One of the key problems of modern engine construction is the improvement of environmental performance while ensuring a competitive price of produced engines. This is achieved using state-of-the-art control systems, expensive fuel equipment, and complex exhaust gas neutralization systems. The search for ways to improve the environmental performance of transport engines without significant complication of their structure is a priority area of modern research.

Plasma chemical treatment of gas makes it possible to reduce the level of harmful substances in exhaust gases by 1.5–4 times relative to operation on propane-butane without processing. This paper considers the possibility of using a plasma dynamic stabilization technique and conducting an electric discharge without contact with metal electrodes for the implementation of endothermic reactions whose implementation requires energy from an external source. During test experiments, volt-ampere characteristics of the system with needle electrodes were established, the distance between which was 2–5 mm at different feed pressures of propane-butane gas mixture (75 % propane and 25 % butane). At the outlet of the plasma-chemical reactor, a hydrogen-containing gas mixture is obtained, which is subsequently supplied to the combustion chamber through the regular gas fuel system of the engine. Next, when such a gas mixture burns in the combustion chamber, hydrogen acts as a catalyst for chemical reactions, which reduces the thickness of the flame extinguishing front, increases the speed and completeness of combustion of the gas mixture. Based on the results of comparative motor studies, it was found that plasma-chemical treatment of propane-butane has almost no influence on the effective efficiency of the engine and specific fuel consumption. It should also be noted that the use of plasma-chemical reactors on board a vehicle allows them to be integrated into regular gas fuel engine systems with minimal changes in their structure, which has almost no effect on the mass-size indicators and maintenance conditions of the gas fuel system

Keywords: gas mixture, needle electrodes, propane-butane, plasma-chemical treatment, exhaust gases, environmental indicators

UDC 621.43
DOI: 10.15587/1729-4061.2022.259477

REVEALING THE EFFECT OF PLASMA-CHEMICAL TREATMENT OF PROPANE-BUTANE FUEL ON THE ENVIRONMENTAL CHARACTERISTICS OF THE INTERNAL COMBUSTION ENGINE

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Received date 21.04.2022
Accepted date 06.06.2022
Published date 29.06.2022

***How to Cite:** Avramenko, A., Vnukova, N., Kozlovskyi, O., Zipunnikov, M., Hradovych, N., Darmofal, E., Khaneichuk, K. (2022). Revealing the effect of plasma-chemical treatment of propane-butane fuel on the environmental characteristics of the internal combustion engine. Eastern-European Journal of Enterprise Technologies, 3 (10 (117)), 14–20. doi: https://doi.org/10.15587/1729-4061.2022.259477*

1. Introduction

The use of innovative technologies for processing traditional and alternative hydrogen-based fuels makes it possible to increase the completeness of their combustion and improve the environmental performance of the engine during its operation [1, 2]. Among the modern methods of electrophysical effect on fuel, the most effective are physicochemical and plasma-chemical techniques of its activation [3, 4]. The effects of the use of plasma-chemical fuel processing technologies on vehicles are based on the implementation of the process of partial plasma fuel reforming [5, 6] followed by the enrichment of fresh charge with hydrogen and its radicals, which are obtained in the process of electrophysical processing.

When conducting an electrical discharge without contact, oscillatory-excited molecules are rather slowly deactivated in collisions and, at the same time, quickly enter chemical reactions. In moderate-pressure discharges at electron temperatures of 1–3 eV, most of the discharge power is spent on exciting the oscillatory levels of molecules. This effect makes it possible to direct most of the energy contribution to the desired chemical transformations, leaving the gas as a whole cold (the inverse reactions are slowed down). When carrying out a plasma-chemical reaction, the process occurs at low average mass temperatures, due to the activity of components with disturbed electron shells, which ensures the desired result. In this case, the total energy consumption for the plasma-chemical reaction may be several times less than in thermal or catalytic processes. The technique of dynamic stabilization of plasma and conducting an electrical discharge without contact opens up new possibilities characterized by the durability in a wide range of operating pressure and the ability to work in aggressive environments.

2. Literature review and problem statement

Work [7] emphasizes that the results of combustion processes in terms of their material and energy balances in relation to the performance of usable work, as well as the creation of pollutants, to a large extent depends on the molecular nature of the appropriate type of fuel. The development of effective low-emission combustion processes in accordance with air and climate quality targets involves a more thorough study of the molecular properties and reactions of conventional, bio- and synthetic fuels. The above results of studies indicate that the use of low-temperature plasma of the gas discharge can significantly reduce the characteristic time of mixture ignition [8]. It is shown that the self-ignition temperature of the mixture, previously processed in the discharge, was 1200–1700 K, while without discharge – 1400–2000 K. That intensifies the ignition process, which makes it possible to increase the completeness of combustion of fuel and reduce the level of toxicity of spent gases from the internal combustion engine (ICE). However, there remained unresolved issues related to the impact of plasma-chemical treatment of propane-butane on the effective efficiency of the engine and specific fuel consumption while solving issues related to climate-occurring emissions into the air. The kinetics and transportation of CO_2 microwave plasma by modeling the results of a one-dimensional radial liquid model and experiments [9] are investigated. The model is used as an addition to experiments to assess the main chemical reaction under the diffuse and compressed plasma modes.

Work [10] shows that the thermodynamic unevenness of plasma-chemical processes, which are characterized by the oscillatory-excited electronic state of reagents, makes it possible to increase the energy efficiency of endothermic reactions. The reason for the high efficiency [11] of non-equilibrium processes is selectivity, that is, the localization of discharge energy only on the main channel of the chemical reaction. Despite many difficulties in modeling the interaction of plasma-liquid, in recent years significant progress has been made in resolving the issue of linking the kinetics of gas-phase plasma with the liquid [12]. There are direct discharges of the liquid phase and the necessary studies of discharge ignition and rare phase ionization processes for more accurate modeling of processes. The focus is on fuel consumption [13] and indirectly considered issues of increasing the efficiency of the ICE and issues related to the prevention of climate change. The parameters affecting the ICE efficiency and specific fuel consumption are not considered. The use of a stochastic approach to determining specific parameters [14] for the efficiency of plasma-chemical treatment of propane-butane mixture is fundamentally impossible. The results of studies [15] suggest that it is expedient to build a model that describes the kinetics of plasma-chemical reactions and to compare the results of modeling with experimental data.

3. The aim and objectives of the study

The aim of this study is to identify the impact of conversion of carbon hydrogen-containing gas mixtures on the environmental characteristics of ICE to manage climate and prevent climate change.

To accomplish the aim, the following tasks have been set:

– to analyze carbon hydrogen-containing gas mixtures at the inlet to the plasma-chemical reactor using the method of gas chromatography;

– to conduct tests of ICE with the use of basic fuel and a propane-butane mixture, depending on the mode parameters of operation.

4. The study materials and methods

We have practically tested the developed technology in the following hardware design. The structure of the unit of discharge electrodes was chosen on the basis of the need for uniform distribution of electrical potential in the zone of plasma chemical reaction. Power was supplied out from a high-voltage high-frequency unit with falling volt-ampere characteristics. To start the process on the electrodes of the capacitive divider, the voltage was maintained at the level of 30 kV. After the ignition and stabilization of the discharge, the voltage on the electrodes decreased to the level of 3–7 kV with a current of 1.7 mA. The current frequency was determined on the basis of the resonance characteristics of the system; its value was at least 30 kHz.

The object of bench tests to determine working indicators in accordance with GOST 14846-81 is the MeMZ-307.1 engine (Ukraine) (4H 7.5/7.35) with the electronic control unit (ECU) "MIKAS-7.6" (Ukraine). The bench includes an engine with a loading device and measuring instruments for its operation indicators under conditions of controlled mode change. The motor research bench includes a DC balancing dynamometer, the type of DS 926-4/V (Ukraine) with a built-in speed sensor and a weight device for measuring torque, a motor generator, a thyristor excitation device, and a control panel.

The MeMZ-307.1 engine is gasoline, four-stroke with an in-line vertical arrangement of cylinders and liquid cooling. The main technical characteristics of the engine are given in Table 1 [12].

The engine model as part of the motor bench is equipped with a binary power supply system, which allows the use of both liquid and gas fuel with distributed injection. The engine has a water-cooling system and an exhaust gas (EG) discharge system, with equipment for determining the main components that make up them.

The scheme of the fuel supply system with a plasma-chemical reactor is shown in Fig. 1.

Table 1

Basic parameters of the engine MeMZ-307.1

Engine parameter	Parameter value
Number of cylinders	4
Cylinder diameter, mm	75
Piston stroke, mm	73.5
Cylinder capacity, l	1.3
Degree of compression	9.8
Rated power at 5,200–5,500 min^{-1}, kW (hp)	47 (64)
Maximum torque at 3,000–3,500 min^{-1}, N·m (kgf·m)	102 (10.4)
Idle speed, min^{-1}	870±70
Engine weight, kg	95

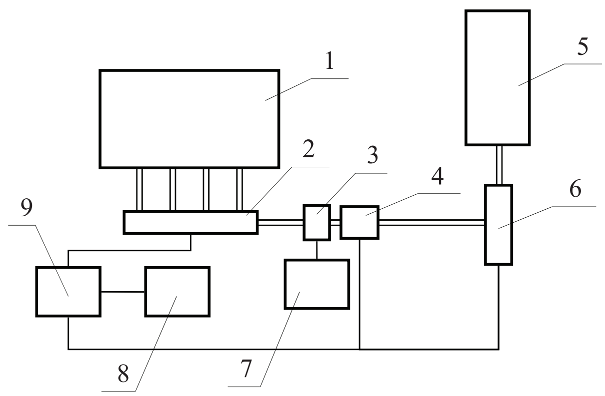

Fig. 1. Scheme of fuel supply system with plasma-chemical reactor: 1 – engine; 2 – fuel ramp; 3 – plasma-chemical reactor; 4 – pressure and fuel temperature sensor; 5 – cylinder; 6 – gearbox; 7–9 – control unit

Control over the power system, as well as the ignition system, is executed by an electronic unit that monitors a workflow in the engine cylinders by the signals of the corresponding sensors.

The electronic control unit (ECU) during the operation of the engine evaluates the results of calculations for different modes of operation, enters them into the memory card, and issues control signals to maintain the necessary characteristics of the engine. The ECU "self-learning" or adaptation is a continuous process while the corresponding settings are stored in the RAM of the electronic unit. Special software is used on the bench to determine ICE parameters that enter the K-line of the adapter in real time. Next, the results of the diagnostics are transmitted to the computer system for registration and processing of experimental data.

Communication between the electronic control unit of the engine and a personal computer is implemented using the ISO-9141 K-line protocol. To display and edit ICE parameters, specialized DwScan software is used, which enables reading the parameters of ICE MeMZ-307.1 (Ukraine) with ECU; it has a version of the software "MIKAS-7.6" (Ukraine).

5. Results of studying the performance of an electric-plasma-chemical module as part of the gas fuel system in an internal combustion engine

5. 1. Analysis of carbon hydrogen-containing gas mixtures at the inlet to the plasma-chemical reactor by a gas chromatography method

Analysis of the component composition of the gas mixture at the inlet to the plasma-chemical reactor makes it possible to determine the optimal conditions for the conversion of hydrogen-containing gas mixtures. To this end, methods of gas chromatography were used to analyze carbon hydrogen-containing gas mixtures. There is a possibility of using the described technology for the implementation of endothermic reactions, the implementation of which requires energy consumption from an external source. These types of reactions include the conversion of various carbon hydrogen-containing compounds and water, as a result of which energy-active hydrogen radicals are formed.

Owing to the devised procedure for maintaining the dynamically stabilized non-equilibrium properties of plasma, the reaction at a pressure of 0.1–4.0 MPa is ensured. With plasma-chemical conversion methods, energy consumption for the process is reduced to covering the enthalpy of the reaction with an energy utilization rate of about 80 % [11]. At the same time, the cost of highly organized and, as a result, the most expensive electricity is 25–30 % while the rest of the energy contribution is provided by the chemical energy of carbon contained in the starting materials.

Using an example of an electric discharge with positive polarity at the tip of the electrode (Fig. 2), the characteristic volt-ampere characteristics (VAC) of the discharge at different gas pressures in the discharge chamber are considered. These data are summarized on the basis of research results reported in [16–18].

Dotted lines indicate the areas of VAC that correspond to the non-stationary stage of discharge current, which is characterized by the presence of streamers, non-closing the electronic space. Solid lines indicate the areas of VAC that correspond to the nonstationary stage of discharge with streamers that lock the discharge space [10].

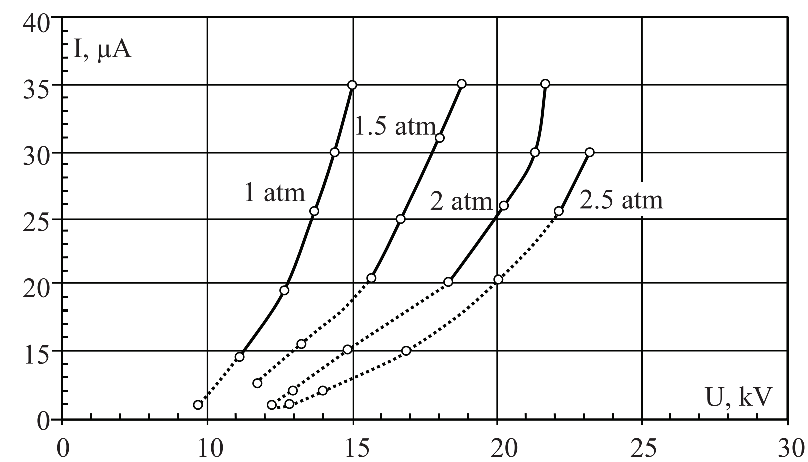

Fig. 2. Volt-ampere characteristics of discharge in the electrode system needle-plane with positive potential on the tip at different air pressures from 0.1 to 0.25 MPa, *d*=10 mm

Dotted lines highlight the areas of VAC with streamers, non-closing the discharge space; solid lines mark the areas of VAC corresponding to the nonstationary stage of discharge current with streamers that close the discharge gap.

Analysis of data in Fig. 2 reveals that the area of existence of the discharge with streamers that close the discharge gap is shifted to the area of higher voltages applied to the discharge gap, with an increase in the pressure of the gas in the discharge chamber. At the same time, at different gas pressures, the circuit of the discharge gap is locked by a streamer at close values of the average reduced voltage of the electric field

$$(E/P)_{av}=U/(d\cdot P),$$

where d is the interelectrode distance; P – gas pressure, U – voltage at a discharge gap; E is the voltage of the electric field.

The results of visualization and photo registration of the discharge combustion process indicate that as the pressure of the gas increases, the dimensions of the discharge radiation region are significantly reduced, the radiation is concentrated near the sharp electrode and the angle of opening of the cone of the radiation zone changes significantly. With increasing gas pressure, the discharge enters a streamer-diffusion combustion mode. Starting approximately from the middle of the discharge gap and to the surface of the anode, geometry changes – a reduction in the longitudinal direction and its expansion in the zone of intersection of the reaction volume. At the same time, the radiation zone, which has a diffusion nature, increases the contribution of the ion component to the full discharge current. Oscillography of the shape of current pulses showed that their duration decreases as the pressure increases.

An important characteristic of the discharge, which is directly related to the intensity of the electric field, is the speed of movement of the streamer in a discharge gap. The average rate of streamer propagation was defined as the ratio of the length of the streamer to the time of its distribution in a discharge gap. The distribution time was determined from the oscillograms of current pulses. The length of the streamers locking the discharge gap was equal to the length of the discharge gap, and the length of the unlocking streamers was determined by analyzing the photo registration of the gas discharge.

It was established that in the area of E/P values that correspond to the mode of streamers, non-closing the discharge gap, the streamer speed slowly increases with an increase in E/P. In this case, the average rate of streamer propagation is ~$3\cdot10^6$ cm/s and does not depend on the amount of gas pressure. In the area of E/P values corresponding to the locking mode of the streamers, the rate of the streamer also depends little on the pressure. The value of streamer speed increases with the growth of E/P much larger than in the case of streamers, non-locking the discharge gap, and reaches ~$1.5–2.0\cdot10^7$ cm/s.

It was established that the high-frequency barrier discharge is stable in a wide pressure range of 0.05–0.4 MPa. The difference in the potentials of electric current on the terminals of the reactor is 20–30 kV and depends on the surface conductivity of the dielectric barriers and the geometric dimensions of the reaction gas volume. The nature of plasma formation depends on the surface conductivity of the dielectric. To create a dielectric barrier between electrodes, it is advisable to use ceramics based on barium titanium. The lower voltage value ensures the formation of plasma in the reaction zone, filled with many microcharges formed by conductive electrical discharge channels. At a higher voltage, there is a uniform distribution of plasma throughout the gas gap.

The chromatogram of the original gas mixture, which was used in our research, is shown in Fig. 3; the volt-ampere characteristics of the discharge in the propane-butane gas mixture for the pressure range of 0.1–0.15 MPa are depicted in Fig. 4. For our research, the gas chromatograph LHM-8MD was used. The propane-butane gas mixture considered in this work was bought in the retail network of gas stations and is typical for gas refueling of automobile engines.

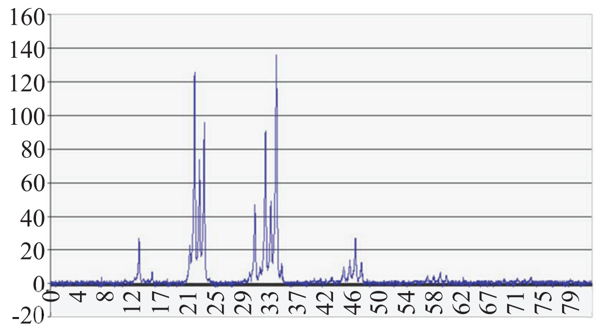

Fig. 3. Mass spectrum of the propane-butane gas mixture

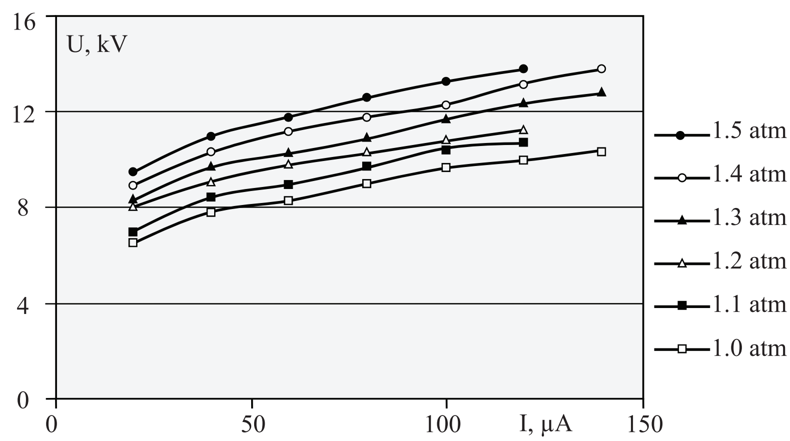

Fig. 4. Volt-ampere discharge characteristics in the propane-butane gas mixture (75 % propane and 25 % butane) for a pressure range of 0.1–0.15 MPa

During test experiments, volt-ampere characteristics of the system with needle electrodes were obtained, the distance between which was 2–5 mm at different feed pressures of the propane-butane gas mixture (75 % propane and 25 % butane). The results of the research were used to develop the structure and select the regime characteristics for the plasma-chemical reactor (Fig. 4).

5. 2. Results of tests using fuel and a propane-butane mixture depending on the change in operating parameters

During the operation of ICE, it is possible to control and change the parameters of its operation, such as the duration of fuel injection, the ignition angle Θ, idling revolutions, etc. During our comparative motor studies, we changed the angle of ignition advance under an interactive mode, which was automatically installed by ECU. As a result of processing the data from the iteration series, the optimal ignition advance angle for a specific fuel composition and the mode of ICE operation were determined, which ensured its effective operation under a detonation-free mode in a wide range of loads.

It is known that the introduction of additional electricity consumers on board the vehicle leads to an increase in fuel consumption and a deterioration in the environmental performance of ICE. Thus, turning on the headlights of long-range light (which consume an average of 100–120 watts) leads to an increase in fuel consumption by 7–12 %; for LED lamps, these figures are significantly lower [13]. Therefore, when installing additional equipment, it is necessary to minimize the level of energy consumption. In this regard, the power required for the operation of the plasmatron was limited to no more than 50 watts, which does not create an overload for a regular onboard electric generator. The characteristics of the designed electric-plasma-chemical module are given in Table 2.

Table 2

Technical characteristics of the electric-plasma-chemical module

No.	Parameter	Unit of measurement	Value
1	Power	W	50
2	Supply voltage	V	12
3	Voltage between the electrodes	kV	30
4	Overall dimensions of the control system	mm	200×180×100
5	Overall dimensions of the electric-plasma-chemical module	mm	100×50×50

The arrangement of the electric-plasma-chemical module as part of the MeMz gas fuel system is shown in Fig. 5. The scheme of the system corresponds to that depicted in Fig. 1.

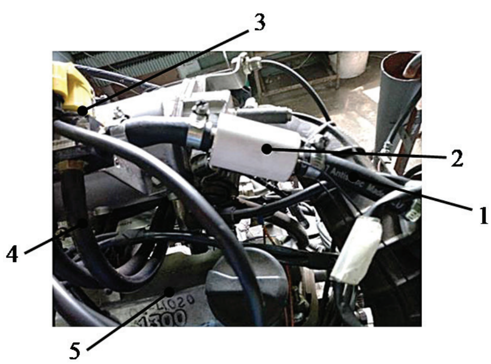

Fig. 5. Layout of an electric-plasma-chemical module in the fuel supply system: 1 — the main line of propane-butane supply; 2 — plasma-chemical reactor; 3 — unit of gas nozzles; 4 — the main fuel supply line from the gas nozzle to the engine; 5 — MeMz engine

A comparison of the results of ICE tests with the use of basic fuel and a propane-butane mixture, depending on the mode parameters of its operation, is shown in Fig. 6.

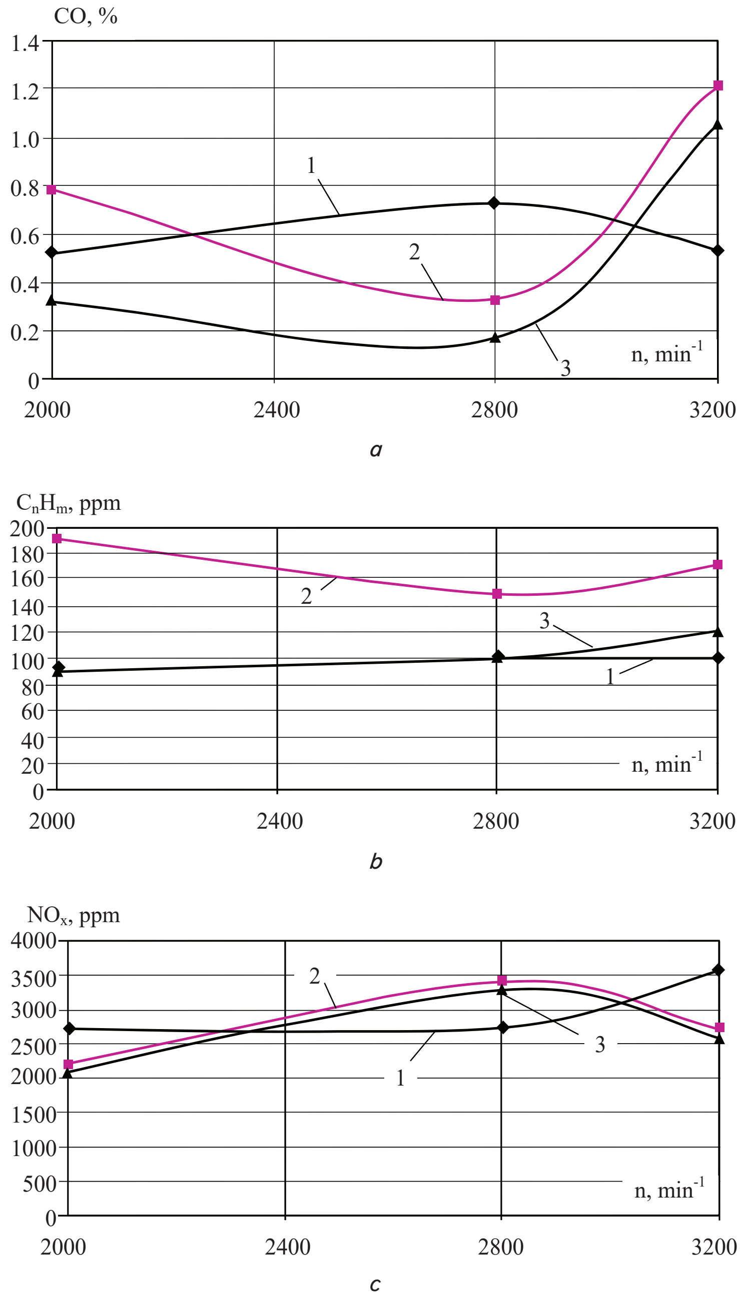

Fig. 6. Change in the level of toxicity of exhaust gases from the MeMZ-307 engine when working on high-speed characteristics: *a* — CO, %; *b* — C_nH_m, ppm; *c* — NO_X, ppm; 1 — gasoline A-95; 2 — propane-butane; 3 — propane-butane with plasma-chemical treatment

In the course of our research, it was established that under the characteristic operating modes there is a decrease in the level of carbon monoxide (CO) emissions during the operation of the engine on propane-butane, and an increase in emissions at maximum torque mode (relative to the operation of the engine on gasoline). The plasma-chemical treatment of gas makes it possible to reduce by 1.5–4 times the level of CO in exhaust gases relative to the operation on propane-butane without processing. The level of emissions of unburned hydrocarbons (C_nH_m) when working on propane-butane is higher than when working on gasoline, and the plasma-chemical processing of gas makes it possible to improve this indicator, almost to the level of emissions when the engine is running on gasoline.

6. Discussion of results of studying the use of high-frequency plasma in the fuel system of a car engine

Our results (Fig. 6) of comparative motor studies on the assessment of the effect of the plasma-chemical treatment of propane-butane mixture on the technical, economic, and environmental indicators of the engine show that the use of on-board fuel preparation systems makes it possible to improve the environmental performance of the engine by improving the efficiency of the combustion process of the fuel-air mixture.

A feature of the proposed method is the use of high-frequency plasma directly in the fuel system of the car engine (Fig. 5). This makes it possible to reduce energy consumption for the functioning of the system and, taking into consideration the short time of gas staying in an ionized and energetically excited state, to bring the fuel processing zone as close as possible to the consumer – the piston engine.

The peculiarities of the high-frequency plasma of the barrier discharge depend on the factors due to the final rate of energy transfer from the electric field to molecules, atoms, and ions of the gas medium and the associated formation of various plasma states. If the process of discharge propagation is suspended at the stage of evolution, and then the process of energy supply is restored, then the average characteristics of the plasma will be fundamentally different, compared with the parameters under a stationary mode. This effect represents the main difference in the proposed technology.

The experiments show that the generation of discharge should be carried out in accordance with the modes that ensure the deionization of the reaction space in the inter-discharge period. The desired effect is achieved by selecting the time and amplitude parameters of pulses to excite the electrical discharge with the obligatory re-pumping and introduction of reactive current limiters. The devised technique of the dynamic stabilization of plasma and conducting an electrical discharge without contact opens up new opportunities characterized by the durability in a wide range of operating pressure and the ability to work in aggressive environments.

According to the results of our comparative motor studies, it was found that the plasma-chemical treatment of propane-butane has almost no effect on the effective efficiency of the engine and specific fuel consumption. However, at the same time, new highly active fuel components that appear in the process of the plasma-chemical processing of gas contribute to an increase in the completeness of combustion of fuel by reducing the ignition temperature, which contributes to improving the environmental performance of the engine.

NO_X nitrogen oxide emissions (Fig. 6) increase slightly under partial load modes (relative to gasoline performance) and decrease by 22 % under the mode of maximum torque for propane-butane. Plasma-chemical treatment of propane-butane can reduce NO_X emissions by an additional 7 %, compared to the operation of the propane-butane engine without processing.

Given the restrictions on energy consumption on board the car, a plasma-chemical reactor with a power consumption level of up to 50 W per hour is considered in this work.

For an in-depth study of the processes of formation of toxic and carcinogenic compounds, in further investigations, it is desirable to additionally select gas samples from the area of the flame extinguishing front – near the walls of the combustion chamber. This information would refine the boundary conditions for numerical modeling of combustion processes.

To advance the method considered in this work, to improve the environmental performance of the engine, further research should be supplemented with numerical modeling of the processes of formation of high-frequency plasma and combustion of activated gas in the engine cylinder.

7. Conclusions

1. Analysis of the component composition of the gas mixture at the inlet to the plasma-chemical reactor makes it possible to determine the optimal conditions for the conversion of hydrogen-containing gas mixtures. The characteristic volt-ampere characteristics of discharge at different gas pressures in the discharge chamber have been considered. In the area of *E/P* values that correspond to the mode of non-closing gap discharge streamers, the streamer speed slowly increases with an increase in *E/P*. In this case, the average rate of streamer propagation is ~$3\cdot10^6$ cm/s and does not depend on the amount of gas pressure.

2. The plasma-chemical gas treatment makes it possible to reduce by 1.5–4 times the level of CO in exhaust gases relative to the operation on propane-butane without processing. The level of emissions of unburned hydrocarbons (C_nH_m) when working on propane-butane is higher than when working on gasoline; the plasma-chemical treatment of gas makes it possible to improve this indicator, almost to the level of emissions when the engine is running on gasoline.

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