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DETERMINING THE INFLUENCE OF SYNTHESIS GAS ADDITIVES ON THE ENVIRONMENTAL PERFORMANCE OF INTERNAL COMBUSTION ENGINE

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The object of research is the environmental parameters of a reciprocating engine when using a synthesis gas additive to the main fuel. The research is aimed at solving the problem of reducing the concentration of harmful components in the exhaust gases of an internal combustion engine by adding synthesis gas to the main fuel.

Experimentally, the dependences of the effect of the addition of synthesis gas to ethanol on the change in the environmental performance of a piston engine with spark ignition were obtained.

The positive effect of the addition of synthesis gas obtained by thermochemical conversion to ethanol in an amount of up to 5 % by weight on the environmental performance of a spark-ignition piston engine was established. Provided that the engine achieves the same effective power, the use of a synthesis gas additive to the main fuel made it possible to reduce the concentration of CO by 61.5 % and CH by 51.3 % in the exhaust gases.

The addition of synthesis gas contributed to the formation of radicals that activate oxidation chain reactions, and also made it possible to increase the normal combustion rate of the fuel-air mixture by 6.25 %. This ensures normal engine operation on a leaner fuel-air mixture (α=1.21) without deterioration of environmental, energy and economic performance.

The simultaneous reduction of the concentration of harmful components in the exhaust gases and engine efficiency can be achieved by using fuels with a wide concentration limit of ignition and high combustion rate in a lean mixture.

The experimental data obtained can be used in the design or modernization of transport and stationary power plants with internal combustion engines as an approach to meet ever-increasing environmental standards

Keywords: synthesis gas, fuel ethanol, thermochemical utilization, exhaust gases, air ratio

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1. Introduction

The composition of exhaust gases (EG) from internal combustion engines (ICE) almost entirely (up to 99 %) consists of products of complete combustion, namely carbon dioxide and water vapor, as well as residual oxygen and nitrogen from the air. However, the environmental level of perfection of the internal combustion engine is determined precisely by this small proportion of harmful components, the reduction of which is an urgent and planetary problem. It is also worth noting that the operation of internal combustion engines affects not only environmental pollution with harmful toxic components but also global warming on the planet (greenhouse gas emissions – CO_2).

The exhaust gas composition of an internal combustion engine is a certain reflection of the effective organization of the work cycle. Changes in the conditions of the combustion process of the fuel-air mixture in the working cylinder of the engine, for example, the injection advance angle (ignition timing for gasoline and gas internal combustion engines), the quality of injection and mixture formation, and the excess air coefficient are reflected in the composition of the exhaust gas. Exhaust gas analysis makes it possible to quickly diagnose the engine without disassembling it.

Thus, rational organization of the work process is an effective way to reduce the toxicity of internal combustion engines. In addition, along with improving the work process, an effective method for reducing harmful substances from exhaust gases, as well as decarbonization, is the use of alternative fuels. At the same time, the expansion of the use of alternative fuels in internal combustion engines is also an important part of energy strategy in the developed countries of the world (green policy of carbon-free energy), associated with reducing the use of hydrocarbon fuels. As alternative fuels for internal combustion engines, fuels obtained from vegetable oils, alcohols (methyl and ethyl), synthesis gas of various compositions (hydrogen-containing gas) and pure hydrogen can be used.

Particularly promising is synthesis gas, the advantage of which is a wide raw material base for its production (any type of raw material) [1]. The main components of synthesis gas are hydrogen (H_2) and carbon monoxide (CO); however, depending on the feedstock and production methods, the composition may also include methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6), and other components. Due to the presence of hydrogen in the synthesis gas, the environmental performance of the engine is significantly improved. A significant disadvantage of using synthesis gas as an independent fuel in internal combustion engines is its lower specific heat of combustion compared to traditional fuels (25...30 MJ/kg). This leads to a decrease in engine power. One of the possible ways to use synthesis gas in internal combustion engines is to use it as an additive to the basic fuel [2]. This technique could solve the problem of a significant reduction in engine power. In turn, the influence of synthesis gas additives to the main fuel on the environmental parameters of the engine remains poorly understood. This is due to the fact that the composition of the exhaust gas is influenced by many different factors (type of basic fuel, composition of synthesis gas, amount of additive, etc.). Therefore, research into this area is relevant today.

2. Literature review and problem statement

The application of synthesis gas depends on many factors, making careful control of parameters for modern engines important.

Work [3] discusses the process of producing synthesis gas by gasification using air as an oxidizer. The influence of such process parameters as the equivalence coefficient, surface velocity, temperature, pressure, biomass particle size, and gasifier design on the quality of the resulting gas is considered. Features of the use of synthesis gas in spark-ignition and compression-ignition engines are discussed. Increased H_2 content was found to reduce CO and CH emissions but increase NO_X emissions. However, the work lacks information about the impact of the use of synthesis gas additives to the main fuel on the environmental parameters of internal combustion engines.

Work [4] reports experimental studies of the operating parameters of internal combustion engines using synthesis gas obtained by gasification of biomass as fuel. 3 types of fuel were tested as biomass, such as wood chips, charcoal, and gasohol 91. It was found that wood chips can produce a higher quality synthesis gas composition than charcoal, but the engine power is less than when using gasohol 91. However, the work lacks recommendations and data on the selection of rational values for the excess air coefficient and synthesis gas composition.

Paper [5] describes experimental studies on a single-cylinder diesel engine with constant speed and direct injection, running on synthesis gas and diesel fuel. Engine operating parameters were studied at four different ratios of H_2 and CO in the synthesis gas. At partial loads (i.e., 20 % and 40 %), the use of synthesis gas resulted in deterioration of performance and increased emissions. At higher loads, synthesis gas showed good competitiveness compared to diesel mode. At all test loads, NO_x emissions were highest for 100 % H_2 syngas compared to other fuels, with a maximum value of 240 ppm found at 100 % load. However, when replacing H_2 with CO fractions of 25 %, 50 %, and 100 %, emissions dropped to 175 ppm, 127 ppm, and 114 ppm, respectively. In addition, higher levels of CO and HC emissions were recorded for syngas with CO fractions of 25 %, 50 %, and 100 %. However, the work lacks data on the possible use of synthesis gas additives to the main fuel and the technique for producing synthesis gas.

Work [6] reports a study into the influence of various synthesis gas compositions on the characteristics and exhaust emissions of a compression ignition engine with injection of decan as a pilot fuel. NO_x and soot emissions generally decreased with increasing syngas/decan ratio, while CO and total CH emissions increased. In addition, relationships between engine performance/emissions and the properties of various synthesis gas compositions were established. However, there is no data on the possibility of using synthesis gas additives and its production technique.

Paper [7] studied the combustion characteristics of synthesis gas in a compression ignition engine with a biodiesel mixture as ignition fuel. The simulated high-hydrogen synthesis gas was assumed to be a product of biomass gasification with the introduction of carbon dioxide adsorption. Combustion characteristics showed that the maximum degree of replacement of pilot fuel with simulated synthesis gas reaches 47 %. The work examines effective and indicator performance indicators but there is no analysis of the influence of synthesis gas on environmental performance indicators.

Work [8] describes in sufficient detail the process of combustion of diesel fuel with syngas micro additives but there is no analysis of the influence of additives on the environmental performance of the engine.

In [9], the operation of an engine running on synthesis gas obtained by converting methanol was studied. Experimental indicator diagrams are presented, as well as combustion heat release characteristics. However, there is no analysis of the influence of the composition of the synthesis gas and the amount of additive on engine performance.

As a result of our review of literature, it was found that most studies focus specifically on studying the influence of synthesis gas on the operating process of internal combustion engines. However, experimental and theoretical studies in the field of the possible influence of the use of synthesis gas additives to the main fuel on the environmental parameters of internal combustion engines have not been fully disclosed and studied. This especially concerns the issue of the influence of the composition and amount of synthesis gas addition to the basic fuel on the change in harmful emissions from the exhaust gases of internal combustion engines.

3. The aim and objectives of the study

The purpose of our work is to determine the possibility of improving the environmental performance of an internal combustion engine with spark ignition by using synthesis gas additives to ethanol. Experimental studies will allow us to evaluate the effectiveness of using hydrogen-containing gas additives to the main fuel as a method for reducing harmful substances in exhaust gases from ICE.

To achieve the goal of studying environmental indicators, it is necessary to solve the following basic tasks:

– to establish reliable characteristics of changes in the environmental performance of a spark-ignition piston engine when using base fuel and with synthesis gas additives;

– to establish the influence of the addition of synthesis gas on changes in the environmental performance of a spark-ignition engine.

4. The study materials and methods

The object of our experimental research is the environmental performance of a piston engine when using a synthesis gas additive to the base fuel. The subject of the study is the characteristics of changes in environmental indicators depending on the addition of synthesis gas during the combustion of the air-fuel mixture in the working cylinder of an internal combustion engine.

The working hypothesis of the study assumes that rational addition of synthesis gas to the main fuel could significantly improve the environmental performance of spark-ignition internal combustion engines without deteriorating the energy and economic performance.

When conducting experimental studies, it was assumed that the composition, temperature, and pressure of the synthesis gas at the inlet to the engine under different operating conditions are constant.

To implement the purpose of the research and the assigned tasks, an experimental bench (Fig. 1) of a power plant with a thermochemical conversion reactor based on an engine with external mixture formation 1Ch 6.8/5.4 is used [10, 11]. The four-stroke spark-ignition gasoline engine 1H 6.8/5.4 is loaded with a standard electric current generator. It can operate on gasoline, ethanol, gaseous fuel (propane-butane, synthesis gas), as well as a mixture of liquid and gaseous fuels.

Fig. 1. General view of a power plant with a thermochemical conversion reactor

The engine exhaust system was converted by installing a thermochemical conversion reactor (Fig. 2) in order to recover exhaust gas heat. In this case, the reactor performs the function of a heat exchanger and a noise suppressor at the same time.

Fig. 2. Four-stroke engine 1Ch 6.8/5.4 with thermochemical conversion reactor

Air consumption on the engine was determined using a gas meter RG-40 (relative error range ±1.0 %), and synthesis gas – Gallus 2000 (relative error range ±0.5 %). Liquid fuel consumption was determined by weight (measurement error ±1 g). Temperature measurements were carried out using a digital device OVEN UKT38-Shch4.TP (accuracy class – 0.25) and chromel-copel *L* (TCHK), as well as chromel-alumel (TCA) thermocouples. The engine was indicated using a specialized continuous dynamic pressure sensor Kistler 7613C. The crankshaft rotation speed was controlled using a digital frequency meter Ch4-34A (absolute error ±1 s^{-1}). The composition of the synthesis gas (CO=34 %, H_2=43 %, CH_4=23 % by volume) was determined using a NeoCHROM Class B chromatograph. The specific lower calorific value of the resulting synthesis gas is 28.79 MJ/kg, density – 0.629 kg/m^3, the normal speed of flame propagation of a stoichiometric mixture of air and synthesis gas is 0.96 m/s, the amount of air required for combustion is 8.27 kg/kg. The specific energy capacity of the charge for the resulting synthesis gas is 3425 kJ/m^3 for external mixing and 4617 kJ/m^3 for internal mixing. To measure the amounts of harmful components in the exhaust gas composition, a gas analyzer was used with a measurement range of the volume fraction of CO – 0...10 %, the volume fraction of hydrocarbons in terms of hexane CH – 0...5000 ppm. Atmospheric pressure was determined using an aneroid barometer BAMM-1 (measurement range 80...105 kPa, relative error ±0.5 %), and relative humidity – with a PBU-1 psychrometer (relative error ±5 %).

5. Results of experimental studies of environmental performance of the engine when using synthesis gas additives

5. 1. Studying the characteristics of changes in environmental performance of a spark-ignition engine

The main harmful components of positive ignition engines are carbon monoxide CO and hydrocarbons CH. The formation of CO and CH is primarily associated with incomplete combustion of the air-fuel mixture at rich mixtures (air excess coefficient $\alpha<1$). Based on this, when conducting experimental studies, to ensure a minimum level of harmful emissions and the required engine power, the excess air coefficient varied within the range α=1.02...1.21. The ignition timing was $\Theta=20°$ p.k.v., and the crankshaft rotation speed was n=3000 min^{-1}. Fig. 3 shows the results of experimental studies of changes in emissions of harmful substances from exhaust gases when the engine is running on ethanol and with synthesis gas additives up to 5 % by weight.

Thus, when operating an engine with forced ignition on pure ethanol, depending on α, the concentration of hydrocarbons varied within the range CH=375...490 mln^{-1}, and the concentration of carbon monoxide CO=0.21...0.28 %.

The addition of synthesis gas to ethanol made it possible to significantly reduce the concentration of CH and CO in the engine exhaust gas. In accordance with our experimental data (Fig. 3), the concentration of these components in the exhaust gas was CH=190...215 mln^{-1} and CO=0.1...0.15 %. It is worth noting that a decrease in harmful exhaust gas components is observed over the entire engine load range (Fig. 4).

Thus, when the same effective engine power is achieved when running on ethanol and with synthesis gas additives, the percentage reduction in harmful components in the exhaust gas is: CO – up to 61.5 %, CH – up to 51.3 %.

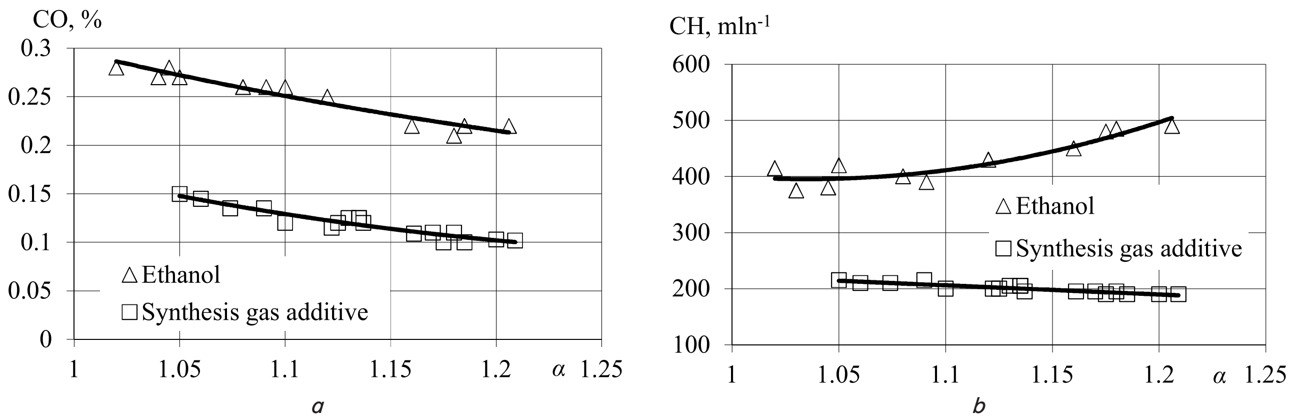

Fig. 3. Concentration of harmful substances in the exhaust gases of an engine with forced ignition 1Ch 6.8/5.4 depending on the excess air ratio: *a* – CO concentration; *b* – CH concentration; Δ – when working on pure ethanol; □ – when operating on ethanol with synthesis gas additives

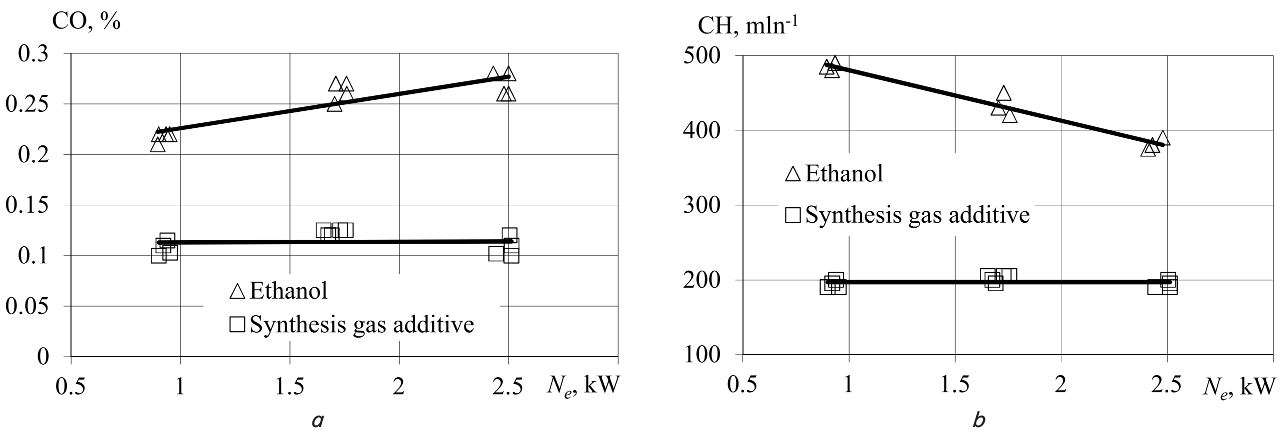

Fig. 4. Concentration of harmful substances in the exhaust gases of an engine with forced ignition 1Ch 6.8/5.4 depending on the effective power: *a* – CO concentration; *b* – CH concentration; Δ – when working on pure ethanol; □ – when operating on ethanol with synthesis gas additives

5. 2. Investigating the influence of synthesis gas additives on changes in the environmental performance of internal combustion engines with spark ignition

The results of experimental studies on the effect of adding synthesis gas to ethanol on the concentration of harmful components in the exhaust gas during 1Ch 6.8/5.4 engine operation are shown in Fig. 5.

Based on the processing of experimental data (Fig. 5), approximating curves of the effect of synthesis gas additives on changes in CH and CO emissions were constructed:

$$CO = 0.0019G_{s-g}^2 - 0.0247G_{s-g} + 0.17682, \quad (1)$$

$$CH = 0.8674G_{s-g}^2 - 12.8G_{s-g} + 230.74, \quad (2)$$

where G_{s-g} – synthesis gas additives by weight, %.

A decrease in the concentration of harmful substances in the exhaust gas is observed over the entire range (1.35...5 % by weight) of synthesis gas additives to ethanol. Thus, the decrease in CO was about 33.3 %, and the decrease in CH was 11.6 %.

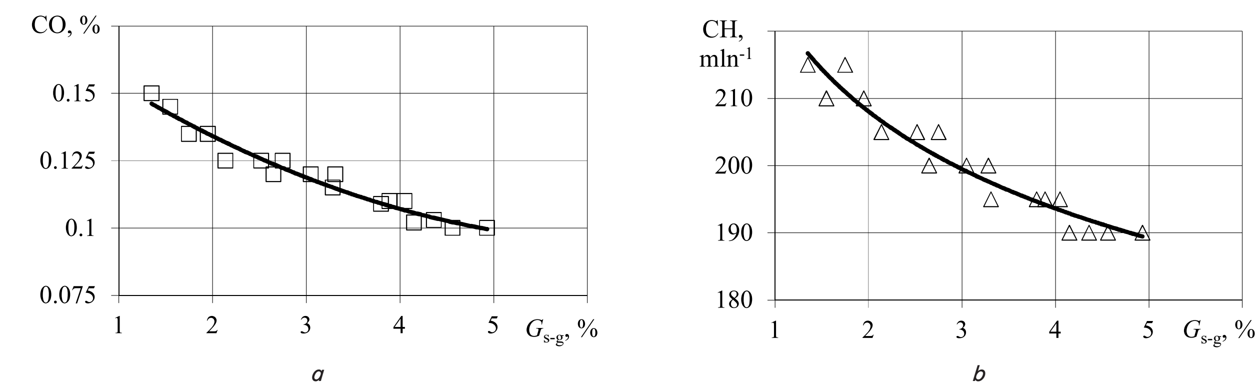

Fig. 5. Concentration of harmful substances in the exhaust gases of the 1Ch 6.8/5.4 engine with forced ignition, depending on the addition of synthesis gas by weight to ethanol: *a* – CO concentration; *b* – CH concentration

The synthesis gas used in the experiment contains a significant amount of hydrogen, which makes it possible to significantly increase the normal combustion rate of the air-fuel mixture (Fig. 6). The change in the normal combustion rate of a stoichiometric air-fuel mixture depending on the addition of synthesis gas to ethanol was obtained based on the known composition of synthesis gas and the dependence for determining the speed of flame propagation in a mixture of complex gas with air. Thus, the addition of synthesis gas makes it possible to increase the normal combustion rate of the air-fuel mixture by 6.25 % (from 0.4 to 0.425 m/s).

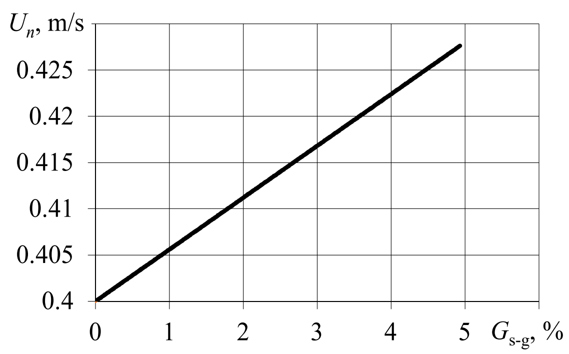

Fig. 6. Change in the normal combustion rate of a stoichiometric air-fuel mixture depending on the addition of synthesis gas to ethanol

As the excess air coefficient increases (depletion of the air-fuel mixture), a decrease in the combustion rate is observed, up to misfire. Additions of synthesis gas within 5 % by weight made it possible to increase the excess air coefficient to α=1.21 without reducing the combustion rate of the air-fuel mixture.

6. Discussion of results of experimental studies on the use of synthesis gas additives on the environmental performance of the engine

Research shows that the chemical composition of the fuel has a significant impact on the toxicity of exhaust gases. The use of alcohol (ethanol) with syngas additives as motor fuel improves the combustion process due to the formation of radicals that activate oxidation chain reactions. At the same time, the nature of the change in the concentration of the main toxic components of exhaust gases obtained as a result of experimental studies is due to reaction-kinetic laws and does not contradict the theory of combustion.

Thus, when operating on pure ethanol, in zones of richer mixtures, increased values of CO concentrations are observed (Fig. 3, *a*), which is explained by the lack of oxygen for complete oxidation of the fuel. At the same time, with an increase in the excess air coefficient, the CO concentration decreases, and the CH concentration, on the contrary, increases (Fig. 3, *b*). The increase in CH concentration with increasing α is explained by a slowdown in the combustion rate and incomplete combustion of the lean air-fuel mixture. Thus, when an engine runs on ethanol (gasoline), neither enriching nor depleting the air-fuel mixture results in a simultaneous reduction in the concentration of both harmful components.

A simultaneous reduction in the concentration of harmful components in the exhaust gas, as well as engine efficiency, can be achieved through the use of fuel with a wide concentration ignition limit and a high combustion rate with a lean mixture.

When using synthesis gas additives to the main fuel, a decrease in the concentration of both harmful components is observed (Fig. 3, 5). This is explained by the fact that hydrogen is largely present in the synthesis gas, which makes it possible to activate oxidation chain reactions and maintain the combustion rate when the air-fuel mixture is lean (Fig. 6).

There are many ways to produce synthesis gas from various types of raw materials, but not all of them can be implemented in power plants with internal combustion engines. For example, obtaining synthesis gas on board a vehicle and replacing base fuel with it is quite a difficult task. Therefore, in contrast to [3, 4], in which synthesis gas is considered as an alternative to base fuel, the results obtained in this work allow us to consider synthesis gas additives as a mechanism for reducing harmful emissions from exhaust gases. At the same time, obtaining synthesis gas in an amount commensurate with a 5 % addition by weight to the main fuel is a fairly simple task that does not require significant costs and significant design changes in the power plant. In the current study, the method for producing synthesis gas is based on the use of thermochemical exhaust heat recovery (Fig. 2). In turn, our results can serve as recommendations regarding the organization of the operating cycle of spark-ignition internal combustion engines running on alcohol fuel.

Our results of experimental studies into the use of synthesis gas additives to improve the environmental performance of a spark ignition engine are limited by the limits of changes in operating parameters. Namely, the coefficient of excess air (α=1.02...1.21), the amount of synthesis gas additive (up to 5 % by weight), the constant composition of the synthesis gas, as well as the engine speed (n=3000 min^{-1}).

A disadvantage of the results is the lack of research into the effect of syngas addition on the formation of other harmful components contained in the processed engine gases, for example, nitrogen oxides and aldehydes. The addition of synthesis gas to other types of liquid and gaseous fuels, for example, gasoline and propane-butane, is also of interest and requires additional experimental research. In the future, it is planned to conduct such studies, as well as experiments on a diesel engine.

7. Conclusions

1. Experimental characteristics of changes in the environmental performance of a piston engine with spark ignition on ethanol and with synthesis gas additives to ethanol up to 5 % by weight were established. A positive effect of the addition of synthesis gas on the environmental performance of the engine has been found, which is manifested in a decrease in CO from 0.21...0.28 % to 0.1...0.15 %, and CH from 375...490 mln^{-1} to 190...215 mln^{-1}.

2. It has been established that the use of a synthesis gas additive of up to 5 % by weight makes it possible to increase the normal combustion rate of the air-fuel mixture by 6.25 %, which in turn allows the use of leaner mixtures (α=1.21) without deteriorating the environmental, energy, and economic indicators of engine operation.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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