygen gas $\rho_{O_2} = 1.43$ kg/m^3, the density of hydrogen is $\rho_{H_2} = 0.09$ kg/m^3, the density of Brown's gas is $\rho_{HHO} = 0.54$ kg/m^3. One litre of HHO gas contains 0.67 l of H_2 gas, the mass of which is $m_{H_2/l} = 0.06$ g.

Efficiency ratio of HHO gas generator:

$$\eta_{HHO} = \frac{E_{hydrogen}}{E_{electric}}, \qquad (2)$$

where: $E_{electric}$ – the amount of electric power consumed for production of one litre of HHO gas, J:

$$E_{electric} = \frac{U \cdot I \cdot t}{Q_{HHO}}; \qquad (3)$$

$E_{electric} = 12000$ J.

$E_{hydrogen}$ – the amount of energy released by burning of the hydrogen contained in 1 litre of HHO gas, J:

$$E_{hydrogen} = H_u \cdot m_{H_2/l}; \qquad (4)$$

$E_{hidrogen} = 7200$ J. $\eta_{HHO} = 0.6$.

The remaining part of electric power in the gas generator turns into heat.

Upon burning of hydrogen in an engine merely about 30% of its energy is converted into mechanical work and the total net efficiency of HHO production and use constitutes $\eta_{e_{HHO}} \approx 0.18$.

The electric power used for electrolysis is obtained from the automobile's battery (Fig. 1), which is charged by an electric power generator when the engine is running. Brown's gas generator is supplied with a modulated electric current. By changing the gain coefficient the strength of the current is altered and the amount of HHO produced in adjusted. The electric circuit supplying the current to the Brown's gas generator is connected to a relay switch. When shutting the internal combustion engine down this relay disconnects power supply to the gas generator and the supply of gas is discontinued.

A small amount of gas produced by the HHO generator is directly supplied into the engine's intake manifold. When flowing along the manifold the gas is mixed with the intake air drawn into the cylinders. At the end of the compression stroke diesel fuel is sprayed into the gas mixture and the high temperature of the gas causes fuel ignition. HHO gas improves the quality and velocity of the air-and-diesel-fuel mixture combustion.

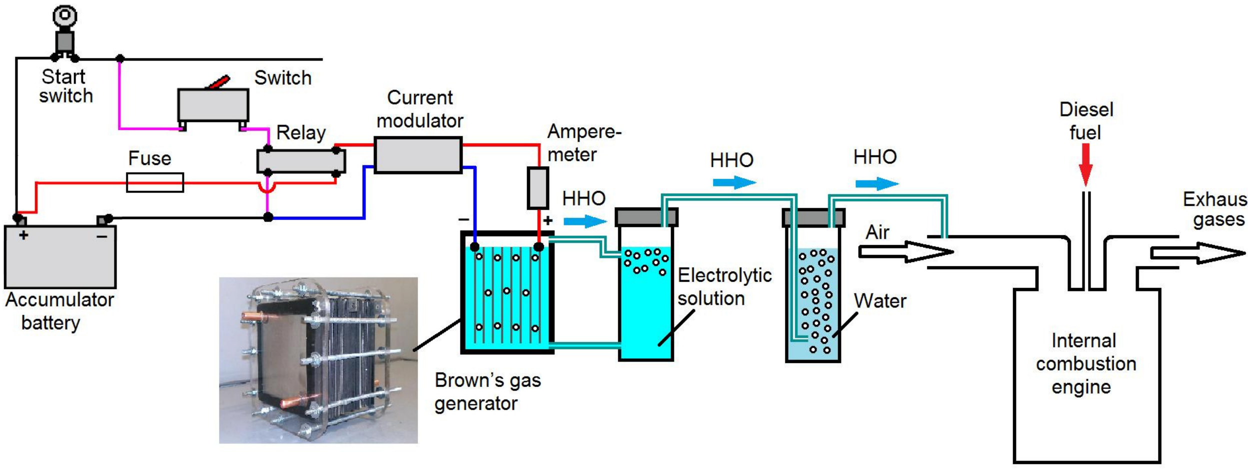

Fig. 1. Structural scheme of HHO gas generator installation in an automobile

3. Test methodology

Tests have been performed using the automobile Volkswagen Passat with a 1.6 TD (SB) diesel engine. The automobile has a HHO gas generator installed. The automobile has been tested using MAHA company's dynamometer rolling road LPS 2000. Composition of engine exhaust gases (CO, CO_2, HC, NO_x) was measured by the gas analyser TECHNOTEST 488, smokiness was measured by AVL DiCom 4000. For the purposes of measuring fuel consumption an electronic fuel consumption meter connected to a dynamometer rolling road has been installed in the automobile. Tests have been performed when the automobile was running on the fourth gear and developing various established speeds v (Table 2). When driving at the specified constant speeds the automobile is affected by particular loads of resistance to motion and air resistance. In case of testing the automobile on a dynamometer rolling road the calculated load is imposed on the traction wheels. Taking into consideration transmission losses, it has been calculated that in order to achieve the set speeds the engine has to develop the set brake horsepower P_e (Table 2).

With engine running under different operating conditions fuel consumption per hour B_d, comparative net fuel consumption b_e and engine net efficiency ratio η_e have been established according to the measured test values.

Tests have been performed three times under all operating conditions; average measured and calculated values are presented in the results.

When testing the engine under different operation conditions, the proportion of HHO gas volume, %, in the drawn in air and Brown's gas mixture is changing (Table 2):

$$P_{V_{HHO}} = \frac{Q_{HHO} \cdot 100}{Q_{air}}, \tag{5}$$

where: Q_{HHO} – the amount of HHO gas supplied into the engine, *l*/min. $Q_{HHO} = 1.5$ *l*/min.

Q_{air} – the amount of air drawn into the engine, l/min:

$$Q_{air} = \frac{2 \cdot V_H \cdot \eta_v \cdot n}{\tau}, \tag{6}$$

V_H – engine litre capacity, *l*; $V_H = 1.6$ *l*; η_v – Volumetric efficiency of cylinders; n – Engine shaft rotation frequency, min^{-1}; τ – Engine timing frequency, $\tau = 4$.

The proportion of hydrogen gas as compared to the mass of the injected diesel fuel, % (Table 2):

$$P_{mH_2} = \frac{m_{H_2} \cdot 100}{m_{diesel}}, \tag{7}$$

where: m_{H_2} – the mass of pure hydrogen in the HHO gas delivered to the cylinder, kg:

$$m_{H_2} = \frac{2 \cdot V_h \cdot \eta_v \cdot P_{V\,HHO} \cdot \rho_{H_2}}{3 \cdot 100}, \tag{8}$$

m_{diesel} – the mass of diesel fuel injected into the cylinder, kg:

$$m_{diesel} = \frac{V_h \cdot \eta_v \cdot \rho_{air}}{14.5 \cdot \lambda}. \tag{9}$$

It is stated in the announced scientific research papers that significant improvement of engine operational characteristics is noticed in the cases when the proportion of hydrogen as compared to the mass of fuel injected into the cylinder amounts to 1–5%. The tests have been performed with only 0.1–0.2% of additionally supplied hydrogen. Increase of HHO gas production using the energy generated by the test automobile's battery results in higher internal energy loss. It is rational to supply larger amounts of hydrogen from a separate tank.

Table 2. Engine operational characteristics of an automobile driving at various speeds

Automobile speed v, km/h	50	60	70	80	90
Engine shaft rotation frequency n, min^{-1}	1640	1970	2300	2620	2940
Engine brake power P_e, kW	4.7	6.5	8.5	11.4	14.9
Proportion of HHO gas volume in the sucked in mixture $P_{V\,HHO}$, %	0.14	0.12	0.10	0.09	0.08
Proportion of H_2 gas as compared to the mass of the injected diesel fuel P_{mH_2}, %	0.19	0.15	0.13	0.11	0.09
Water consumption kg per 100 km run	0.097	0.081	0.069	0.061	0.054

Addition of H_2 gas into combustible mixture requires correction (delay) of fuel injection advance angle, whereas hydrogen increases mixture burning speed.

High pressure fuel pump plunger stroke to the piston top dead centre (BTDC – before top dead centre) was decreased from 0.9 mm to 0.85 mm.

4. Test results

Supply of HHO gas decreases the amount of carbon monoxide gas in exhaust gases by 7–12.5% (Fig. 2). The amount of CO decreases because hydrogen improves the combustion process in ensures complete burning of carbon, which turns into carbon dioxide.

This is confirmed by 2.5–4.5% decrease of oxygen amount and up to 2% increase of CO_2 amount in exhaust gases (Fig. 3).

Additional supply of HHO gas caused insignificant decrease in the amount of hydrocarbons in exhaust gases (up to 1.5%) (Fig. 4). This reveals that hydrogen additive also improves combustion reaction in hydrocarbons.

With supply of HHO gas at 50 km/h automobile speed (4.7 kW engine load) the amount of NO_x is 5.5%

smaller than without additional supply of hydrogen (Fig. 5).

With increase of automobile speed this difference decreases gradually (up to 70 km/h), whereas further increase of speed and engine load with additional supply of HHO gas leads to greater emission of NO_x than in cases with no HHO supplied. Upon reaching the speed of 90 km/h and 14.9 kW engine load NO_x emissions using HHO gas are 3.5% larger than in cases with no gas supplied. This reveals that using hydrogen at small loads ensures more efficient combustion which results in decrease of the amount of free oxygen and decrease of NO_x amount in exhaust gases. Increase of engine load and rotation speed creates a richer mixture and the amount of NO_x decreases, thus additional supply of hydrogen gas increases the combustion temperature of the combustible mixture and increases the amount of nitrogen oxides.

A small amount of HHO gas drawn into engine cylinders together with air improves combustion of diesel fuel and PM amount decreases by 4–8% (Fig. 6).

Additional supply of HHO gas increases fuel consumption up to 1.7% and decreases engine net efficiency ratio up to 2.5% (Fig. 7), since efficiency ratio of hydrogen production and use in an engine constitutes only $\eta_{ehho} \approx 0.18$.

Engine economic efficiency parameters can be improved by more efficient production of HHO gas and by precise setting of the optimum fuel injection moment.

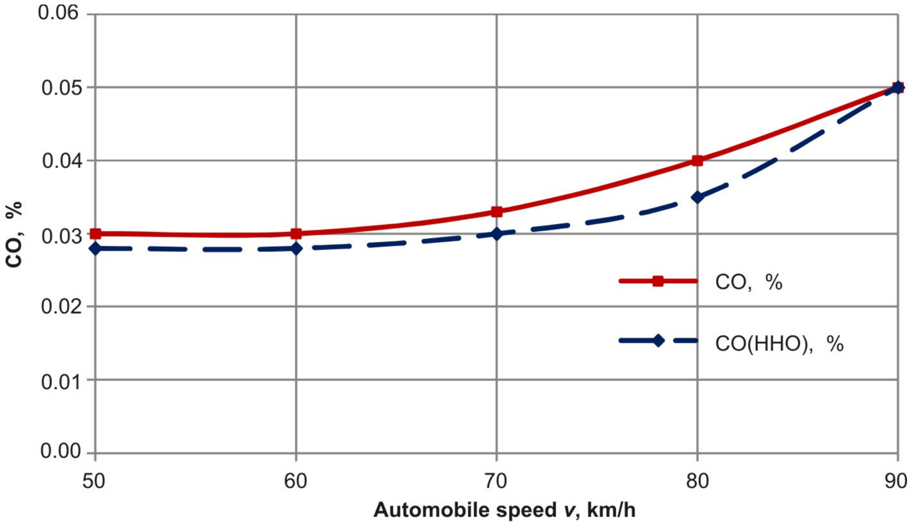

Fig. 2. Amount of CO in exhaust gases

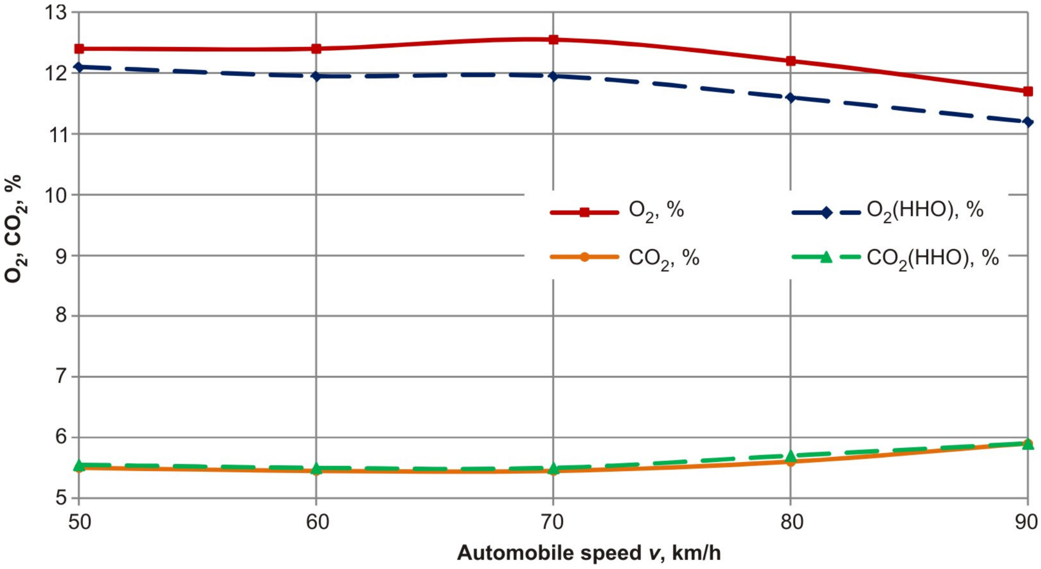

Fig. 3. Amounts of CO_2 and O_2 in exhaust gases

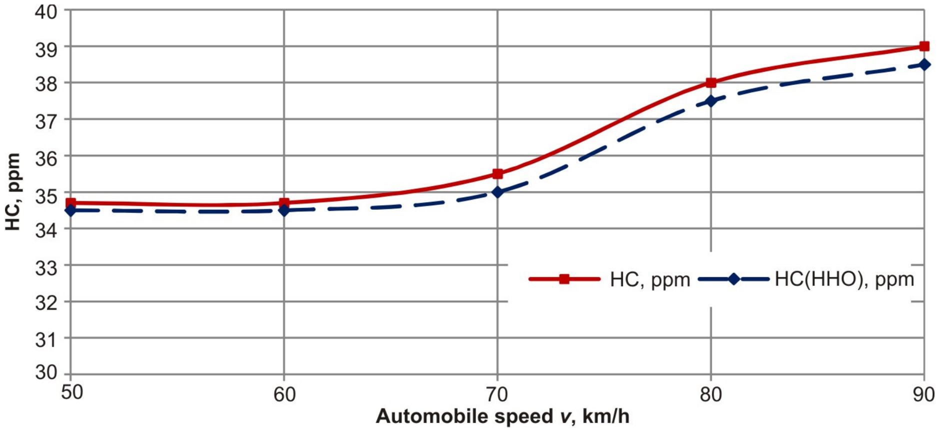

Fig. 4. Amount of HC in exhaust gases

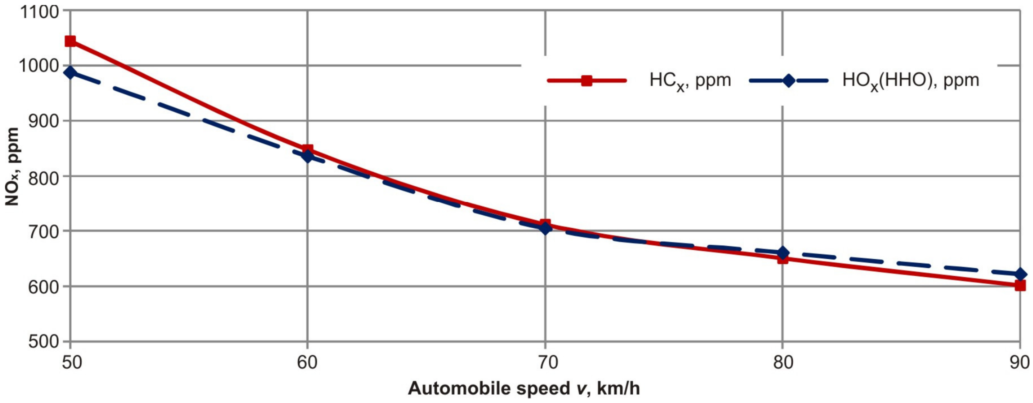

Fig. 5. NO_x amount in exhaust gases

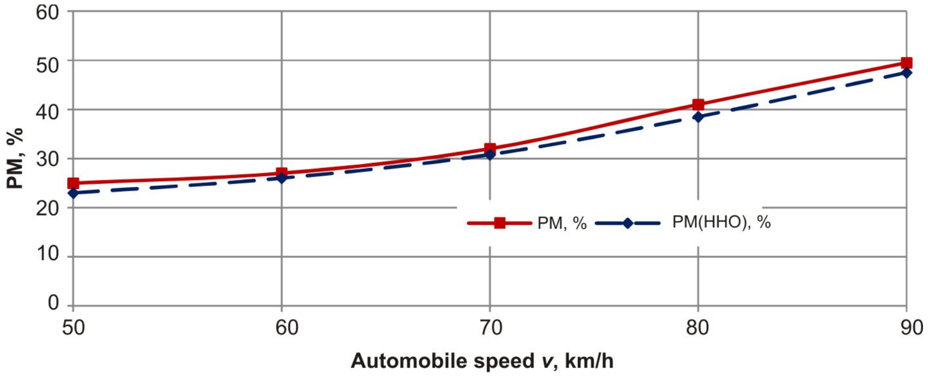

Fig. 6. Amount of particulate mater in exhaust gases

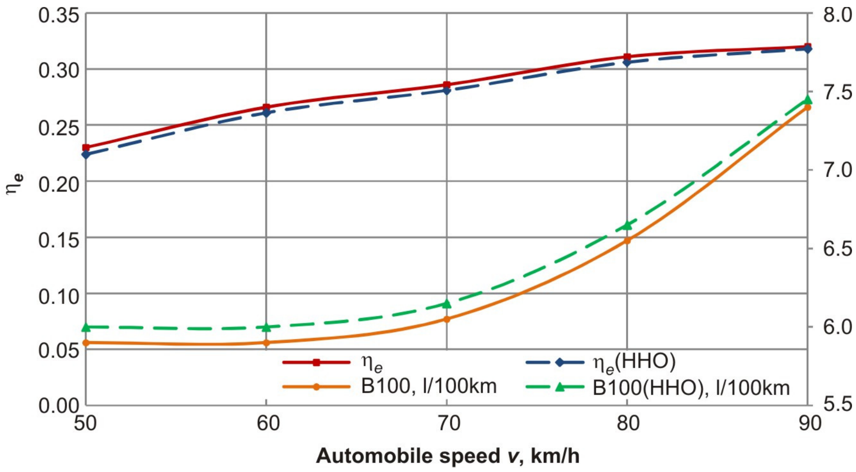

Fig. 7. Engine fuel consumption and net efficiency ratio

Conclusions

1. Dynamometer rolling road tests have revealed that a small amount of HHO gas (1.5 l/min) drawn into engine cylinders together with air improves combustion of diesel fuel under various engine speed and load conditions and decreases concentration of toxic substances in exhaust gases: O_2 gas amount decreases by 2.5–4.5%; CO gas amount decreases by 7–12.5%; CO_2 gas amount increases up to 2%; HC amounts decreases up to 1.5%; PM amount decreases by 4–8%; NO_x gas amount decreases up to 5% at small engine loads.

2. Additional HHO gas supply at medium engine loads leads to 3.5% increase of NO_x gas concentration in exhaust gases and with further increase of load additional supply of gas increases nitrogen oxides concentration.

3. Efficiency ratio of HHO gas production and use in an engine constitutes only $\eta_{eHHO} \approx 0.18$. Therefore, using this gas in a diesel engine running under medium loads results in up to 1.7% fuel consumption increase and up to 2.5% net efficiency ratio decrease.

4. Economic efficiency of diesel engines with additional HHO supply needs to be further investigated. In this article the environmental parameters had been analysed. No economic calculation had been done.

5. HHO gas can improve environmental characteristics of engines without catalyst exhaust gases neutralizers.

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