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DISTINCTIVE FEATURES OF OPERATION OF AN INTERNAL COMBUSTION ENGINE RUNNING ON HYDROGEN-CONTAINING FUELS

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Experimental investigations have been carried out on an internal combustion engine with hydrogen added to the hydrocarbon fuel, i.e., gasoline. The possibility of improving the energy and environmental indices in the case of hydrogen feed to the engine's air path has been shown. It has been established that increase in the fraction of hydrogen in the fuel mixture causes the operating process of the engine to improve, with the result that the flow rate of gasoline as a function of the H_2 fraction decreases by nearly 70%. Considerable reduction in the content of CO, CO_2, and CH (of approximately 5–60% depending on the amount of the added H_2) is observed. However, adding hydrogen to the fuel-air mixture leads to an increase in the content of nitric oxides in the combustion products because of the growth in the velocity of propagation of the flame and increase in the combustion temperature.

Keywords: *hydrogen, operating process of an internal combustion engine, combustion products, fuel flow rate, elasticity of discharge, power of an engine, excess-oxidant coefficient.*

One trend in alternative power engineering — the development and investigation of operating processes of an internal combustion engine with hydrogen mixed with hydrocarbon fuels and primarily with gasoline (benzine) — has been developed recently. The wide concentration limits, low ignition energy, and high reactivity of hydrogen make it possible to positively act on the fuel-air mixture, improving its properties. This trend is interesting in that one can substantially increase the fuel economy of a commercial engine and diminish the amount of harmful emissions into the atmosphere by modifying the engine slightly.

The process of combustion of the fuel in heat engines is a combination of complex physicochemical phenomena occurring under substantially unsteady conditions and short periods of time. For example, in forced-ignition engines, these are sparking and the development of a combustion site, heat exchange of the fuel with air and of the fuel mixture with the environment through the cylinder walls, evaporation of the fuel, macro- and micromixing of the vapor and droplets of the fuel, burning of the fuel-air mixture, heat exchange of the combustion products with the atmosphere through the cylinder walls, the Mache effect, and others. Under such conditions, the mechanisms of formation of combustion products are by no means ideal as a rule.

We dwell on the distinctive features of their formation in forced-ignition engines. At the end of the compression stroke, the fuel mixture is spark-fired and the flame front propagates in the combustion chamber. This process continues in the expansion stroke, too. Optimum conditions for propagation of the flame as far as both the temperature and pressure of the mixture and the structure of flow inside the cylinder are concerned are created in a piston engine near the top dead center. Therefore, when the position of the combustion phase relative to the top dead center is optimum, its completion can be expected by approximately $25–30^{\circ}$ of the angle of rotation of the crankshaft. Carbon monoxide CO is formed in fuel-overenriched local zones of the combustion chamber, whereas nitric oxides NO_x, in particular NO, are formed in high-temperature combustion products in nonequilibrium reactions involving nitrogen and oxygen. As soon as the flame reaches the cylinder walls, it dies out, leaving behind a very thin layer of unburned fuel whose thickness is usually of the order of several hundredths of a millimeter. The unburned fuel is also left above the piston ring in the gap between the piston crown and the cylinder wall. In the expansion stroke, we have rapid cooling of the combustion products. Chemical reactions slow down as a result of the drop in the temperature and the concen-

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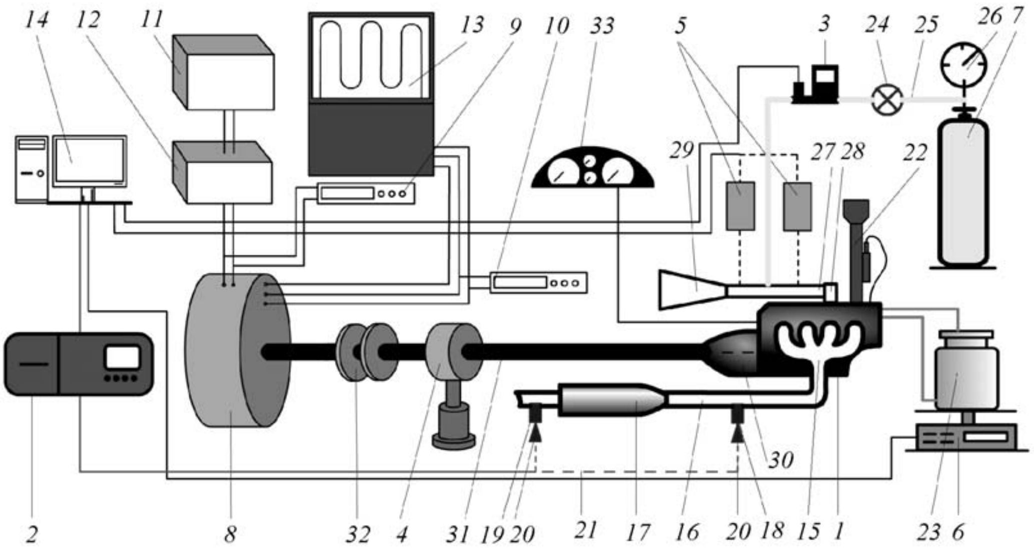

Fig. 1. Schematic diagram of the experimental bench for investigation of the processes of combustion of hydrogen-containing fuels in an internal combustion engine: 1) Honda-D15B2 internal combustion engine; 2) CARTEC-CET 2200 C gas analyzer; 3) FMA-2612A flow controller; 4) M40-500 torque generator; 5) ÉMIS-VIKhR' flow meter; 6) electronic balance; 7) cylinder with hydrogen; 8) GSK-30 M three-phase synchronous alternator; 9 and 10) voltmeters; 11 and 12) transformers; 13) load resistor; 14) computer; 15) engine's outlet; 16) exhaust pipe; 17) catalytic neutralizer; 18 and 19) holes for sampling of the gas; 20) probe; 21) flexible hose; 22) system of visualization of the process of combustion in the cylinder; 23) gasoline tank; 24) cock; 25) pipeline; 26) manometer; 27) air filter; 28) air branch pipe; 29) intake pipe; 30) automatic transmission; 31) main shaft; 32) muff; 33) engine's instrumentation panel.

trations of CO and NO are "frozen." Next, after the opening of the exhaust valves, the combustion products containing CO, CO_2, and NO_x leave the cylinder, entraining part of the layer of hydrocarbons CH_x deposited on the wall.

The use of hydrogen as a main fuel and primarily as an addition to gasoline makes it possible to substantially diminish the toxicity of the combustion products and to increase fuel economy. This is due to the high reactivity and wide concentration limits of combustion of hydrogen, which positively influence the completion of chemical reactions in the burning of the fuel-air mixture.

In oxidation of hydrogen in air, the only toxic components are nitric oxides NO_x. Furthermore, certain amounts of CO and CH_x will always be contained in the combustion products of an actual engine as a consequence of the partial combustion of motor oil penetrated into the chamber. However, the concentration of these components is low, which has been confirmed by a number of investigations [1–3]. Thus, when hydrogen is used as a gasoline additive, the basic toxic combustion products are CO, CH_x, and NO_x.

In this work, we consider distinctive features of the course of the operating process and the formation of combustion products in a Honda-D15B2 forced-ignition gasoline engine with gasoline containing hydrogen as additive in the range 0–20% of the volume of air entering the engine. Hydrogen was fed to the air path via a special system making it possible to change its flow rate in the range 0–100% of the volume of air entering the engine. The engine's operation was investigated on an experimental bench intended for comprehensive study of the intracylinder processes, the composition of the combustion products, and the energy indices and velocity and load characteristics of the engine. The bench included the following main parts:

(1) the basic power plant: a Honda-D15B2 forced-ignition gasoline four-stroke four-cylinder internal combustion engine ($N_{e,\max} = 66$ kW and $\varepsilon = 9.3$) featuring a system for distributed fuel injection;

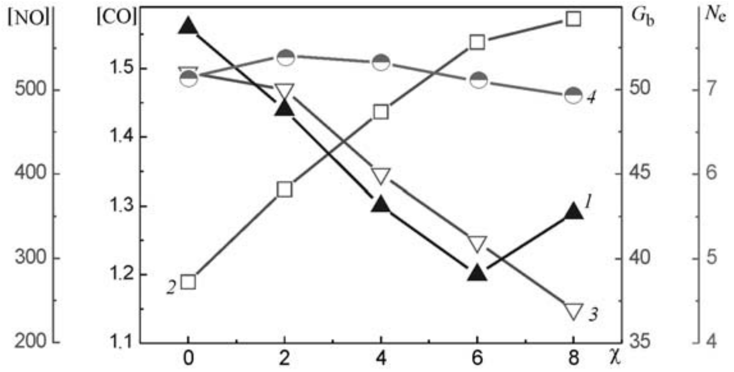

Fig. 2. Emission of CO (curve 1) and NO (curve 2) and dynamics of change in the gasoline flow rate G_b (curve 3) and the engine’s power N_e (curve 4) vs. amount of H_2 added to air. [NO], ppm; [CO], χ, %; G_b, g/min; N_e, kW.

(2) the digital gas analyzer intended for quantitative measurement of the components of combustion products: CO, CO_2, O_2, CH_x, and NO;

(3) the ÉMIS-VIKhR’ ÉV-200 vortex transducer for measurement of the volume flow rate of air entering the engine with a measurement error of 2%;

(4) the FMA-2612A electronic flow controller for measurement and control of the mass and volume of hydrogen fed to the engine;

(5) the Scout-SPU6000 electronic balance for measurement of the gasoline consumption;

(6) the M40-500 torque generator making it possible to determine power and torque on the main shaft;

(7) the GSK-30 M three-phase synchronous alternator for generation of electric power followed by its transmission to the load resistor;

(8) the air-cooled load resistor;

(9) the computer for receiving, processing, and analyzing information from the measuring equipment.

A diagram of the experimental bench is shown in Fig. 1. The principle of its operation and the procedure of measurements of the composition of combustion products have been presented in [4, 5] in detail.

Engine’s Operation on a Lean Mixture (α = 0.97) and when the Amount of Hydrogen Added Is Low (χ = 0–8%). This set of experiments was carried out in the load regime for the initial power N_e = 7.15 kW on gasoline, excess-oxidant coefficient α = 0.97, and rotational velocity of the crankshaft n = 2680 min^{-1}. During the operation, we took the energy and environmental characteristics of the engine as functions of the content of hydrogen in the mixture. We determined the following basic parameters: the volume of air entering the engine, the volume and mass content of hydrogen in the mixture, the gasoline consumption, the engine’s power and torque, the qualitative and quantitative composition of combustion products (CO, CO_2, O_2, CH_x, and NO), the crankshaft’s rotational velocity, the excess-oxidant (air) coefficient, and a number of other auxiliary indices enabling us to control the experiment.

The procedure of determination of the above parameters envisaged reaching the prescribed regime of operation on the main fuel (gasoline) and subsequent increase in the hydrogen feed from 0 to 8% of the volume of air entering the engine at fixed N_e = const and n = const.

The most indicative characteristics for comparison of the toxic properties of the products of combustion of hydrogen-containing fuels in an internal combustion engine are those based on the H_2 fraction in the fuel-air mixture. The dependences characterizing the content of CO, CO_2, O_2, CH_x, and NO in the combustion products of the engine under study which operated on gasoline with hydrogen added in amounts of 0 to 8% of the volume of air entering the engine are presented in Figs. 2 and 3. These figures also give the dependences of the change in the specific fuel consumption, the engine power, the crankshaft rotational velocity, and the excess-oxidant coefficient on the fraction of hydrogen in the mixture: $G_b = f(H_2)$, $N_e = f(H_2)$, $n = f(H_2)$, and $\alpha = f(H_2)$.

The experiments have shown a relatively low level of certain toxic components in the combustion products of the gasoline-hydrogen-air mixture and a substantial reduction in the fuel consumption. The concentrations of CO, CH_x, and CO_2 attained their maxima in the products of combustion of gasoline with air. With increase in the H_2 frac-

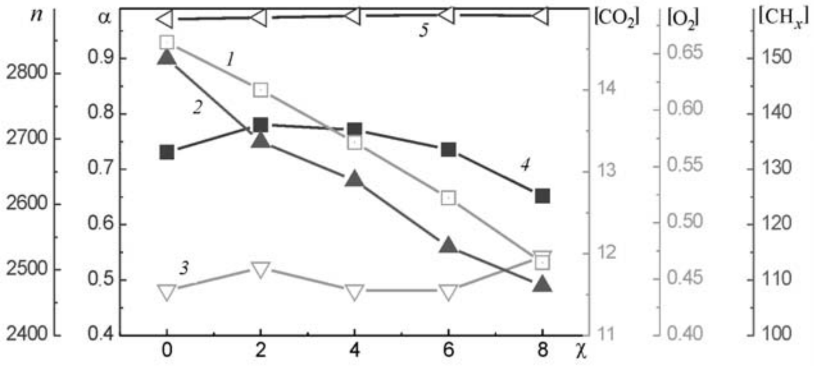

Fig. 3. Emission of CO_2 (curve 1), CH_x (curve 2), and O_2 (curve 3) and change in the crankshaft's rotational velocity n (curve 4) and the excess-oxidant coefficient α (curve 5) vs. amount of H_2 added to air. n, min^{-1}; [CO_2], [Q_2], and χ, %; [CH_x], ppm.

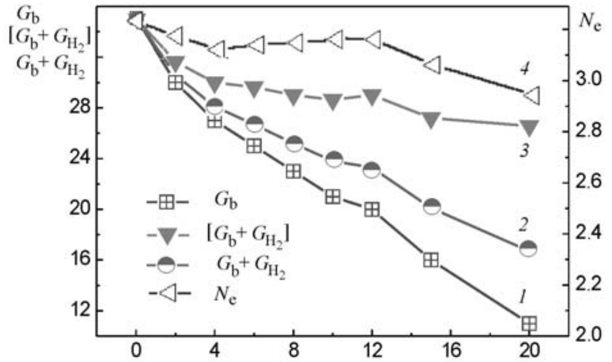

Fig. 4. Dynamics of the fuel-energy parameters vs. H_2 fraction in the stoichiometric mixture: 1) flow rate of gasoline G_b; b) flow rate of combined fuel (gasoline + hydrogen) $G_b + G_{H_2}$ (without allowance for the calorific value of hydrogen); 3) flow rate of combined fuel (gasoline + hydrogen) $[G_b + G_{H_2}]$ (with allowance for the calorific value of hydrogen); 4) engine's power N_e. G_b, $G_b + G_{H_2}$, and $[G_b + G_{H_2}]$, g/min; N_e, kW.

tion in the fuel-air mixture, i.e., with decrease in the C/H ratio in the element composition of the fuel, the content of CO and CH_x substantially drops; in the case of addition of hydrogen in an amount of 8% the concentrations of these components are lower by 17 and 27% respectively than in operation of a gasoline-fueled engine (curve 1 in Fig. 2 and curve 2 in Fig. 3). The largest gain in CO (23%) was observed with a 6% fraction of H_2. Increase in the fraction of hydrogen in the mixture caused the NO content in the combustion products to grow (curve 2 in Fig. 2). For example, with a 8% fraction of H_2, the NO concentration attained 585 ppm, which is 2.15 times higher than in operation on gasoline.

At the same time, the presence of molecular hydrogen in the fuel-air mixture caused the concentration of CO_2 in combustion products to decrease; with a 8% fraction of hydrogen, the reduction amounted to 18% (curve 1 in Fig. 3). The concentration of O_2 in the combustion products with hydrogen added in an amount of 8% of the volume of air entering the engine remained virtually constant (curve 3 in Fig. 3).

It is of great interest to analyze the influence of hydrogen on the fuel-energy indices of the engine. When the engine was fueled by gasoline with hydrogen added in an amount of 8% of the volume of air entering the engine and the excess-air coefficient was $\alpha = 0.97$, the power was preserved at the level of that of a main-fueled engine. With 2% and 4% fractions the power increased by 4 and 2.5% respectively; when 8% H_2 was fed it diminished by 3% (curve 4 in Fig. 2). Substantial gain in the fuel consumption began with increase in the concentration of hydrogen in

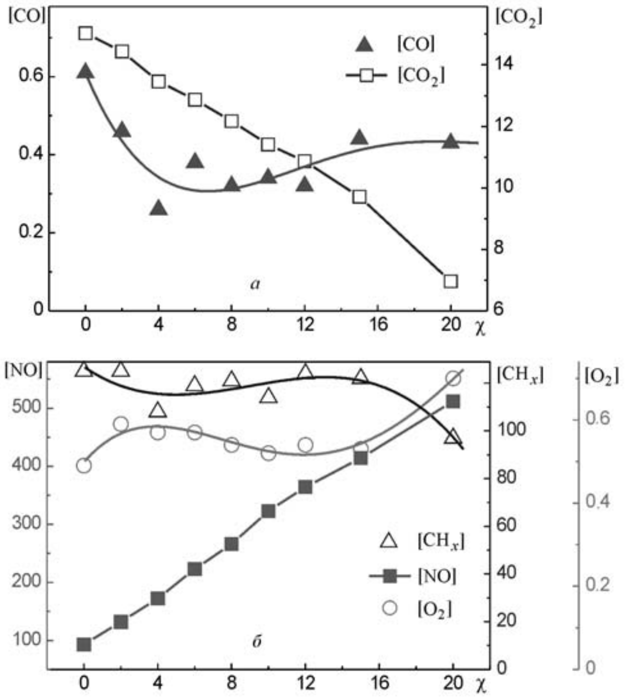

Fig. 5. Dynamics of emission of combustion products vs. H_2 fraction in the stoichiometric mixture: a) CO and CO_2; b) CH_x, O_2, and NO. [CO], [CO_2], and [O_2]. %; [CH_x] and [NO], ppm.

the fuel mixture. Thus, in the case of hydrogen added in amounts of 4, 6, and 8%, the consumption (flow rate) of gasoline was G_b = 45, 41, and 37 g/min respectively versus 51 g/min for pure gasoline.

Engine's Operation on a Stoichiometric Mixture (α = 1) and when the Amount of Hydrogen Added Is High (χ = 0–20%). We have an analogous regularity on the dynamics of energy and environmental indices when the engine is fueled by a stoichiometric mixture as demonstrated by Figs. 4 and 5.

The experimental results have shown that when the fuel mixture is enriched with hydrogen in an amount to 12% of the volume of air entering the engine and the excess-air coefficient is α = 1, the power is virtually preserved at the level of that of the basic engine. Further enrichment with H_2 to 20% leads to a reduction of 9% in the power (see Fig. 4). The emission of CO, CO_2, and CH_x significantly decreases, whereas fuel economy substantially grows. It is seen that the flow rate of gasoline G_b (curve 1) and the flow rate of combined fuel $G_b + G_{H_2}$ (curve 2) have virtually an inverse linear dependence on the amount of hydrogen added. For example, when 6% hydrogen is added to the hydrogen-air mixture, G_b diminishes by 29% and $G_b + G_{H_2}$ decreases by 24%; in the case of enrichment with hydrogen in amounts of 12 and 20%, G_b decreases by 43 and 69%, and $G_b + G_{H_2}$ by 33 and 52% respectively.

The substantial reduction in the gasoline flow rate with preservation of the engine's power cannot be explained only by the high calorific value of hydrogen, which is 2.7 times higher than that of gasoline. An analysis has shown that the consumption (flow rate) of combined fuel $G_b + G_{H_2}$ with allowance for the calorific value of hydrogen in terms of gasoline considerably diminishes, too, and is 27 g/min with a 20% fraction of hydrogen, which is 23% lower than in the case of operation on gasoline (curve 3 in Fig. 4). Here, apparently, the kinetics of combustion of hydrogen fruitfully influences the process of burning of the entire mixture, improving the burning, whereas the high rate of oxidation of hydrogen contributes to the decrease in the heat loss.

However, the high oxidation rate is responsible for the growth in the combustion temperature, which in turn causes the NO yield to increase compared to the operation on gasoline. Thus, it follows from Fig. 5b that when 20% hydrogen is added, the emission of NO increases more than 4 times.

Elasticity of the Emission of Combustion Products. Using the elasticity of the function we can compute the relative increment in the dependent variable $\Delta y/y$, which corresponds to the relative increment in the independent variable $\Delta x/x$. The elasticity of the function $y = f(x)$ relative to the variable x represents the limit of the ratio of the rela-

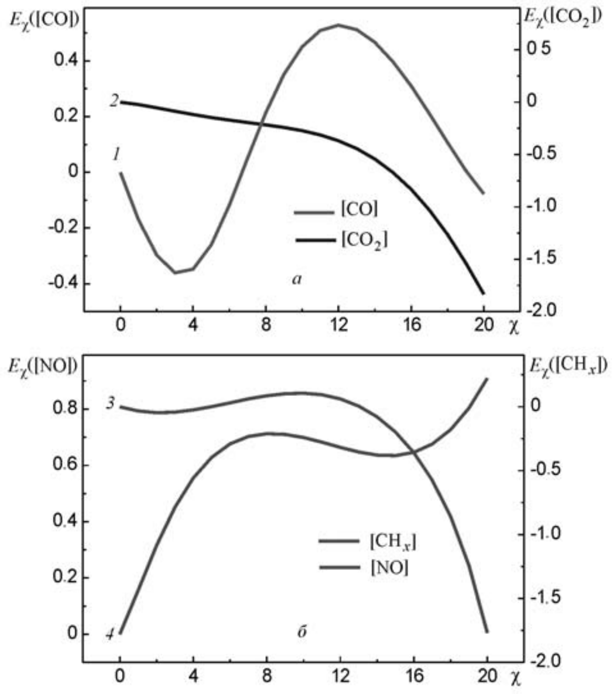

Fig. 6. Elasticity of emission of the combustion products CO (curve 1), CO_2 (curve 2), CH (curve 3), and NO (curve 4) vs. hydrogen fraction in the fuel-air mixture. $E_\chi([CO])$, $E_\chi([CO_2])$, $E_\chi([NO])$, and $E_\chi([CH_x])$, %.

tive increment in the function to the relative increment in the argument when the increment in the argument tends to zero (if the derivative of the function under study exists):

$$E_x(y) = \lim_{\Delta x \to 0}\left(\frac{\Delta y}{y} : \frac{\Delta x}{x}\right) = \frac{x}{y}\lim_{\Delta x \to 0}\frac{\Delta y}{\Delta x} = \frac{x}{y}\frac{dy}{dx}.$$

This means that the elasticity shows the approximate percent increment in the function, which corresponds to an increment of 1% in the argument.

Processing of experimental data gives the elasticity of CO, CO_2, CH, and NO emissions:

$$E_\chi([CO]) = \frac{-0.1125\chi + 0.0274\chi^2 - 18.3703\cdot 10^{-4}\chi^3 + 37.1494\cdot 10^{-6}\chi^4}{0.610 - 0.1125\chi + 0.0137\chi^2 - 6.1234\cdot 10^{-4}\chi^3 + 9.287\cdot 10^{-6}\chi^4},$$

$$E_\chi([CO_2]) = \frac{-0.2695\chi - 0.0922\chi^2 + 0.0206\chi^3 - 15.065\cdot 10^{-4}\chi^4 + 33.165\cdot 10^{-6}\chi^5}{15.045 - 0.2695\chi - 0.0461\chi^2 + 0.00685\chi^3 - 3.77\cdot 10^{-4}\chi^4 + 6.633\cdot 10^{-6}\chi^5},$$

$$E_\chi([CH]) = \frac{-5.3853\chi + 1.4932\chi^2 - 0.0827\chi^3}{126.904 - 5.3853\chi + 0.7466\chi^2 - 0.0267\chi^3},$$

$$E_\chi([NO]) = \frac{12.943\chi + 4.650\chi^2 - 0.5367\chi^3 + 0.0165\chi^4}{94.543 + 12.943\chi + 2.325\chi^2 - 0.179\chi^3 + 0.00412\chi^4}.$$

Figure 6 plots the elasticities of CO, CO_2, CH, and NO concentration in the combustion products versus the amount of hydrogen fed to the cylinder. The plots show the dynamics of percent growth in the emission (increase or decrease), which corresponds to a change of 1% in the hydrogen fraction. For example, when χ = 4% an increase of

1% in the fraction of hydrogen produces a reduction of 0.35, 0.12, and 0.025% in the concentrations of CO, CO_2, and CH respectively and a growth of 0.55% in the emission of NO; when $\chi = 15\%$ the drop in the concentrations of CO, CO_2, and CH amounts to 0.40, 0.67, and 0.20% respectively, whereas the growth in NO is 0.63%.

Conclusions. The obtained data confirm the possibility of using hydrogen efficiently as a gasoline additive to obtain satisfactory fuel-energy and environmental indices of an internal combustion engine.

Increase in the fraction of hydrogen in the fuel mixture leads to an improvement of the efficiency of the engine's operating process, with the result that the gasoline flow rate as a function of the H_2 fraction decreases by approximately 70%. Addition of hydrogen at intake (up to 20% of the volume of air entering the engine) compared to the operation on gasoline also leads to:

(a) considerable reduction in the content of CO, CO_2, and CH (of nearly 5–60% depending on the amount of doping with H_2);

(b) substantial increase (by several times) in the concentration of nitric oxides in the combustion products.

It is impossible to reduce the emission of NO with hydrogen-containing fuels in heat engines without additional measures aimed at diminishing the combustion temperature of the fuel-air mixture. In this connection, with allowance for the wider concentration limits of ignition of hydrogen-containing mixtures, it seems possible to attain low concentrations of NO in operation in the region of lean mixtures.

NOTATION

$E_\chi([CO])$, elasticity of CO with respect to χ; $E_\chi([CO_2])$, elasticity of CO_2 with respect to χ; $E_\chi([NO])$, elasticity of NO with respect to χ; $E_\chi([CH_x])$, elasticity of CH_x with respect to χ; G_b, flow rate of gasoline; $G_b + G_{H_2}$, flow rate of combined fuel (gasoline and hydrogen without allowance for the calorific value of hydrogen); $[G_b + G_{H_2}]$, flow rate of combined fuel (gasoline and hydrogen with allowance for the calorific value of hydrogen); N_e, engine's power; n, crankshaft's rotational velocity; y, function; x, variable; ε, compression ratio; χ, fraction of hydrogen in the fuel-air mixture. Subscripts: b, gasoline (benzine); H_2, hydrogen; e, effective.

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