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Abstract. The paper deals with the influence of the type of fuel and the conditions of discharging behind the throttle during idling mode on the toxicity of exhaust gases of spark-ignition engines. The effect of hydrogen additives on exhaust emissions when working on gasoline and compressed natural gas is shown. A comparison of the toxicity of exhaust gases when working on a single-cylinder research engine and a four-cylinder engine at idle.

1. Introduction

Increase of ecological safety of automobile engines is general world trends. This is due to attempts to improve the environmental situation in large cities, where the share of cars falls to 50% of all pollutants emitted into the air. At the same time, the spark ignition engine is the main source of energy for most cars. Therefore, the requirements for environmental safety of produced cars are constantly becoming tougher. As a result, a gradual transition from gasoline engines to gas, as more environmentally friendly [1]. Also, engines with the addition of hydrogen are being actively studied and are already being used [2, 3, 4, 5]. To a greater extent this applies to gas engines [6, 7, 8]. Compressed natural gas (CNG) and hydrogen requires a minimum of adaptation of the power system used for CNG [9, 10, 11]. In this regard, the work analyzed the type of fuel (gasoline, gasoline with the addition of up to 6% hydrogen, CNG, CNG with the addition of up to 15% hydrogen) on the toxicity of exhaust gases in a single-cylinder research unit and a four-cylinder engine at idle.

2. Experimental technique

Experimental studies were carried out on a single-cylinder UIT-85 installation (Figure 1a) and on a VAZ-2111 spark-ignition engine (Figure 1b). Include information about the geometric parameters of the engine UIT-85: number of cylinders – 1; working volume – 0.652 l; compression ratio – 7; diameter of the cylinder – 85 mm; piston stroke – 115 mm; length of connecting rod – 266 mm; rotational speed – 900 rpm; ignition – spark plug, at a fixed ignition advance angle of 13 BTDC for a more visual comparison of the results obtained. A include information about the geometric parameters of engine VAZ-2111: number of cylinders – 4; working volume – 1.499 l; compression ratio – 9.8 or 7.5 when using a special research plate (Figure 1c); diameter of the cylinder – 82 mm; piston stroke – 71 mm; length of connecting rod – 121 mm; rotational speed - 880 rpm (regular mode idling); ignition – spark plug, the ignition timing was chosen for optimal main fuel flow rate, it ranged from 24 to 35 BTDC when working on petrol from 30 to 42 BTDC at work on CNG when running on a compression ratio 7.5 ignition timing was in the range of from 35 to 42 BTDC for all studied fuels.
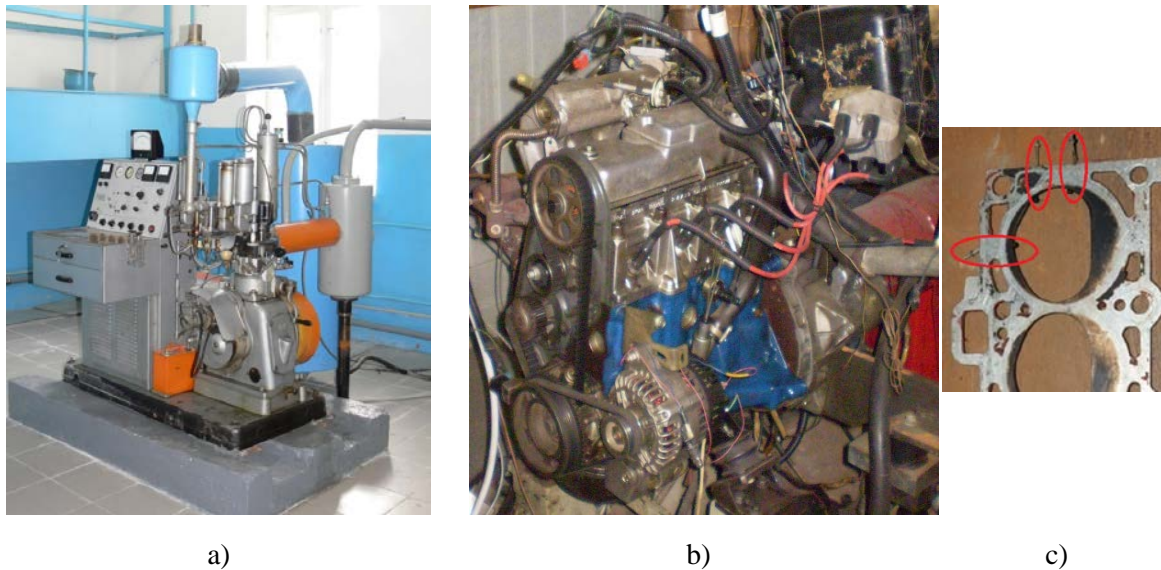
a)   b)   c)

Figure 1. The UIT-85 plant (a) and (b) the VAZ-2111 engine; (c) research plate with sensors ionization, lowering the compression ratio of the VAZ-2111 engine to 7.5.

The portable gas analyzers «META» Avtotest-01.03P and Avtotest-02.03P determined the concentration of toxic components (NO_x, CH and CO) in the exhaust gases. The measurement error on the passport of the gas analyzer is 5%. The pressure in the engine cylinder was measured with a Kistler pressure sensor. Local conditions of propagation of the flame front was determined by means of sensors of ionization.

3. Results and Discussion

Consider the influence of the type of fuel on the toxicity of exhaust gases when working on the research single-cylinder unit UIT-85. Work on the UIT-85 according to the temperature during the combustion process corresponds to the work of the atmospheric engine at maximum loads. Figure 2 shows toxicity for products of incomplete combustion. Figure 2a shows the toxicity of hydrocarbons (CH). Figure 2b shows the concentration of carbon monoxide (CO) in the exhaust gases. And figure 3 shows the toxicity of nitrogen oxides (NO_x). As can be seen, CO toxicity does not depend on the type of fuel, but is determined mainly by the excess air ratio (Figure 2b). At the same time, the toxicity of CH and NO_x depends on the nature of the flow of combustion. This is seen in Figures 2a and 3. Figure 2a shows that, when operating on CNG, CH toxicity is the highest of the studied fuels. When hydrogen is added to CNG, the CH concentration decreases, but it is still greater than when operating on gasoline with hydrogen. At the same time, in Figure 3, similar NO_x values are observed when working on CNG and gasoline, and CNG and gasoline with the addition of 5% hydrogen. With an increase in the proportion of hydrogen to 10 and 15% toxicity of NO_x, respectively, increases. These results on exhaust emissions are explained by the following reasons. First, the mass of exhaust gases in the transition to natural gas is reduced by about 10%. Secondly, the results are given at a constant ignition advance angle, and the characteristics of combustion of CNG and gasoline are very different. Therefore, during the combustion of CNG significantly increases the first phase of combustion [12]. This increases the duration of the entire combustion process. At the same time due to the greater speed of the laminar combustion of a high heat release rate at the end of the main phase of combustion [13]. This is reflected in close to maximum values of temperature and, consequently, a high concentration of NO_x. CH toxicity is more influenced by the parameters of the wall layer [14]. When working on CNG, the wall layer becomes larger in area due to the increased duration of combustion. The density of the wall layer is also quite high, due to the high heat generation rates at the end of the combustion

process. This leads to an increase in exhaust gas specific toxicity for CH. The addition of hydrogen to CNG leads to a greater increase in the rate of activation of the combustion process. This results in a significant reduction in the ignition delay. The difference in the duration of the first phase of combustion when working on gasoline with the addition of hydrogen and CNG with the addition of hydrogen becomes insignificant. This leads to a more marked reduction in CH toxicity for CNG. Also for CNG, the addition of hydrogen more significantly increases NO_x [15]. This shows a greater dependence of the toxicity of exhaust gases with the addition of hydrogen to CNG than to gasoline.
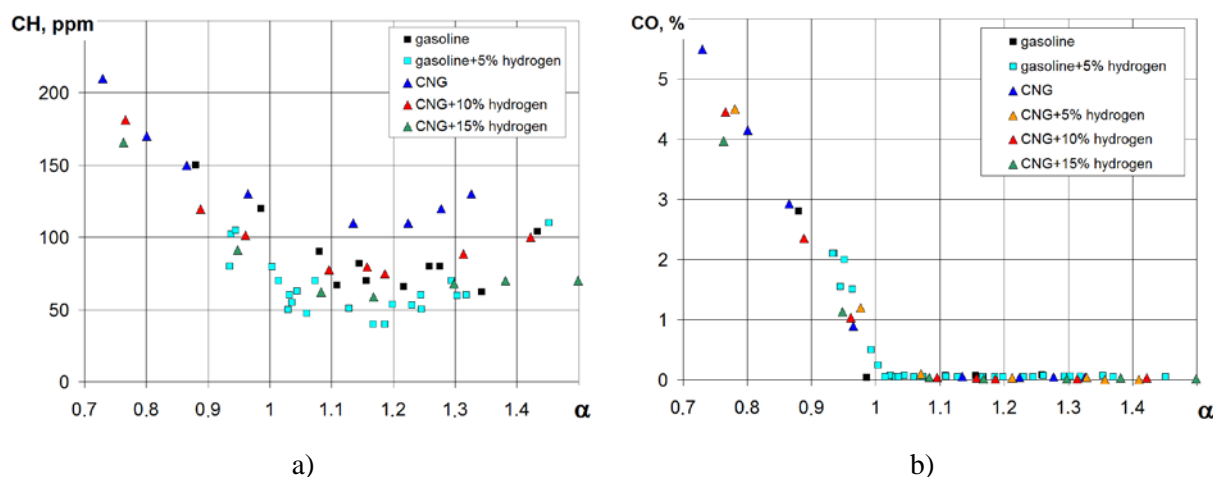

Figure 2. The concentration of toxic components in the exhaust gases for UIT-85 when operating on gasoline, gasoline with 5% hydrogen, CNG and CNG with hydrogen: (a) unburned hydrocarbons (CH); (b) carbon monoxide (CO).
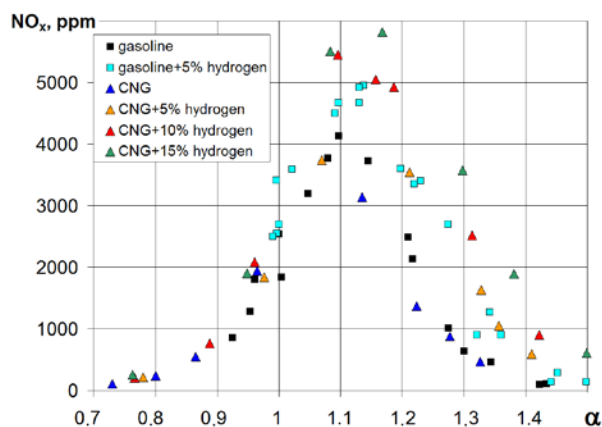

Figure 3. The concentration of nitrogen oxides (NO_x) in exhaust gases for UIT-85 when operating on gasoline, gasoline with 5% hydrogen, CNG and CNG with hydrogen.

The engine at idle is greatly influenced by the proportion of residual gases in the working mixture [16]. The amount of residual gases depends on the position of the throttle, which creates a vacuum in the intake manifold. Figure 4 shows the discharge in the intake manifold at idle mode of the VAZ-2111 engine when operating on gasoline, gasoline with hydrogen, CNG and CNG with hydrogen, for compression levels 9.8 (Figure 4a) and 7.5 (Figure 4b). From figure 4a, it can be seen that when working on gasoline and gasoline with hydrogen, the vacuum in the intake manifold falls in the region of one curve. When operating on CNG, the vacuum in the intake pipe decreases. This is due to the

large opening of the throttle. The addition of hydrogen to CNG increases the efficiency of the combustion process and on lean mixtures, the valve for CNG with hydrogen closes more. When the engine is running at a compression ratio of 7.5, a similar picture is observed. Only when working on CNG and gasoline, greater throttle opening is required for stable engine performance. This is due to a decrease in the efficiency of the combustion process with a decrease in the degree of compression.
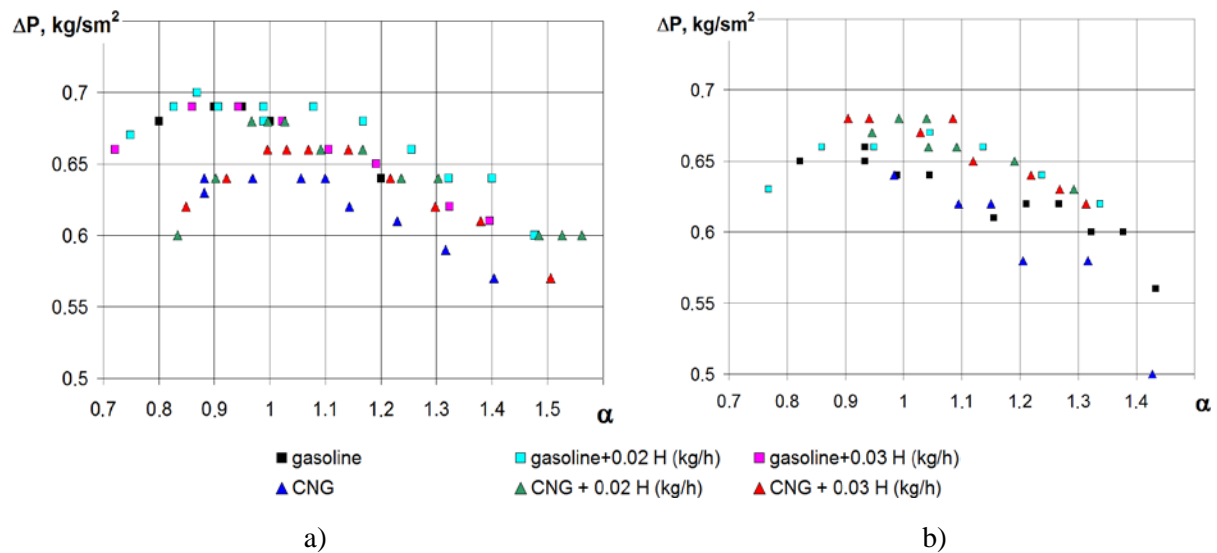

a)   b)

Figure 4. Discharge in the intake pipe in the engine VAZ-2111 when operating on gasoline, gasoline with hydrogen, CNG and CNG with hydrogen: (a) compression ratio of 9.8; (b) compression ratio 7.5.

a)   b)

Figure 5. Air consumption in the engine VAZ-2111 when operating on gasoline, gasoline with hydrogen, CNG and CNG with hydrogen: (a) compression ratio of 9.8; (b) compression ratio 7.5
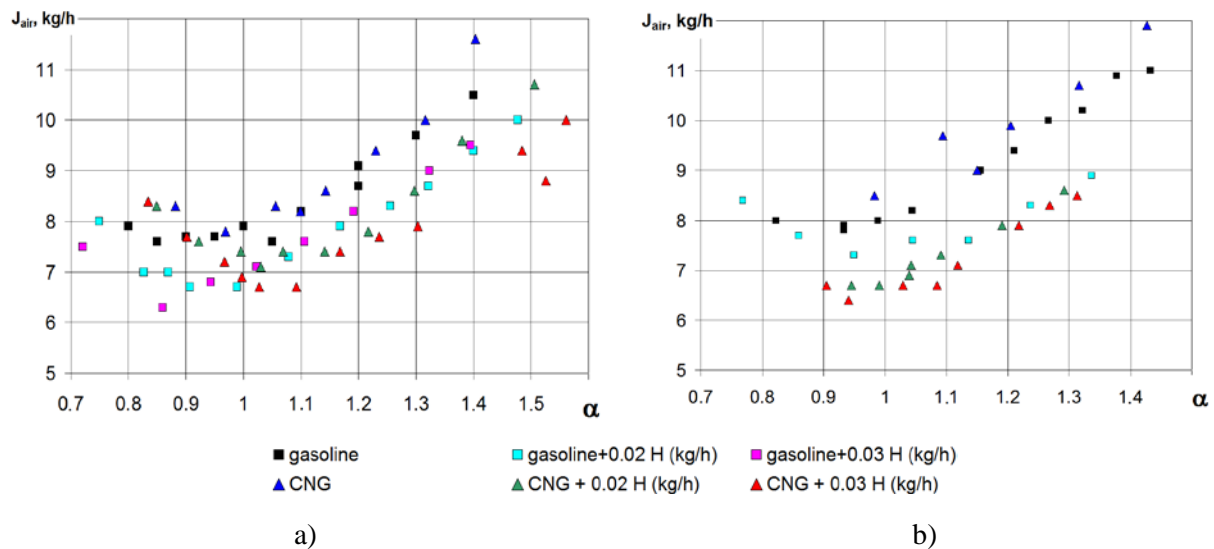
The discharge characteristic in the intake manifold is complemented by the results of the airflow characteristics presented in Figure 5. In general, the airflow characteristic corresponds to the discharge reading in the intake manifold. With a larger vacuum is more resistance and less airflow. Thus, in the engine cylinder there is a greater proportion of residual gases that impede the normal course of the

combustion process. From figure 5a it can be seen that the air consumption characteristic for gasoline and CNG lies on the same curve. With the addition of hydrogen, part of the air is displaced, which corresponds to a decrease in air consumption. For a compression ratio of 7.5 (Figure 5b), a similar picture is observed, only to ensure stable operation of the engine, the airflow is somewhat higher.

Consider the effect of fuel type on toxicity when the engine is idling at a compression ratio of 9.8 and 7.5. Figure 6 shows the CH concentration in the exhaust gas as a function of the excess air ratio. From figures 6a and 6b, it can be seen that the toxicity of CH when operating on CNG and gasoline is on the same curve and weakly depends on the degree of compression. The addition of hydrogen to gasoline leads to some reduction in CH toxicity [17]. A significant reduction of the toxicity of CH is observed with the addition of hydrogen in CNG. What is noticeable for both the considered degrees of compression. This is due to a better activation of the process of combustion of natural gas in the initial phase of combustion. In the main phase of combustion of CNG due to its higher diffusion, activity allows for rapid and complete combustion [18].
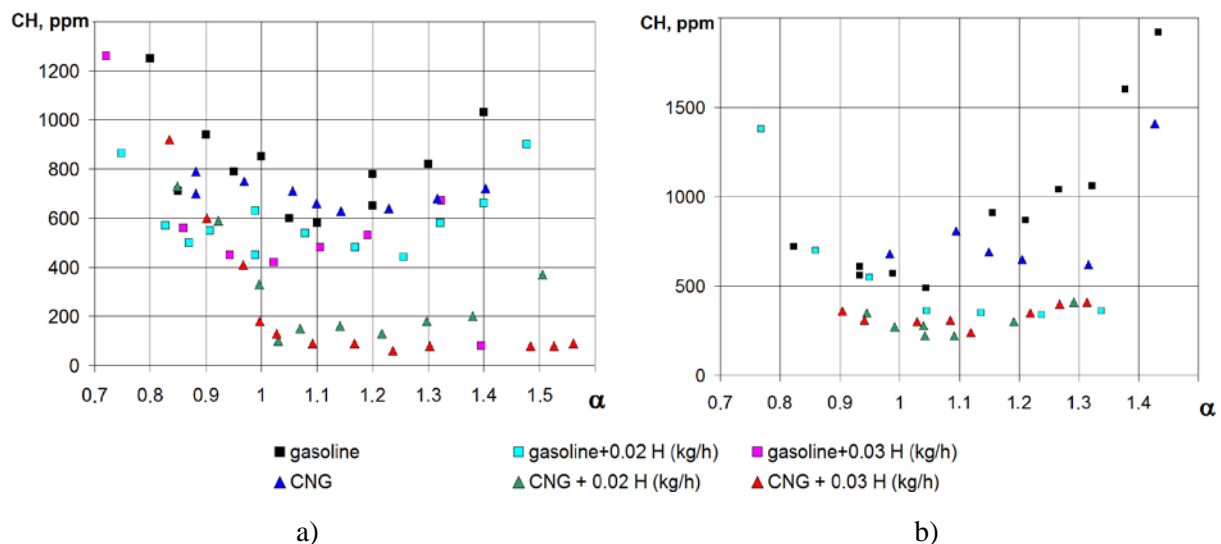

a)   b)

Figure 6. CH concentration in a VAZ-2111 engine when operating on gasoline, gasoline with hydrogen, CNG and CNG with hydrogen: (a) compression ratio of 9.8; (b) compression ratio 7.5.

Figure 7 shows the CO concentration for a compression ratio of 9.8 and 7.5. For poor mixtures (from 1 to 1.6) with a compression ratio of 9.8, the concentration of CO ranges from 0.15 to 0.3%. The lower values correspond to work on CNG, CNG with hydrogen and gasoline with hydrogen. When working on gasoline, the CO concentration ranges from 0.28 to 0.4%. In the zone of rich mixtures, gasoline also exhibits higher toxicity than other fuel options. With a compression ratio of 7.5, the picture is generally similar, only in the lean zone the CO values already lie in the same range from 0.24 to 0.42 for all types of fuel. For a rich mixture, the picture is similar, only with a decrease in the degree of compression, CO toxicity increased. Such results show that with a decrease in the degree of compression in the ballasted working mixture, residual gases decrease the completeness of fuel combustion. This is reflected in the increase in CO concentration in the exhaust gases.

Figure 8 shows the NO_x concentration for compression levels 9.8 and 7.5. For the compression ratio of 9.8, the following picture is typical. When hydrogen is added to gasoline, a marked increase in NO_x toxicity occurs for all excess air ratios. This shows the increase of heat release rate with the addition of hydrogen for the same throttle position. At the same time, with the addition of hydrogen in CNG, a decrease in NO_x in the area of poor mixtures (1 to 1.5). This is due to the greater closing of the throttle and reducing the filling of the cylinders. Thus, hydrogen increases the rate of heat release. But by reducing the amount of fuel introduced into the engine cylinder as the concentration of residual

gases increases, the temperature in the combustion process decreases. This is reflected by a decrease in NO_x. These results are well illustrated by Figure 8b. It can be seen from the figure that with the addition of hydrogen and a greater closure of the throttle, NO_x reduction is provided for both CNG and gasoline. This effect is especially noticeable in lean mixtures, where the concentration of NO_x is limited only by the temperature of the combustion process.
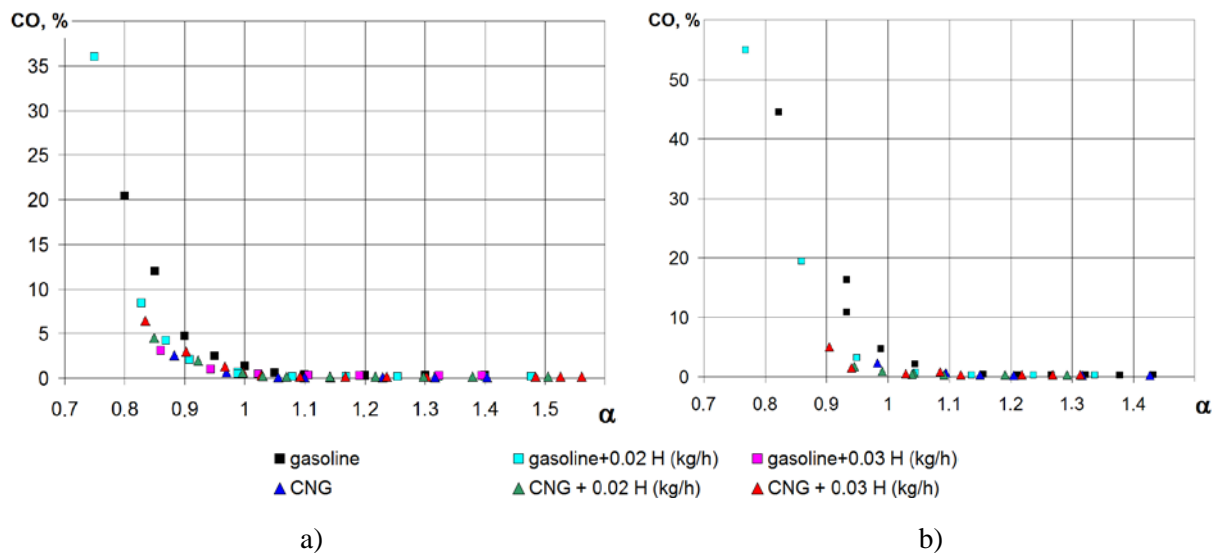

Figure 7. CO concentration in the engine VAZ-2111 when operating on gasoline, gasoline with hydrogen, CNG and CNG with hydrogen: (a) compression ratio of 9.8; (b) compression ratio 7.5.

Figure 8. NO_x concentration in the engine VAZ-2111 when operating on gasoline, gasoline with hydrogen, CNG and CNG with hydrogen: (a) compression ratio of 9.8; (b) compression ratio 7.5.
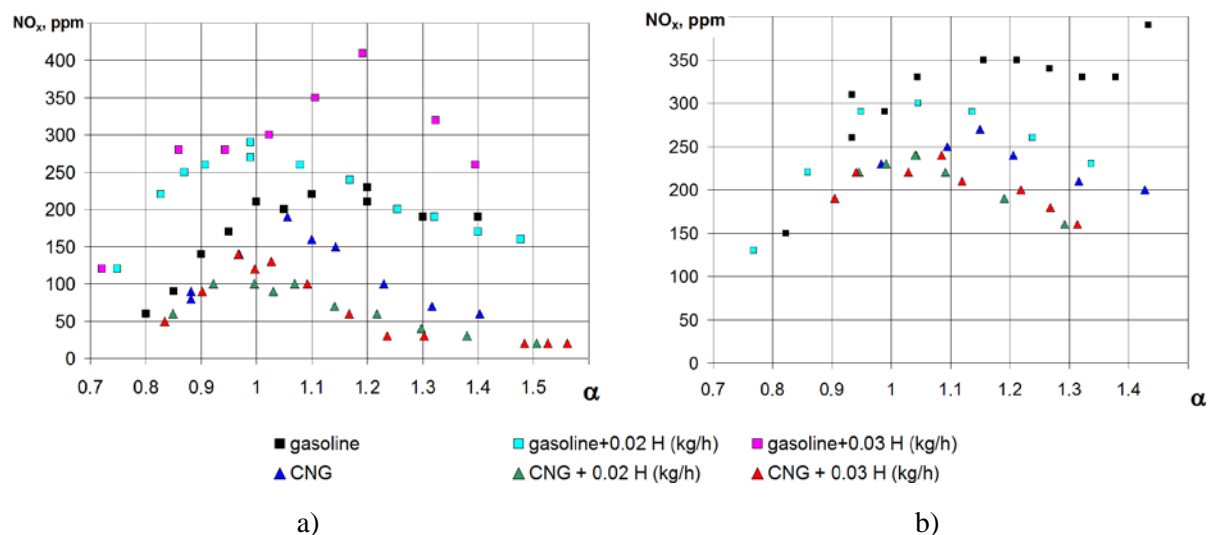
The results reflect the main issues related to the use of hydrogen as an activator of the combustion process of the main hydrocarbon fuels (gasoline and CNG) for spark ignition engines [19, 20, 21]. Hydrogen increases the rate of heat generation and fuel combustion. This leads to an increase in toxicity of nitrogen oxides and a decrease in CH, both when operating on CNG and on gasoline, with a constant throttle position. In the case of idling and low loads, the addition of hydrogen stabilizes the

combustion process, which allows to cover the throttle more. This leads to a reduction of toxicity as NO_x and products of incomplete combustion CH and CO. It should be noted that the effect of hydrogen in such cases is more effective when working on CNG. This, combined with a simpler layout of the power system (hydrogen can be refueled with CNG into one cylinder during refueling and use one universal power system for CNG and CNG with hydrogen), makes this type of fuel quite realistic for mass use in the near future. The use of hydrogen as an additive to gasoline does not bring so many positive results. The use of hydrogen significantly increases the cost of the fuel system. Comparing the characteristics of CNG and gasoline toxicity, it can be noted that CNG reduces toxicity when idling at the optimum ignition timing (angle increased by 5 – 8 BTDC compared to gasoline). The same pattern is observed if we use the optimal ignition timing at full load. It should be noted that during the combustion of CNG, lighter CH are formed, which are more easily oxidized in exhaust gas neutralization systems. The only drawback of CNG is a reduction in cylinder filling. This is solved by installing a compressor, which is an effective solution due to the high detonation properties of CNG.

4. Conclusion

1. The ambiguous effect of the addition of hydrogen to the main fuel (CNG and gasoline) on the toxicity of exhaust gases is shown. There is some reduction in the products of incomplete combustion of CH and CO, but at the same time, NO_x increases markedly.

2. It is shown that CNG can provide a reduction in exhaust emissions, both for NO_x and for CH and CO, while maintaining the engine performance indicators, if the optimum ignition angles are selected.

3. A significant reduction in toxicity was obtained for both NO_x and CH and CO when switching from gasoline to CNG at idle. But for effective combustion, it is necessary to use methods of intensifying the combustion process in the working mixture that is strongly ballasted with exhaust gases. As a variant of the proposed use of the additive hydrogen to the fuel to reduce the toxicity, especially because the principal difference is the addition of 4% (0.02 kg/h) or 6% (0.03 kg/h) of hydrogen was not detected.

4. The use of a reduced degree of compression in idling mode made it possible to better show the effect of the degree of throttling on engine toxicity indicators. It is shown that it is not the degree of ballasting itself that affects the nature of the combustion process, but the conditions for the formation of a stable burning center. If the initiation of the combustion process is successful, then a high content of residual gases in the working mixture reduces the concentration of toxic components in the combustion products.

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