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IMPROVING EFFICIENCY INDICATORS AND REDUCING CO_2 EMISSIONS BY USING HYDROGEN AND METHANE ADDITIVES TO GASOLINE IN A SPARK-IGNITION ENGINE

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This study investigates the working process in a 4Ch7.6/6.6 gasoline engine when using hydrogen and methane additives to fuel. The task addressed relates to the lack of a single methodological approach to the comparative quantitative assessment of the impact of various gas additives on combustion parameters, efficiency indicators, and CO_2 emissions. As a result, there is a complication of the justified choice of the optimal component to increase energy efficiency and reduce the carbon footprint of the existing fleet of gasoline engines.

This work advanced semi-empirical relationships for determining the parameters of the Wiebe model when methane is added to gasoline, which are based on scaling through the ratio of laminar flame velocities. Based on the results from mathematical modeling, it was established that when adding 10% hydrogen, the combustion dynamics indicator m decreases by 32.4–38.7% while the combustion duration φ_z is reduced by 26.1–28.2%. It was determined that the specific effective fuel consumption decreases by 13.9–14.3%, the effective efficiency increases by 0.5–1.8%, and the volume fraction of CO_2 decreases by 14.1%. When methane is added to 10%, the dynamics parameter m increases by 3.2–3.9%, and, accordingly, the combustion duration φ_z increases by 2.4–2.6%, while the specific consumption decreases by 2.3–4.8%, the effective efficiency increases by 1.4–3.7%, and a decrease in CO_2 is also observed, which is 11.7%.

A defining feature is the quantitative results of the effect at the same proportion of the additive (10%), according to which hydrogen provides a 1.2-fold greater reduction in CO_2 compared to methane, but at the same time an improvement in fuel efficiency is observed. The results allow for a reasonable choice of the type of additive for a comprehensive increase in efficiency and environmental friendliness or moderate decarbonization at minimal engine modernization

Keywords: hydrogen addition, methane addition, Wiebe model, combustion parameters, decarbonization of transport

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1. Introduction

The transport sector occupies one of the leading positions in the global energy balance; it acts both as a global energy consumer and one of the main sources of anthropogenic environmental pollution. According to data from international energy institutions, the share of transport reaches more than 25% of final energy consumption and makes a significant contribution to the share of global carbon dioxide (CO_2) emissions. This explains its central place in modern decarbonization strategies on the path to sustainable development [1, 2].

Considering current approaches to the decarbonization of transport, it is worth noting that attention of scientists and politicians is mostly focused on reducing CO_2 emissions as the main factor of global warming. However, an equally fundamental problem remains, which is the energy efficiency of transport power installations. Internal combustion engines (ICEs), which will dominate the world's vehicle fleet for a long time, convert only a part of the chemical energy of the fuel into usable mechanical work, while the rest of the thermal energy is irreversibly dissipated in the biosphere [3].

Based on the results from a generalized energy analysis, for modern gasoline engines this efficiency rarely exceeds 30%. Accordingly, about 70% of the fuel energy is lost through exhaust gases, cooling systems, and heat transfer [4]. In this context, CO_2 emissions appear not simply as harmful gas but as an indicator of a double burden on the environment. They signal both carbon and thermal pollution since both phenomena are inseparable components of the combustion process.

That leads to the important statement that CO_2 acts as a kind of barrier to reducing thermal emissions. The amount of dissipated heat is directly proportional to the amount of fuel burned. Accordingly, increasing the efficiency of fuel use (or reducing its consumption) gives a synergistic effect when both greenhouse gas emissions and anthropogenic thermal load are simultaneously reduced. Paradoxically, the problem of thermal pollution from power installations in transport industries, unlike carbon pollution, still remains on the periphery of scientific research in the transport industry [5].

It is worth recognizing that, despite the rapid development of electric and hybrid power installations, internal combustion engines, especially gasoline engines, will remain relevant in the foreseeable future. This is due not only to the limited infrastructure and high cost of batteries but also to the uneven access to "green" electricity on a global scale [2, 6]. In this regard, the search for so-called transitional solutions that could increase the energy efficiency of existing engine fleet without the need for their radical modernization is becoming particularly relevant.

One of the most promising areas is the use of gas additives to gasoline. The introduction of additional gas components into the operating cycle can significantly affect the combustion kinetics and the overall energy balance of the engine. Among such additives, hydrogen and methane are of greatest interest due to their unique physicochemical properties, as well as the potential for partial replacement of carbon fuel, which additionally contributes to the reduction of specific CO_2 emissions [7, 8].

At the same time, the impact of such additives is not limited to changing the chemical composition of the fuel. Due to the differences in the physicochemical processes of different fuels, they are able to change the rate of the combustion process, the distribution of heat release in the cylinder and, accordingly, the ratio between usable work and heat losses. These indicators are determined by the efficiency factor (EF), which is the main indicator for determining the efficiency of engine engineering. Therefore, the use of gas additives can be considered not only as a means of reducing CO_2 emissions, but also as a tool for reducing heat losses and increasing the overall energy efficiency of gasoline engines, which directly corresponds to the goals of sustainable development.

In connection with the above, it is relevant to conduct comparative studies on the impact of various gas additives to gasoline on engine efficiency indicators and CO_2 emissions using co-related analysis methods. Of particular interest is the use of mathematical modeling of the working process, which makes it possible to study the impact of fuel composition on combustion parameters and engine energy balance in a wide range of modes without the need for additional experimental studies.

2. Literature review and problem statement

Paper [9] reports the results of research on future decarbonization technologies in the transport sector. The authors argue that electrification and hybridization of transport power installations are promising solutions towards decarbonization. However, the issue of increasing the efficiency and environmental friendliness of the existing fleet of gasoline engines, which will dominate in the coming decades, remains unresolved. The reason is the lack of search for transitional solutions, and the focus of researchers on radically new technologies.

Study [10] gives an analysis of the impact of adding hydrogen in a spark-ignition engine operating as part of a hybrid power installation on environmental friendliness and fuel efficiency indicators. The results indicate a positive effect of the use of hydrogen additives. However, it does not consider a comparison of the efficiency of hydrogen additives with other gas additives, for example, methane, which complicates the selection of optimal additives to traditional fuels based on the specific operating conditions of the power installation. The reason is the lack of a single methodological approach to compare the impact of various gas additives on the working process in spark-ignition engines.

The authors of work [11] gave an exergy analysis of a hydrogen internal combustion engine with the use of turbocharging. The results of the analysis indicate a high potential for using hydrogen as a fuel to increase the efficiency of the internal combustion engine. However, the authors do not investigate the impact of small hydrogen additives to traditional fuels, which could become a transitional solution in the direction of increasing the efficient and environmental performance of engines. This is explained by the complexity of experimental research on the use of multicomponent and hybrid fuel mixtures in a wide range of ICE operating modes.

In work [12], a study of methods for utilizing heat and recovering energy lost in internal combustion engines was conducted. It was shown that a significant potential for increasing efficiency lies in optimizing the combustion process. However, the question of the influence of fuel composition on the nature of heat release and, accordingly, on the magnitude of heat losses remains unresolved. The reason is the multifactorial nature of the combustion process, which makes it difficult to isolate the influence of a single component of the fuel mixture.

Study [13] examines the working process of a spark-ignition engine using G30 fuel enriched with hydrogen. The experimental data obtained in the work indicate an improvement in efficiency indicators. However, the authors investigate only hydrogen additives, without considering alternative gas components. This is due to the complexity of conducting experimental studies with different types of fuel additives taking into account the same engine and application conditions. A review paper [14] systematizes the results of studies of alternative fuels for spark-ignition engines. Hydrogen, natural gas, biofuels, and other types of fuels are considered. However, the issue of comparative quantitative assessment of the influence of different additives on the parameters of the working process within a single methodology remains unresolved. The reason is the diversity of experimental data obtained on different engines and under different conditions, which makes it impossible to compare them correctly. In work [15], the influence of hydrogen enrichment on the working parameters of an engine running on methanol is experimentally investigated. The positive effect of adding hydrogen was shown. However, the authors did not pay attention to the study of the effect of methane as an additive to gasoline, although methane is much more accessible and has a developed infrastructure. This is due to the traditional focus of researchers on hydrogen as a promising fuel of the future. The authors of [16] studied the effect of HCNG mixtures (hydrogen + natural gas) on the environmental performance of spark-ignition engines. Positive results were obtained regarding the reduction of emissions. However, the effect of methane as an additive to gasoline remains out of consideration. Hypothetically, it can be assumed that the effect of small methane additions will be insignificant, however, confirmation of the hypothesis requires a study of the quantitative effect of the additive on engine performance.

In study [17], the operation of a spark-ignition engine on pure gasoline and methane is compared. The difference in efficiency and emissions of harmful substances is determined. However, the authors study the operation of an internal combustion engine exclusively on pure methane, without taking into account the possibility of using it as an additive.

This approach makes it difficult to assess the impact of using methane as a transitional solution for gasoline engines without their significant modernization on the path to decarbonization in the context of a Sustainable Development strategy.

In [18], the combustion of LPG/DME gas mixtures in a spark-ignition engine was investigated. The dependences of the operating process parameters on the mixture composition were obtained. However, the issue of applying the proposed approach to mixtures of gasoline with gas additives, in particular hydrogen and methane, remains unresolved. The reason is the specificity of the selected fuels, which does not allow direct extrapolation of the results.

The authors of a review study [19] analyzed low-carbon fuels for spark-ignition engines, in particular compressed natural gas and liquefied petroleum gas. The prospects of using gas fuels to reduce CO_2 emissions are shown. However, the authors note the lack of a coordinated approach to the comparative assessment of various additives within a single methodology, which complicates the formation of general conclusions regarding their relative effectiveness.

Thus, our review of the literature allows us to identify an unresolved problem. It consists in the absence of a single methodological approach to the comparative quantitative assessment of the influence of hydrogen and methane additives to gasoline on the parameters of the combustion process, efficiency indicators, and CO_2 emissions of a gasoline engine. The reason is the diversity of experimental data obtained on different engines under different conditions, the complexity and high cost of conducting experiments with multicomponent fuel mixtures. In addition, researchers are focused either on the use of pure hydrogen or methane, without considering them as additives to gasoline. A possible approach to overcome these difficulties may be the use of mathematical modeling of the working process using the Wiebe model, the parameters of which are determined on the basis of physically justified scaling through the laminar flame propagation velocity. At the same time, the parameters of the dynamics and combustion time of the known Wiebe model have been determined only for some alternative ICE fuels.

Therefore, for computational comparative studies, it is important to determine the parameters of the Wiebe model to ensure a single methodological approach to assessing the efficiency of complex physicochemical processes of fuel combustion in the ICE cylinder when using different fuel additives. This approach makes it possible to provide single conditions for comparison and obtain quantitative estimates of the influence of different additives on the parameters under study.

The above allows us to state that it is advisable to conduct a study aimed at determining the influence of hydrogen and methane additives to gasoline on efficiency indicators and CO_2 emissions in a gasoline engine.

3. The aim and objectives of the study

The aim of our study is to quantify the impact of hydrogen and methane additives to gasoline on the efficiency and CO_2 emissions of a spark-ignition engine based on a single methodological approach that makes it possible to compare the efficiency of different gas additives. This will make it possible to reasonably choose the type of additive to increase energy efficiency and reduce the carbon footprint of the existing fleet of gasoline engines depending on the existing infrastructure and modernization priorities.

To achieve this goal, the following tasks were set:

– to build semi-empirical dependences for determining the parameters of the Wiebe model when adding methane to gasoline;

– to determine the dynamics and duration of combustion in the 4Ch7.6/6.6 engine when operating on gasoline with hydrogen and methane additives up to 10% at maximum torque and rated power;

– to determine the influence of the proportion of gas additive on the specific effective fuel consumption g_e and effective efficiency η_e, as well as the volume fraction of CO_2 in the exhaust gases.

4. The study materials and methods

The object of our study is the working process in a 4Ch7.6/6.6 gasoline engine when using hydrogen and methane additives to fuel. The choice of the specified engine is due to its wide application in passenger cars and the possibility of comparing the results with the available experimental data.

The principal hypothesis assumes the use of a semi-empirical approach based on scaling the parameters of the Wiebe model through the ratio of laminar flame propagation velocities. This approach could allow us to quantitatively assess and compare the impact of hydrogen and methane additives to gasoline on the efficiency indicators and CO_2 emissions of a spark-ignition engine within a single methodological approach. It is assumed that hydrogen would provide intensification of the combustion process, and methane, on the contrary, would slow it down, while both additives could contribute to reducing CO_2 emissions by changing the elemental composition of the fuel. This study is aimed at testing this hypothesis by mathematical modeling of the working process.

The parameters of the Wiebe model for gasoline are determined experimentally when the engine is operating at external speed characteristics and remain valid for basic comparison. The determination of the effect of gas additives on combustion kinetics is performed mainly by changing the laminar flame velocity. Heat release in the cylinder is described by the single-zone Wiebe mathematical model.

The work does not take into account the influence of gas additives on the formation of nitrogen oxides, carbon monoxide, and unburned hydrocarbons during combustion. Engine operation under transient modes and partial load modes is also not considered. In the calculations, the share of gas additives is limited to the range from 0 to 10% by volume.

The experimental study that was conducted at the laboratory complex of the Department of Engines and Hybrid Power installations, the National Technical University "Kharkiv Polytechnic Institute", involved identifying the mathematical model of the working process in an automobile engine. During the experimental studies, the engine operated on gasoline. The model identification is carried out with the aim of its further refinement and the possibility of determining the performance of the engine with additives to the main fuel. During the experimental study, a number of measures are taken to obtain an indicator diagram and determine the basic combustion parameters.

The technical characteristics of the experimental engine are given in Table 1.

The 4Ch7.6/6.6 engine is controlled by an engineering electronic control unit, which is functionally similar to the Bosch M7.9.7 module. The engineering unit is controlled by the J5 On-Line Tuner software, which makes it possible to determine the excess air ratio, engine crankshaft speed, hourly air flow rate, and ignition advance angle. Mass fuel consumption is determined by the weighing method. A chromel-aluminum thermocouple and galvanometer are used to determine the exhaust gas temperature. A K-Line adapter cable is used to connect to the engineering unit.

Table 1

Technical characteristics of engine 4Ch7.6/6.6

No. of entry	Engine parameter ID	Parameter value
1	Location and number of cylinders	In a row, 4
2	Cylinder diameter, mm	76
3	Piston stroke, mm	60.6
4	Geometric compression ratio	9
5	Rated engine power, kW	40
6	Rated crankshaft speed, min^{-1}	5,600
7	Maximum torque, N m	77.9
9	Engine displacement V_h, l	1.1
10	Engine weight, kg	127

The automated system complex for measuring engine parameters includes a number of components, such as a TDC sensor, an AVL cylinder pressure sensor, a crankshaft angle sensor, an amplifier unit, an ADC board PCI L-Card 783-86, Powergraph 3.3.9 Pro software, as well as EngineAnalysisPro v1.0 software. The engine load is provided by an electric balancing machine (Fig. 1).

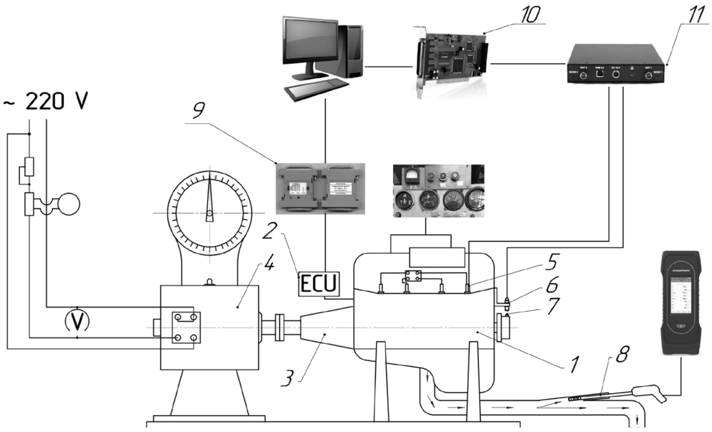


Fig. 1. Bench diagram:
1 — engine equipped with control and measuring instruments and devices that enable its operation; 2 — diagnostic connector; 3 — gearbox; 4 — loading device / electric motor for driving the crankshaft during scrolling; 5 — pressure sensor in the engine cylinder AVL 6 — crankshaft rotation angle sensor; 7 — TDC mark; 8 — Sauermann Si-Ca 230 gas analyzer probe; 9 — K-Line adapter; 10 — PCI L-Card 783-86 ADC board; 11 — amplifier

We identified the mathematical model by superimposing the calculated and indicator diagrams and heat release characteristics, as well as comparing the effective engine performance indicators [20].

In the study, a single-zone model was used for the mathematical notation of the combustion process in a gasoline engine with spark ignition in operation, in which the heat release law is fitted to the Wiebe function. This approach is generally accepted in computational studies of internal combustion engine operating processes due to sufficient accuracy, physical interpretability of parameters, and relative computational complexity [21].

The Wiebe model is used to describe the combustion process of the fuel-air mixture as a function of time or the crankshaft rotation angle. It is widely used in world engine engineering in studies of the influence of fuel composition, operating modes and ignition parameters on the kinetics and duration of combustion [22]. In general, the Wiebe function is written as

$$x = 1 - \exp\left[-C \cdot \left(\frac{\varphi - \varphi_0}{\varphi_z}\right)^{m+1}\right], \quad (1)$$

where φ_0, φ_z, φ are the combustion start angle, combustion duration, and the current value of the crank angle during the combustion process, respectively; C is a constant characterizing the completeness of fuel combustion; m is an indicator of combustion dynamics.

The constant C in expression (1) is determined from the following dependence

$$C = \ln\left(1 - pol\right), \quad (2)$$

where pol – the fraction of fuel that burns completely during the cycle

$$pol = \sum pol_i \cdot r_i, \quad (3)$$

pol_i, r_i – respectively, the completeness of combustion and the volume fraction of the i-th fuel component.

At values of $\alpha < 1.7$, the completeness of combustion was taken constant and equal to 0.92.

The completeness of combustion for hydrogen is taken equal to 0.999, since it is believed that hydrogen burns almost completely at a value of the excess air coefficient $\alpha \leq 10$. The ignition limit and laminar flame front propagation speed for carbon monoxide CO are close to methane CH_4. Therefore, the work assumes that the completeness of combustion of CO at different values of α changes similarly to CH_4.

The basic values of parameters in the Wiebe model for the operation of the engine on gasoline were determined on the basis of experimental indicator diagrams of pressure in the cylinder of the 4Ch7.6/6.6 engine when operating according to the external speed characteristic that are given in Table 2. The identification of parameters was carried out by fitting experimental data to the Wiebe function, which is consistent with classical approaches to analyzing indicator chart data [23].

Based on experimental data obtained by processing indicator diagrams and studying heat release characteristics, the following dependences for the Wiebe model indicators are proposed in the work for calculating the combustion process of gasoline with hydrogen addition:

$$m = m_0 - 12\psi, \quad (4)$$

$$\varphi_z = \left[\left(\varphi_s\right)_0 - 95\psi\right] + \left[\left(\varphi_v\right)_0 - 80\psi\right], \quad (5)$$

where ψ is the fraction of hydrogen in the fuel; m_0 is the combustion dynamics index; $(\varphi_s)_0$, $(\varphi_v)_0$ is the duration of the initial and apparent combustion periods.

Table 2

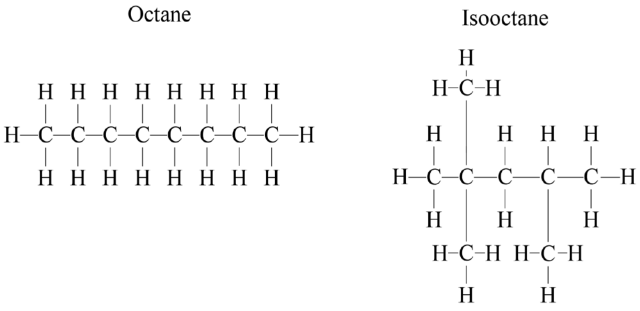
Experimental indicators of the duration and nature of combustion in the 4Ch7.6/6.6 engine

Mode n, min^{-1}	m	φ_z
3870	3.1	67
5590	3.7	62

The obtained experimental values indicate a regular decrease in the duration of combustion with increasing crankshaft rotation speed, which corresponds to the fundamental ideas about the influence of turbulence and ignition conditions on the combustion rate [24]. The values of the shape parameter m for gasoline are in the range typical for gasoline atmospheric engines with spark ignition, which confirms the correctness of the applied approach [25].

To understand the mechanisms of the influence of hydrogen and methane additives on the formation of CO_2, it is necessary to consider the elemental composition and chemical formulas of the studied fuels. The main components that determine the amount of carbon dioxide in the exhaust gases are carbon (C) and hydrogen (H), as well as the ratio between them.

Gasoline is a complex mixture of hydrocarbons containing alkanes, cyclanes, and arenes. For simplified modeling, its composition is often approximated by the formula of isooctane (C_8H_{18}), which is a typical representative of high-octane fuel components. Isooctane, the structural formula of which is shown in Fig. 2, has a molar ratio of $H/C \approx 2.25$. Diesel fuel consists of heavier hydrocarbons, and its average composition can be represented by the formula $C_{12}H_{23}$, with a ratio of $H/C \approx 1.92$. The lower hydrogen-to-carbon content of diesel compared to gasoline is one of the reasons for the higher specific CO_2 emissions per unit of energy released.


Octane

Isooctane

Fig. 2. Structural formulae of normal octane (n-octane) and isooctane

Unlike liquid fuels, gaseous fuels such as methane and hydrogen have a simpler and more well-defined structure. Methane (CH_4) is the simplest hydrocarbon; its molecule consists of one carbon atom and four hydrogen atoms. The H/C ratio for methane is 4, which is the maximum value among all hydrocarbons. This means that when methane is completely burned, each carbon atom has significantly more hydrogen atoms that are oxidized to water (H_2O). As a result, with the same energy output, less CO_2 is produced compared to gasoline or diesel. In addition, it should be noted that engine exhaust gases may contain other carbon-containing compounds in addition to CO_2. Unburned hydrocarbons (C_xH_y), carbon monoxide (CO), and particulate matter (soot) are also present in the exhaust gases, especially when operating on rich mixtures or in diesel engines. However, when a spark-ignition gasoline engine is operating on stoichiometric mixtures, the main product of incomplete carbon oxidation is CO_2.

Hydrogen (H_2) is a unique fuel consisting of a single chemical element. Its structural formula consists of two hydrogen atoms covalently bonded (H–H). Accordingly, the H/C ratio for hydrogen is meaningless since it does not contain carbon. The only product of hydrogen combustion in pure oxygen is water H_2O. When hydrogen is added to gasoline, part of the carbon-containing fuel is replaced by a carbon-free component, which directly reduces the amount of carbon entering the combustion chamber and, as a result, reduces the potential for CO_2 formation.

Thus, a comparative analysis of the elemental composition reveals that the H/C ratio is a key factor determining the specific CO_2 emissions during the combustion of hydrocarbon fuels. The higher this ratio, the less CO_2 is formed per unit of energy. Methane with its maximum $H/C = 4$ has the best performance among hydrocarbons, and hydrogen, having no carbon at all, allows for an even greater reduction in CO_2 emissions when used as an additive. This justifies the choice of these components for studying their impact on the environmental performance of a gasoline engine.

When hydrogen is added to gasoline, with an increase in the hydrogen content, there is a monotonic decrease in both the combustion duration $\Delta\varphi_z$ and the combustion dynamics parameter m. This reflects the acceleration of the initial phase of combustion, which is associated with the physicochemical properties of hydrogen: high laminar flame velocity, wide ignition limits, and increased diffusion.

In the adopted form of the Wiebe function, a decrease in the parameter m reflects a more intense initial heat release, which is consistent with experimental observations and theoretical ideas about the effect of hydrogen on combustion [26].

In the case of adding methane to gasoline, experimental pressure indicator diagrams for identifying parameters in the Wiebe model were absent. Therefore, a physically justified semi-empirical approach based on the fundamental characteristics of flame propagation in fuel-air mixtures was used to determine the combustion parameters.

As shown in classical and modern studies on combustion processes in spark-ignition engines, the kinetics of heat release are mainly determined by the speed of flame front development. However, it is worth noting that the kinetics of heat release also depend on the laminar flame velocity, the level of turbulence, and the thermodynamic state of the working mixture [27]. For the comparative analysis of fuel additives under the same geometric and operating conditions of the engine, the dominant factor is precisely the laminar flame velocity, which makes it possible to consider it as a scaling parameter in semi-empirical combustion models.

According to the physicochemical properties, the laminar flame velocity of gaseous and gaseous fuels under stoichiometric conditions differs significantly. Hydrogen is characterized by the highest values of laminar velocity, while for methane they are significantly lower [28]. The generalized relative values of laminar flame velocity for the studied fuels can be given in the form

$$u_f\left(H_2\right):u_f\left(CH_4\right)\approx 1:0.14...0.16. \tag{6}$$

In this regard, the scaling factors of the Wiebe model parameters reflect not the absolute flame velocity, but the relative intensification of the combustion process compared to the base gasoline fuel.

Taking into account the established experimental relationship between the addition of hydrogen and the reduction in the combustion duration $\Delta\varphi_z$ and the Wiebe shape parameter m, for methane, the scaling of these parameters was applied in proportion to the relative change in the laminar flame velocity. This approach corresponds to the methodology where the parameters of the Wiebe function are related to the flame development velocity and the intensity of the initial phase of combustion.

Physically, this means that fuel additives with a lower laminar flame velocity provide less intense initial heat release compared to hydrogen, which is reflected in:

– larger values of the combustion dynamics parameter m;

– longer combustion duration $\Delta\varphi_z$ for the same additive fraction and engine operating mode.

It is important to note that the applied scaling is not arbitrary but is based on the assumption of similarity of conditions of development of turbulent flame in the engine cylinder while preserving geometry of the combustion chamber, ignition parameters, and speed regime. Under such conditions, the relative influence of fuel composition on combustion kinetics can be adequately described through change of laminar flame velocity, which is confirmed by numerous experimental and computational studies [29].

Thus, the proposed approach to determining parameters for a Wiebe model for methane provides physically consistent and methodically justified comparison of influence of various gas additives to gasoline on combustion process in engine. This makes it possible to form semi-empirical dependences for determining the parameters in a Wiebe model.

The proposed approach combines experimental identification of parameters of Wiebe model for base fuel with physically justified semi-empirical scaling for gas additives. This methodology is widely used in modern computational studies and provides sufficient reliability of results for comparative analysis of different fuel compositions.

At the same time, it should be noted that the obtained dependences are valid for the operating conditions of the internal combustion engine under the modes of external speed characteristics and limited proportions of gas additives (up to 10%). For higher levels of substitution or detailed analysis of the formation of toxic components of exhaust gases, it is advisable to use multi-zone models and extended experimental studies.

5. Results of investigating the influence of gas additives on the engine operating process

5. 1. Semi-empirical dependences for determining parameters in the Wiebe model when adding methane to gasoline

For a mathematical description of the combustion process of benzene-methane mixtures within the single-zone model of the operating process, it is necessary to have quantitative dependences that link the parameters of the Wiebe model with the proportion of the gas additive. Experimental indicator diagrams for mixtures of gasoline with methane in the studied range of proportions are absent, which necessitated the use of a semi-empirical approach to determining these parameters.

Empirical dependences (4), (5) quantitatively describe the influence of hydrogen additives on the parameters of the Wiebe model. Hydrogen and methane belong to gas additives, but have fundamentally different physicochemical characteristics, primarily the laminar flame propagation velocity, which for hydrogen is anomalously high, and for methane – lower than for gasoline. This determines the opposite nature of the influence of these additives on the kinetics of combustion: hydrogen intensifies the process, while methane slows it down.

Taking into account the mentioned physical differences, as well as relying on the fundamental relationships between the flame propagation speed and the heat release parameters, this study proposes semi-empirical dependences for determining the parameters of the Wiebe model when methane is added to gasoline. The proposed dependences have the same structural form as for hydrogen, but with the opposite sign and adjusted numerical coefficients, reflecting the lower intensity of the influence of methane on the combustion rate:

$$m = m_0 + 1.2\xi, \qquad (7)$$

$$\varphi_z = \left[\left(\varphi_s\right)_0 + 8\xi\right] + \left[\left(\varphi_v\right)_0 + 8\zeta\right], \qquad (8)$$

where ζ is the proportion of methane in the fuel; m_0 is the combustion dynamics index; $(\varphi_s)_0$, $(\varphi_v)_0$ are the combustion dynamics index and the duration of the initial and visible phases of combustion for pure gasoline, respectively, determined experimentally (Table 2).

The physical content of the proposed dependences is to reflect the slowdown of the combustion process with an increase in the proportion of methane. An increase in the shape parameter m indicates a decrease in the intensity of heat release at the initial stage, and an increase in the duration of combustion φ_z reflects the general stretching of the process in time. The quantitative values of the coefficients in the semi-empirical dependences are determined based on the assumption that the effect of methane on the combustion rate is much weaker than the effect of hydrogen. This assumption is consistent with the known literature data on the ratio of laminar flame velocities of these gases.

The proposed dependences (7), (8) provide methodological consistency with the approach used for hydrogen and allow us to study the influence of various gas additives on the parameters of the working process of a gasoline engine in a single format.

5. 2. The result of investigating the change in the dynamics and duration of combustion for gasoline-methane mixtures

Using the proposed semi-empirical dependences (7), (8) and experimentally determined basic parameters for pure gasoline (Table 2), the combustion dynamics indicators m, and the total combustion duration φ_z were calculated for engine operation on gasoline with methane addition in the range from 0 to 10% by volume. The calculations were performed for two characteristic operating modes of the 4Ch7.6/6.6 engine: crankshaft rotation frequency $n = 3870$ min^{-1} (maximum torque mode) and $n = 5590$ min^{-1} (nominal power mode).

For comparison, Tables 3, 4 also provide the corresponding parameters for hydrogen additives, calculated from formulae (4), (5) according to experimental data.

Table 3

Wiebe model parameters for maximum torque mode

H_2, %	m	φ_z, °deg	CH_4, %	m	φ_z, °deg
0	3.1	67	0	3.1	67
2	2.86	63.5	2	3.124	67.32
4	2.62	60	4	3.148	67.64
6	2.38	56.5	6	3.172	67.96
8	2.14	53	8	3.196	68.28
10	1.9	49.5	10	3.22	68.6

Table 4

Wiebe model parameters for rated power

H_2, %	m	φ_z, °deg	CH_4, %	m	φ_z, °deg
0	3.7	62	0	3.7	62
2	3.46	58.5	2	3.724	62.32
4	3.22	55	4	3.748	62.64
6	2.98	51.5	6	3.772	62.96
8	2.74	48	8	3.796	63.28
10	2.5	44.5	10	3.82	63.6

The nature of change in the parameters of the Wiebe model when adding gas components is shown in Fig. 3, 4.

Analysis of the data on the calculation of parameters in the Wiebe model for the 4Ch7.6/6.6 engine when operating on gasoline with hydrogen and methane additives up to 10% in the maximum torque (n = 3,870 min^{-1}) and nominal power (n = 5,590 min^{-1}) modes (Tables 3, 4, Fig. 3, 4):

– when adding hydrogen up to 10% by volume, the combustion dynamics indicator m decreases under the mode n = 3,870 min^{-1} from 3.1 to 1.9 (the change is 38.7%), under the mode n = 5,590 min^{-1} from 3.7 to 2.5 (the change is 32.4%). The combustion duration φ_z is reduced, respectively, from 67 to 49.5 degrees of crankshaft rotation (deg. CSR) (the change is 26.1%) and from 62 to 44.5 deg. CSR (change 28.2%);

– when adding methane to 10% by volume, the combustion dynamics indicator m increases under the mode n = 3,870 min^{-1} from 3.1 to 3.22 (change is 3.9%), under the mode n = 5,590 min^{-1} from 3.7 to 3.82 (change 3.2%). The combustion duration φ_z increases, respectively, from 67 to 68.6 deg. CSR (change 2.4%) and from 62 to 63.6 deg. CSR (change 2.6%);

– the absolute change in the parameter m when adding 10% hydrogen is 10 times greater than the change when adding 10% methane. The absolute change in the combustion duration φ_z when adding hydrogen is more than 10 times greater than the change when adding methane to gasoline;

– when the crankshaft speed increases from 3870 to 5590 min^{-1} for pure gasoline, the parameter m increases from 3.1 to 3.7, the combustion duration φ_z decreases from 67 to 62 deg. CSR.

Such a change in the parameters of the Wiebe model corresponds to the fundamental ideas about the influence of turbulence and speed regime on the combustion process. The obtained values for parameters in the Wiebe model for gasoline-methane mixtures (Tables 3, 4) are used in further calculations of the engine operating process to determine its effective and environmental indicators.

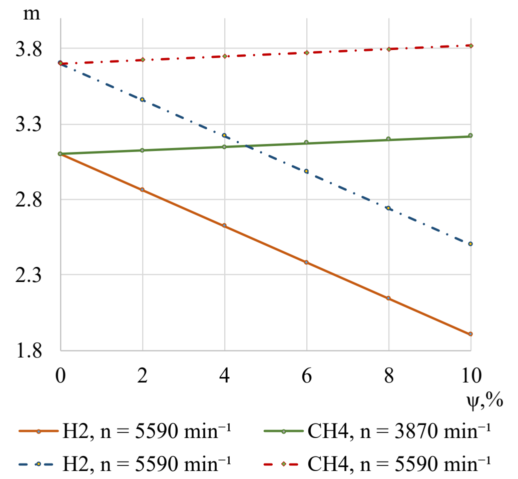


Fig. 3. Dependence of the combustion dynamics indicator m on the volume fraction of the gas additive

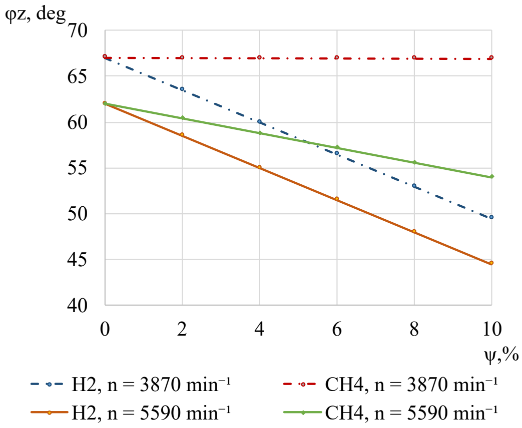


Fig. 4. Dependence of combustion duration φ_z on the volume fraction of the gas additive

5. 3. The result of investigating the influence of gas additive on the effective and environmental performance of the engine

Tables 5, 6 give the calculated results of the integral efficiency indicator Δg_e, which reflects the change in the specific effective fuel consumption in accordance with the increase in the hydrogen and methane additive. Fig. 5, 6 show the change in the effective parameters of the 4Ch7.6/6.6 engine when operating at maximum torque (n = 3,870 min^{-1}) and nominal power (n = 5,590 min^{-1}).

Table 5

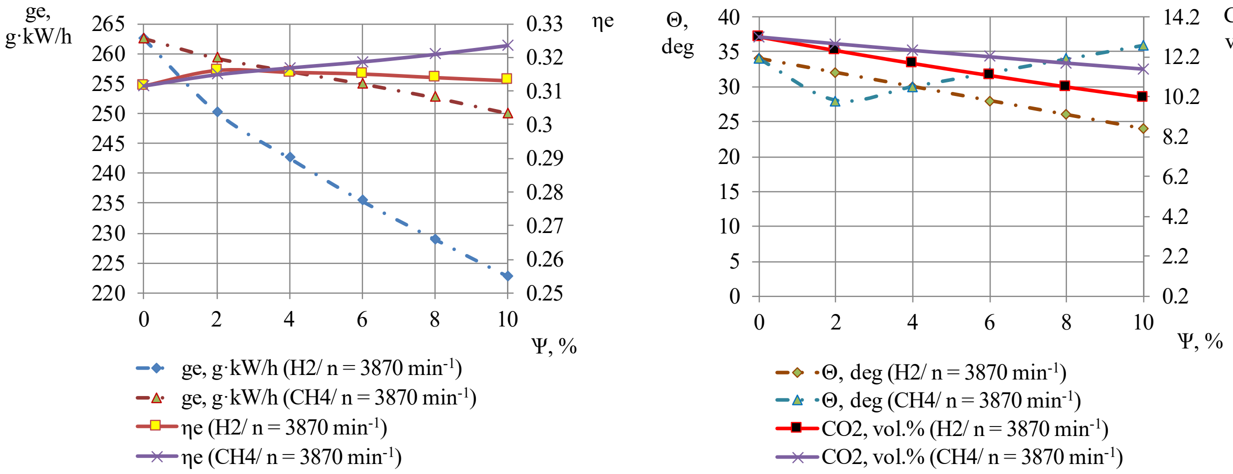
The influence of gas additives on the effective performance of engine under the mode n = 3870 min^{-1}

Additive type	Ψ, %	g_e, g · kW/h	Δg_e, g · kW/h	η_e	$\Delta\eta_e$	Θ, deg	CO_2, vol. %	ΔCO_2, vol. %	N_e, kW
H_2	0	262.6	0	0.3116	0	34	13.19	0	31.45
H_2	2	250.3	–26.4	0.316	0.021	32	12.51	–0.68	31.45
H_2	4	242.6	–34.1	0.3155	0.0205	30	11.87	–1.32	31.48
H_2	6	235.4	–41.3	0.315	0.02	28	11.27	–1.92	31.48
H_2	8	229	–47.7	0.314	0.019	26	10.7	–2.49	31.48
H_2	10	222.8	–53.9	0.3131	0.0181	24	10.17	–3.02	31.46
CH_4	0	262.6	0	0.3116	0	26	13.17	0	31.45
CH_4	2	259.3	–17.4	0.3149	0.0199	28	12.84	–0.35	31.46
CH_4	4	257.1	–19.6	0.3169	0.0219	30	12.52	–0.67	31.49
CH_4	6	255	–21.7	0.3187	0.0237	32	12.21	–0.98	31.48
CH_4	8	252.7	–24	0.3209	0.0259	34	11.9	–1.29	31.49
CH_4	10	250.1	–26.6	0.3235	0.0285	36	11.61	–1.58	31.49

Table 6

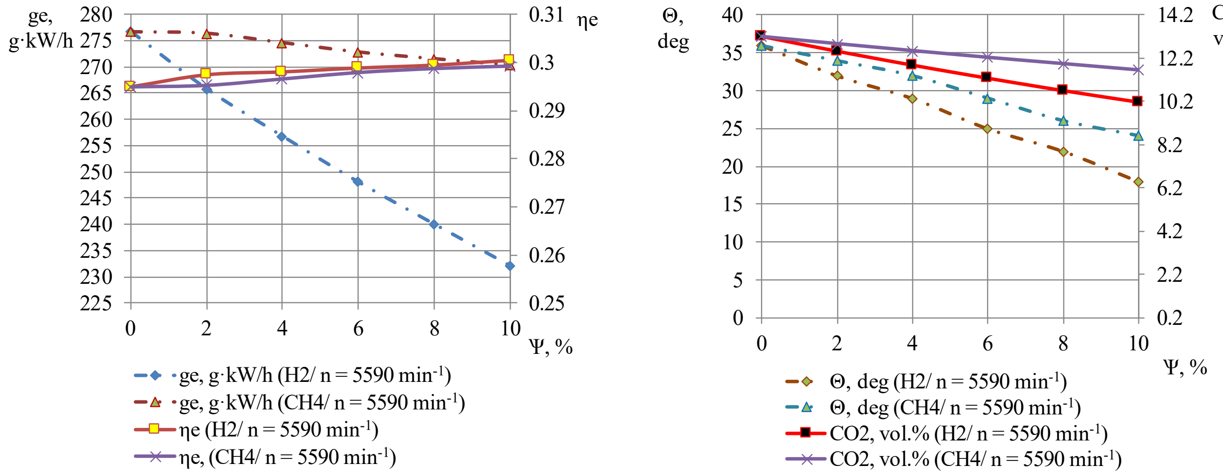
The influence of gas additives on the effective performance of the engine under the mode $n = 5590$ min^{-1}

Additive type	Ψ, %	g_e, g · kW/h	Δg_e, g · kW/h	η_e	$\Delta\eta_e$	Θ, deg	CO_2, vol. %	ΔCO_2, vol. %	N_e, kW
H_2	0	276.7	0	0.295	0	36	13.19	0	38.06
H_2	2	265.8	–10.9	0.2975	0.0025	32	12.51	–0.68	38.15
H_2	4	256.8	–19.9	0.2981	0.0031	29	11.87	–1.32	38.2
H_2	6	248.1	–28.6	0.2989	0.0039	25	11.27	–1.92	38.09
H_2	8	240.1	–36.6	0.2995	0.0045	22	10.7	–2.49	38.12
H_2	10	232.2	–44.5	0.3005	0.0055	18	10.17	–3.02	38.15
CH_4	0	276.7	0	0.295	0	36	13.19	0	38.06
CH_4	2	276.4	–0.3	0.2953	0.0003	34	12.86	–0.33	38.13
CH_4	4	274.6	–2.1	0.2966	0.0016	32	12.54	–0.65	38.15
CH_4	6	272.8	–3.9	0.2979	0.0029	29	12.23	–0.96	38.22
CH_4	8	271.5	–5.2	0.2987	0.0037	26	11.94	–1.25	38.24
CH_4	10	270.3	–6.4	0.2992	0.0042	24	11.65	–1.54	38.16



a *b*

Fig. 5. The influence of gas additives on the effective performance of the 4Ch7.6/6.6 engine when operating at $n = 3870$ min^{-1}: *a* — effective efficiency η_e and specific effective fuel consumption g_e; *b* — volume fraction of CO_2 and ignition advance angle Θ



a *b*

Fig. 6. The influence of gas additives on the effective performance of the 4Ch7.6/6.6 engine when operating at $n = 5590$ min^{-1}: *a* — effective efficiency η_e and specific effective fuel consumption g_e; *b* — volume fraction of CO_2 and ignition advance angle Θ

Fig. 5, 6 show the change in the effective parameters of the 4Ch7.6/6.6 engine when operating under the studied modes.

Analysis of the calculation data on the performance indicators and carbon dioxide content in the exhaust gases of the 4Ch7.6/6.6 engine when operating on gasoline with hydrogen and methane additives up to 10% under the modes $n = 3{,}870\ \text{min}^{-1}$ and $n = 5{,}590\ \text{min}^{-1}$ (Tables 5, 6, Fig. 5, 6):

– for a hydrogen additive of 10% by volume under the mode $n = 3{,}870\ \text{min}^{-1}$, the specific effective fuel consumption g_e decreases from 262.6 to 222.8 g/(kWh) (integral indicator $\Delta g_e = -53.9$ g/(kWh), relative decrease 13.9%). At $n = 5{,}590\ \text{min}^{-1}$, g_e decreases from 276.7 to 232.2 g/(kWh) (integral index $\Delta g_e = -44.5$ g/(kWh), relative decrease 14.3%). Each 2% hydrogen addition provides a 3–3.1% decrease in g_e depending on the engine operating mode;

– the effective efficiency η_e when adding 10% hydrogen increases at $n = 3{,}870\ \text{min}^{-1}$ from 0.3116 to 0.3131 ($\Delta\eta_e = 0.0015$, relative increase 0.5%), at $n = 5{,}590\ \text{min}^{-1}$ from 0.295 to 0.3005 ($\Delta\eta_e = 0.0055$, relative increase 1.83%);

– the ignition advance angle Θ when adding 10% hydrogen decreases under the mode $n = 3{,}870\ \text{min}^{-1}$ from 34 to 24 degrees of CSR, under the mode $n = 5{,}590\ \text{min}^{-1}$ from 36 to 18 degrees of CSR;

– the volume fraction of CO_2 in the exhaust gases when adding 10% hydrogen decreases by 14.1% in both studied modes (from 13.19% to 10.17%);

– for the addition of methane 10% by volume under the mode $n = 3870\ \text{min}^{-1}$ the specific effective fuel consumption g_e decreases from 262.6 to 250.1 g/(kWh) (integral index $\Delta g_e = -12.5$ g/(kWh), relative decrease 4.8%). Under the mode $n = 5590\ \text{min}^{-1}$ g_e decreases from 276.7 to 270.3 g/(kWh) (integral index $\Delta g_e = -6.4$ g/(kWh), relative decrease 2.3%);

– effective efficiency η_e when adding 10% methane increases at $n = 3870\ \text{min}^{-1}$ from 0.3116 to 0.3235 ($\Delta\eta_e = 0.0119$, relative increase 3.7%), at $n = 5590\ \text{min}^{-1}$ from 0.295 to 0.2992 ($\Delta\eta_e = 0.0042$, relative increase 1.4%);

– ignition advance angle Θ when adding 10% methane changes at $n = 3870\ \text{min}^{-1}$ from 36 to 26 degrees of CSR, at $n = 5{,}590\ \text{min}^{-1}$ from 36 to 24 degrees of CSR;

– the volume fraction of CO_2 in exhaust gases when adding 10% methane decreases under the mode $n = 3{,}870\ \text{min}^{-1}$ from 13.17% to 11.61% ($\Delta CO_2 = -1.58\%$, relative decrease 11.7%), under the mode $n = 5{,}590\ \text{min}^{-1}$ from 13.19% to 11.65% ($CO_2 = -1.54\%$, relative decrease 11.7%);

– a comparison of the efficiency of additives at the same volume fraction up to 10% shows that hydrogen provides a reduction in CO_2 by 14.1%, methane by 11.7%. The ratio of the efficiency of hydrogen to methane in reducing CO_2 is 1.2 times.

This effect of additives can be explained by their physicochemical properties. Hydrogen has a high flame propagation speed, wide ignition limits, and the ability to intensify the initial phase of combustion, which is confirmed by the changes in the Wiebe model parameters obtained in subsection 5. 3 (decrease in m and φ_z). In addition, hydrogen has a high calorific value, which makes it possible to increase the total energy yield of the mixture when it is added to gasoline. This helps maintain the engine power level while reducing fuel consumption. Methane, on the contrary, has a lower flame propagation speed compared to gasoline, which leads to a slowdown in the combustion process (increase in m and φ_z) and a shift of heat release to the expansion line, which may be accompanied by an increase in heat losses.

Combustion with the use of hydrogen additives has significant advantages compared to conventional combustion and is considered one of the most promising methods for decarbonization of internal combustion engines in transport. First, hydrogen promotes more complete combustion of gasoline, which reduces the amount of unburned hydrocarbons and reduces the formation of CO_2 due to the oxidation of carbon. Second, hydrogen dilutes the fuel mixture, reducing the concentration of carbon and, accordingly, the amount of CO_2 formed in the exhaust gases. Methane also provides a reduction in CO_2 due to a higher H/C ratio compared to gasoline, but at the cost of some deterioration in fuel economy.

Thus, the priority goal affects the choice of gas additive. Hydrogen increases the efficiency of engines but requires special infrastructure. Methane allows for reduced emissions with minimal changes in design. Despite the different nature of the impact on fuel economy, both gas additives provide an environmental effect in the form of reduced CO_2 emissions, but it is impossible to completely eliminate them due to the presence of carbon in the gasoline base.

6. Discussion of results related to the influence of gas additives on the parameters of the working process and indicators of engine efficiency and environmental friendliness

The results in the study allow us to quantitatively compare the influence of hydrogen and methane additives on the efficiency and environmental friendliness of spark-ignition engines within a single methodological approach. The key achievement is the establishment of the multidirectional influence of additives on the combustion process. The intensification of the combustion process by the addition of hydrogen is due to a decrease in the combustion dynamics indicator m by 32.4–38.7% and the combustion duration φ_z by 26.1–28.2% (Tables 3, 4, Fig. 3, 4). The addition of methane slows down the combustion process, which is characterized by an increase in the dynamic indicator m by 3.2–3.9% and the combustion duration φ_z by 2.4–2.6% (Tables 3, 4, Fig. 3, 4). This directly affects the fuel efficiency of the engine, so when adding 10% hydrogen, a reduction in the specific effective fuel consumption g_e is achieved by 13.9–14.3%, while for methane only by 2.3–4.8%. At the same time, both additives contribute to a reduction in the volume fraction of CO_2 in exhaust gases by 14.1% for hydrogen and 11.7% for methane (Tables 5, 6, Fig. 5, 6).

This difference in the nature of the impact is explained by the physicochemical properties of the gases. The high laminar velocity of the hydrogen flame intensifies the initial phase of combustion, which brings the center of heat release closer to TDC. This is confirmed by modern studies, in which hydrogen acts as an effective activator of the combustion process even at low concentrations [30]. As a result, the fraction of heat converted into usable work increases, and the specific effective fuel consumption decreases. However, the lower combustion velocity of methane slows down the process, shifting the heat release to the expansion line. This is confirmed by the need to increase the ignition advance angle with an increase in the methane fraction (Tables 5, 6, Fig. 5, 6, *b*) to compensate for the shift in the gas distribution phases. The reduction in CO_2 emissions for both additives is due to the replacement of carbon-containing gasoline with components with a higher H/C ratio in the case of methane addition, or its complete absence in the case of hydrogen addition. Hydrogen also contributes to a more complete oxidation of carbon in the gasoline base.

Unlike studies that focus exclusively on the use of gaseous fuels or their mixtures [31], the advantage of our study is the development of a single approach for comparing small additives of up to 10%. This makes it possible to us to assess the potential of transitional solutions for the existing engine fleet in the context of a transport decarbonization strategy. As shown in [32], the use of the Wiebe function for modeling the combustion processes of different fuels is a recognized approach but requires parameter adaptation. Semi-empirical relationships for determining the parameters of the Wiebe model when methane is added (7), (8), which are based on scaling through the ratio of laminar flame velocities, provide methodological consistency with the approach for hydrogen (4), (5).

This solves the problem of the lack of a single methodology for the comparative assessment of the impact of different additives, which makes it possible to obtain comparable quantitative results within the framework of one study.

Our solutions are directly aimed at overcoming the issue of the lack of a single methodological approach to the comparative assessment of the impact of hydrogen and methane additives. The proposed approach, which combines experimental identification of parameters for the base fuel with physically justified scaling for additives, allows for a quantitative assessment of the impact of each of them on combustion parameters, efficiency, and CO_2 emissions. In particular, it was found that hydrogen at a volume fraction in the fuel of 10% provides 1.2 times greater CO_2 reduction than methane, which is a quantitative guideline for choosing the optimal additive. Thus, the issue of uncertainty when choosing the type of additive, which arose under conditions of data fragmentation, is solved by providing specific, comparable indicators obtained under unified conditions. This allows for a reasonable approach to the decarbonization strategy, given that, as indicated in study [33], even small hydrogen concentrations (up to 5%) can significantly increase combustion stability and internal combustion engine efficiency.

The limitation of this study is the consideration of engine operation only under steady-state modes of external speed characteristics and with a limited proportion of gas additives. Our dependences are valid precisely under these conditions. Extension of the results to partial load modes, transient processes or higher concentrations of gas fuel additives requires additional research. In addition, the work focuses on carbon dioxide emissions and does not consider the effect of additives on the formation of other harmful substances, such as NO_x, CO, and unburned hydrocarbons, which can have complex nonlinear dynamics.

The disadvantages of the work include the semi-empirical nature of determining the parameters of the Wiebe model for methane due to the lack of experimental indicator diagrams for gasoline-methane mixtures. However, the proposed approach is based on physically justified scaling through the laminar flame development velocity and provides methodological consistency; our dependences (7), (8) require additional experimental verification. Without such confirmation, there is a risk that the numerical coefficients in these dependences may be refined, although the general tendency of combustion retardation is likely to persist. Also, the calculation of the concentration of nitrogen oxides was not carried out in the work, since the single-zone mathematical model of the working process does not allow one to reliably determine the spatial non-uniformity of the temperature field.

The development of this research is likely to follow two directions. The first includes experimental verification of the obtained semi-empirical dependences by conducting motor tests of the 4Ch7.6/6.6 engine on gasoline-methane mixtures with registration of indicator diagrams. This will allow us to refine the proposed models and increase the accuracy of predictions. The second direction involves expanding the boundaries of the study, taking into account the influence of additives on transient modes and partial load modes, as well as analyzing the formation of all harmful components (NO_x, CO, and CH). This is necessary to draw a comprehensive picture of the influence of gas additives on the working process of engine under real operating conditions.

7. Conclusions

1. Our work has further advanced semi-empirical relationships for determining the dynamics and duration of combustion in the Wiebe model when methane is added to gasoline. Unlike existing approaches, which are based exclusively on experimental data for individual types of fuel, the proposed relationships are based on scaling through the ratio of laminar flame propagation velocities of methane and hydrogen. This allowed us to achieve methodological consistency with previously developed dependences for hydrogen and made it possible to study the influence of various gas additives in a single format. The physical basis of this approach is the determining role of the flame front propagation velocity in the formation of the kinetics of heat release in the engine cylinder.

2. Based on the results from mathematical modeling of the working process in the 4Ch7.6/6.6 engine, the multidirectional nature of the influence of gas additives on the combustion parameters was established. When adding 10% hydrogen by volume, the combustion dynamics indicator m decreases by 32.4–38.7% and the combustion duration φ_z is reduced by 26.1–28.2% depending on the operating mode. This indicates a significant intensification of the initial phase of combustion and the approach of the heat release process to TDC. In contrast, for methane, with the same addition by volume, the opposite trend is observed, the parameter m increases by 3.2–3.9%, and the combustion duration φ_z by 2.4–2.6%. This difference is due to the fundamental physicochemical properties of gases, namely, the abnormally high flame velocity of hydrogen and the lower, compared to gasoline, flame velocity of methane. An important feature is that the absolute change in combustion parameters when hydrogen is added is more than an order of magnitude greater than the change when methane is added.

3. The quantitative impact of gas additives on the integral indicators of engine efficiency and environmental friendliness has been determined. When adding 10% hydrogen, the specific effective fuel consumption g_e decreases by 13.9–14.3%, and the effective efficiency increases by 0.5–1.83% depending on the engine operating mode. For methane, at the same additive fraction, the specific consumption decreases by 2.3–4.8%, and the effective efficiency increases by 1.4–3.7%. The volume fraction of CO_2 in exhaust gases when adding 10% hydrogen decreases by 14.1%, and when adding 10% methane decreases by 11.7%. A comparative analysis revealed that with the same volume fraction of the additive, hydrogen provides a 1.2-fold greater reduction in CO_2 compared to methane. This effect of hydrogen additive is explained both by the replacement of carbon-containing fuel with a carbon-free component, and by the intensification of the combustion process of the mixture, which enables a more complete oxidation of carbon in the main fuel. In the case of methane additive, this effect is explained exclusively by a change in the elemental composition of the fuel mixture. The results allow for a reasonable choice of the type of additive depending on the priority direction of research or modernization of spark-ignition engines. Hydrogen is advisable to use for a comprehensive increase in the efficiency and environmental friendliness of power installations in the presence of the

appropriate infrastructure, and methane as a means of moderate decarbonization at minimal costs for engine modernization.

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, either in numerical or graphical form, 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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Authors' contributions

Andrii Marchenko: Conceptualization, Supervision, Writing – review & editing, Project administration, Validation; **Mykyta Mishchenko**: Resources, Investigation, Formal analysis, Methodology.

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