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DETERMINING THE DEGREE OF UNEVENNESS IN THE WORKING CYCLE OF AN INTERNAL COMBUSTION ENGINE WHEN OPERATING ON DIFFERENT TYPES OF FUEL

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This study investigates the degree of non-uniformity in the working cycle of an internal combustion engine with spark ignition when using different types of fuel. The task addressed relates to the lack of comprehensive experimental studies that take into account the influence of the type of fuel, the composition of the fuel-air mixture, and the statistical characteristics of the working cycle parameters based on a large array of indicator diagrams.

This work reports experimental indicator diagrams of partial engine operating modes when using gasoline, propane-butane, and synthesis gas with a hydrogen content of 43%. It was established that normal engine operation on synthesis gas is ensured at an excess air coefficient of 1.35...1.75. The correspondence of the distribution of maximum combustion pressure to the normal law according to the χ^2 criterion has been confirmed.

It was shown that the presence of hydrogen in the composition of synthesis gas significantly reduced the degree of non-uniformity of the working cycle of the spark ignition engine. It was found that the minimum value of the degree of unevenness of the working cycle is observed within the range of the excess air coefficient of 1.05...1.25. As the mixture is depleted, a gradual increase in the degree of unevenness of the working cycle is observed. When $\alpha \approx 2$ is reached, the unevenness of the working cycle on synthesis gas reaches the minimum value of unevenness when the engine is operating on gasoline at $\alpha = 0.9...1.0$.

A feature of the results is the combination of an experimental approach with a statistical analysis of a large sample of indicator diagrams, which made it possible to reliably estimate the degree of unevenness and establish the optimal ranges of the excess air coefficient for different fuels.

The results could be used in optimizing the working processes of spark-ignition engines, designing mixture control systems, as well as in using alternative fuels, in particular synthesis gas, under partial load conditions

Keywords: hydrogen, excess air ratio, indicator diagram, degree of unevenness in operation cycle

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1. Introduction

Engine operating cycle analysis, as well as the accuracy of parameter calculations that provide insight into patterns of heat generation, cylinder temperature, and other characteristics, are implemented through the processing of reliable experimental indicator diagrams. It is important to consider the cyclic instability of the operating process and eliminate errors made during recording and processing.

Acquiring and processing reliable experimental engine indicator diagrams is accomplished using specially devised methodologies that consider a number of factors, ranging from the operating cycle implementation features to the design. This necessitates processing a significant amount of experimental data, removing systematic errors, performing specific calculations related to statistical analysis of the measured indicator diagrams, and acquiring an averaged indicator diagram. The accuracy of the calculation results obtained from analyzing such an averaged diagram is significantly affected by the selection of a number of single cycles that ensures a sufficient degree of averaging of the indicator diagram. The task of choosing the number of single cycles is solved using mathematical statistics methods depending on the degree of unevenness of the operating cycle.

Cyclic instability of the internal combustion engine's operating cycle depends on many factors. For example, under idle and low loads, the degree of cycle irregularity increases, requiring a greater number of consecutive cycles to obtain an average indicator diagram. Furthermore, the type of fuel used (especially alternative fuel), as well as the excess air ratio, significantly affect the degree of cycle irregularity. Along with the aforementioned factors, the increasing use of alternative fuels in the overall energy consumption balance underscores the importance of further theoretical and experimental research in this area.

2. Literature review and problem statement

The issue of cyclic instability in the operating process of internal combustion engines remains relevant as it directly impacts the efficiency, fuel economy, and environmental performance of the engine. Modern research has shown that cyclic variations in combustion parameters, particularly maximum pressure, and indicator work, are a characteristic feature of spark-ignition engines and depend significantly on mixture formation and combustion conditions. Specifically, study [1] found that when using hydrogen-methane mixtures, cyclic variations decrease with increasing hydrogen content but increase with leaner mixtures, which limits engine stability. Paper [2] summarizes the mechanisms underlying cyclic instability; however, it is a review study and does not include experimental evaluation for specific fuel types.

Experimental studies of cyclic instability are reported in [3, 4]. The authors of [3] demonstrated that when operating on hydrogen, significant variability in cylinder working fluid pressure is observed, especially with changes in the excess air ratio. However, the study was conducted for a single engine and a limited range of operating modes. The effect of hydrogen on reducing cyclic variations was established in [4], but a detailed statistical analysis of the distribution of operating cycle parameters was not performed.

Modeling of cyclic instability was considered in [5], in which the possibility of predicting variations in combustion parameters for hydrogen-gasoline mixtures was demonstrated. However, the results are based on numerical modeling and require experimental confirmation. The influence of cyclic instability mechanisms was investigated in [6] but the analysis is limited to individual factors and does not take into account the complex influence of the air-fuel mixture composition.

Statistical methods for analyzing indicator diagrams are discussed in [7], which proposes an approach to processing cylinder working fluid pressure. However, the study was conducted for diesel and gas-diesel engines and does not take into account the specific characteristics of spark-ignition engines. Similarly, paper [8] found a positive effect of hydrogen on combustion rate and process stability but lacked an analysis of the statistical characteristics of cyclic instability.

Additionally, the effect of small hydrogen additions on engine operating stability with lean mixtures was studied in [9]. It was found that even a small amount of hydrogen (less than 1% by weight) contributes to increased combustion stability and a reduction in cyclic instability, especially at low loads and with lean mixtures. However, the study focused primarily on analyzing overall engine operating stability and cylinder pressure parameters and does not include a comprehensive statistical assessment of the degree of operating cycle irregularity.

The effect of hydrogen addition on the lean combustion limit was studied in [10]. It was found that the use of hydrogen significantly expands the limits of stable combustion and improves engine operating stability with lean mixtures. However, the study focuses on the assessment of lean limit and combustion process parameters, while a detailed statistical analysis of cyclic instability and the degree of duty cycle unevenness is lacking.

Thus, despite a significant body of research into cyclic instability and the use of hydrogen as a fuel additive, comprehensive experimental studies are lacking. Specifically, no studies have been reported that combine the analysis of the influence of fuel type, air-fuel mixture composition, and the statistical characteristics of the operating cycle parameters based on a large array of indicator diagrams.

Therefore, there is a need for comprehensive studies aimed at determining the degree of unevenness in the operating cycle of spark-ignition engines operating on various fuel types. This requires considering the statistical characteristics of the process, as well as the influence of the excess air ratio.

3. The aim and objectives of the study

The aim of our study is to determine and evaluate the degree of irregularity in the operating cycle of a spark-ignition engine operating on different fuel types. Experimental and theoretical studies could allow us to analyze the degree of non-uniformity in subsequent cycles during engine operation at partial loads, as well as the influence of the fuel used and the air-fuel ratio.

To achieve this goal, the following tasks must be solved:

– to obtain reliable indicator diagrams of partial operating modes of a spark-ignition engine using different fuel types;

– to verify the probability distribution law of random variables of maximum combustion pressure $\left(P_z^i\right)$ for normality;

– to determine the influence of the fuel used and the air-fuel ratio on the degree of irregularity in the operating cycle of a spark-ignition engine.

4. The study materials and methods

The object of our study is the degree of irregularity in the operating cycle of spark-ignition internal combustion engines (ICEs) using different fuel types. The subject of the study is experimental indicator diagrams of partial operating modes of ICEs using different fuel types and at different fuel-air mixture ratios.

The study's hypothesis assumes that increased uniformity in the operating cycle of ICEs is achieved due to the presence of free hydrogen in the fuel and its unique physicochemical properties.

It is assumed that the confidence level of the experimental results, in the form of indicator diagrams of partial operating modes of ICEs using different fuel types, is based on the hypothesis about the normal distribution of random measurement errors.

To simplify the study, the deviation in the maximum combustion pressure in the cylinder from cycle to cycle during steady-state ICE operation was used as the criterion for irregularity in the operating process.

The first stage of the study requires obtaining a series of indicator diagrams of partial engine operating modes using different fuel types and at different fuel-to-fuel ratios. To solve this task, a specially designed experimental setup based on a four-stroke, two-cylinder 2Ch 7.2/6 spark-ignition engine is used (Fig. 1). The 2Ch 7.2/6 spark-ignition engine operates as part of a standardized gasoline-electric AC power plant, features air cooling, and a relatively simple design. This simple structure and external mixture formation result in relatively high fuel consumption and low efficiency compared to modern spark-ignition engines. However, since the primary goal of our study is to evaluate the degree of unevenness in the operating cycle when using different fuel types, rather than to improve efficiency, the 2Ch 7.2/6 engine is entirely suitable. It is worth noting that the excess air ratio and ignition timing have a significant impact on the hydrogen combustion process, which are taken into account in the study.

The experimental bench allows for the operation of the engine and indication of the working cycle when using liquid (gasoline, alcohols) and gaseous (propane-butane, synthesis gas, hydrogen) fuels.

Fig. 1. General view of the experimental bench based on the spark-ignition engine 2Ch 7.2/6

Fig. 2 shows the basic diagram of the experimental setup and measurement system. When the engine is running on gas fuel, it is supplied from cylinders 1, located in a separate, enclosed room for safety. Gas fuel consumption was determined by using gas meter 7 (with a relative error limit of ±0.5%), installed immediately downstream of low-pressure gas reducer 5. Liquid fuel consumption in the engine was determined by weight (the measurement error of electronic scale 13 is ±1 g).

Engine 10 is loaded with a three-phase AC generator. The generated electrical energy is supplied to active load 15. Current and voltage values are determined separately in each phase of the generator using voltmeter 16 and ammeter 17.

Temperature measurements on the setup were performed using thermocouples (chromel-copel and chromel-alumel) using a 2TPM1 digital instrument (accuracy class 0.25). The crankshaft speed of the 2Ch 7.2/6 spark-ignition engine was determined using a Ch4-34A digital frequency meter (with an absolute error of ±1 s–1). Under experimental conditions, relative humidity was determined using a PBU-1 psychrometer (with a relative error of ±5%), and atmospheric pressure was measured using a BAMM-1 aneroid barometer (with a measurement range of 80–105 kPa and a relative error of ±0.5%).

To study the degree of unevenness in the operating cycle, it is necessary to obtain reliable indicator diagrams of partial operating modes that would qualitatively and quantitatively (with sufficient accuracy) reflect the actual processes in the engine.

A specialized Kistler 7613C continuous dynamic pressure sensor, which requires no special cooling, was used to record a series of indicator diagrams of partial engine operating modes. The basic parameters of the Kistler 7613C pressure sensor are given in Table 1.

In order to acquire the most reliable indicator diagrams, the sensitive element of the Kistler 7613C sensor was placed as close as possible to the engine combustion chamber (Fig. 3), while the compression ratio remained virtually unchanged.

The bench's measurement system (Fig. 2) allows for objective and reliable measurements of actual operating cycle parameters, as well as indicator diagrams. To prevent the influence of various random factors on the experimental results, additional repeat measurements were conducted under most operating modes.

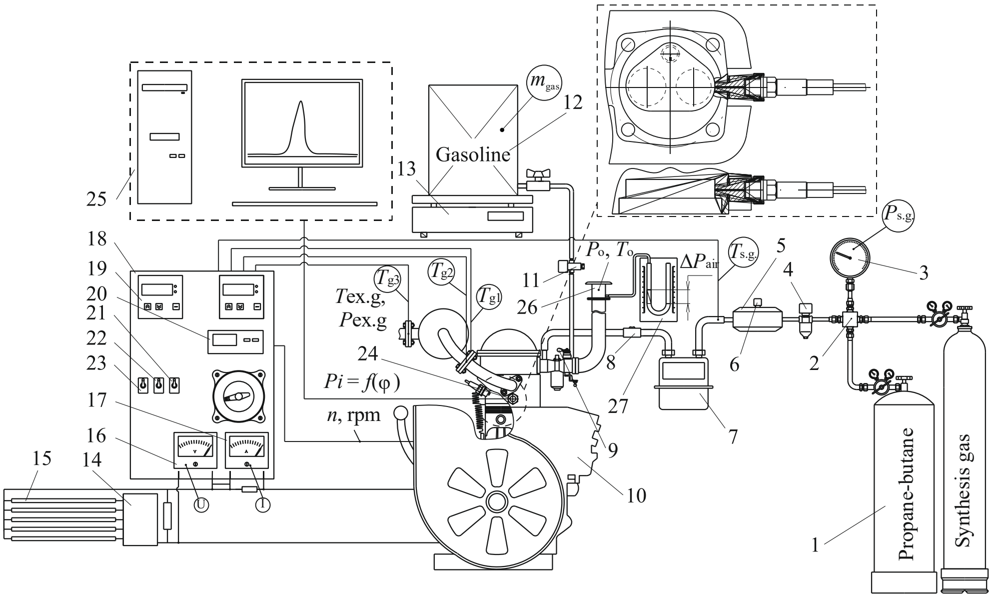

Fig. 2. The experimental setup diagram based on the 2Ch 7.2/6 spark-ignition engine and the measuring system: 1 – cylinders with gas fuel (propane-butane, synthesis gas, hydrogen); 2 – common receiver for switching from one fuel to another; 3 – pressure control gauge; 4 – electromagnetic gas valve; 5 – low-pressure reducer; 6 – electromagnetic valve; 7 – gas meter; 8 – mixture formation quality regulator; 9 – throttle valve; 10 – four-stroke spark-ignition engine 2Ch 7.2/6; 11 – electromagnetic valve for liquid fuel (gasoline, alcohols); 12 – liquid fuel supply tank; 13 – electronic scales; 14 – engine load control unit; 15 – engine load unit; 16 – voltmeter; 17 – ammeter; 18 – instrument panel; 19 – digital instrument 2TRM1; 20 – electronic tachometer; 21 – toggle switch of the electromagnetic valve for supplying liquid fuel; 22 – toggle switch of the electromagnetic valve for supplying gas fuel; 23 – toggle switch of the electromagnetic starting valve of gas fuel; 24 – Kistler 7613C indicator pressure measuring sensor; 25 – personal computer for recording and processing measurement results; 26 – flow meter orifice; 27 – U-shaped liquid pressure gauge

Table 1
Specifications of the Kistler 7613C continuous dynamic pressure sensor

No. of entry	Parameter	Value
1	Natural frequency	≈ 70 kHz
2	Measured media	Liquid, gas
3	Sensor sensitivity	–20 mV/MPA
4	Deviation from linearity over the entire operating range	≤ ± 0,5
5	Operating temperature range of the sensor's sensitive element	– 50...350°C
6	Sensor connector hexagon operating temperature range	– 50...150°C
7	Sensor electronics operating temperature range	– 50...90°C
8	Pressure measurement limits	0...25 MPa
9	Used current	4 mA
10	Sensitivity shift at –200...±150°C	≤ ± 3%
11	Sensitivity shift at –200...±50°C	≈ 1%

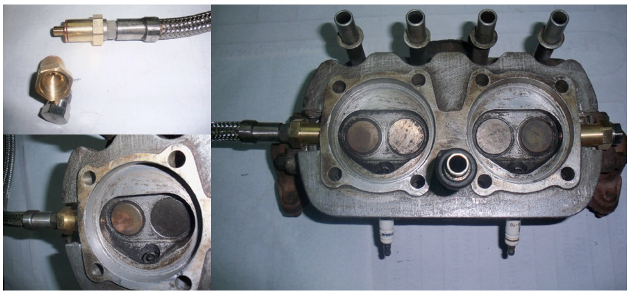

Fig. 3. Placement of the sensitive element of the pressure sensor in the engine head 2Ch 7.2/6

5. Results of studies on the degree of unevenness in the operating cycle when operating on different types of fuel

5. 1. Experimental indicator diagrams of partial operating modes of the 2Ch 7.2/6 engine on different types of fuel

During the engine test series, the following fuels were used: AI-95 gasoline (DSTU 4840–2007), propane-butane (mixture composition according to GOST 27578–87), and syngas. The syngas composition was determined using a Neo CHROM Class B chromatograph. The main components of the syngas are hydrogen (43% by volume), carbon monoxide (34%), and methane (23%). The specific net calorific value of this syngas composition was 28.79 MJ/kg, and the density was 0.629 kg/m^3.

Fig. 4 shows examples of fragments of direct cylinder indicator pressure measurements for a 2Ch 7.2/6 engine operating on various fuels. Due to the physicochemical properties of hydrogen, the ignition timing angle Θ was adjusted over a fairly wide range (Θ = 20...10° p.c. before TDC) to ensure normal and stable engine operation on syngas. Adjusting Θ enabled stable engine operation without self-ignition, backfires, detonation, or a sharp increase in cylinder pressure. Furthermore, the maximum combustion pressure and the maximum pressure after TDC did not exceed those for gasoline operation. Valve timing adjustments were not performed on the engine when using syngas.

Fig. 5 shows an example of processed (expanded) indicator diagrams of the operation of a 2Ch 7.2/6 engine on gasoline and synthesis gas at different values of the excess air coefficient α.

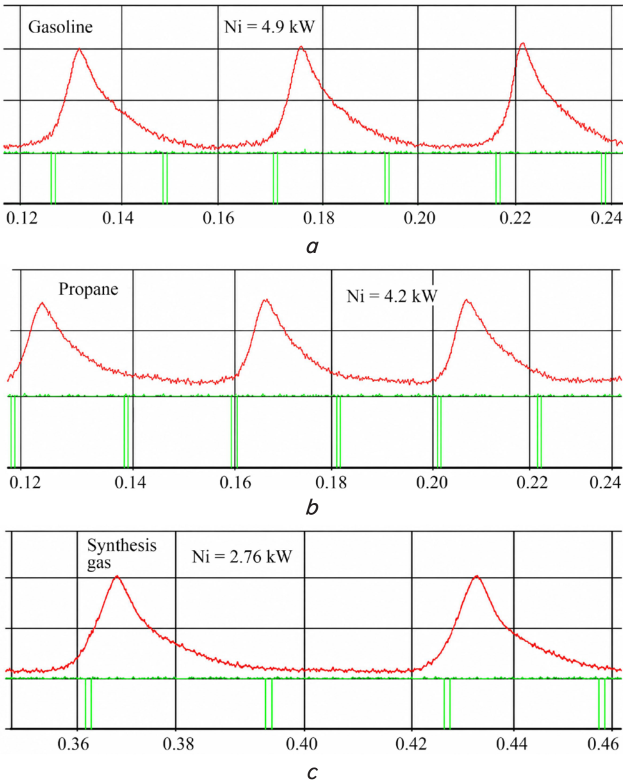

Fig. 4. Fragments of successive working cycles of the 2Ch 7.2/6 engine when running on different types of fuel: *a* – when running on gasoline; *b* – when running on propane-butane; *c* – when running on synthesis gas

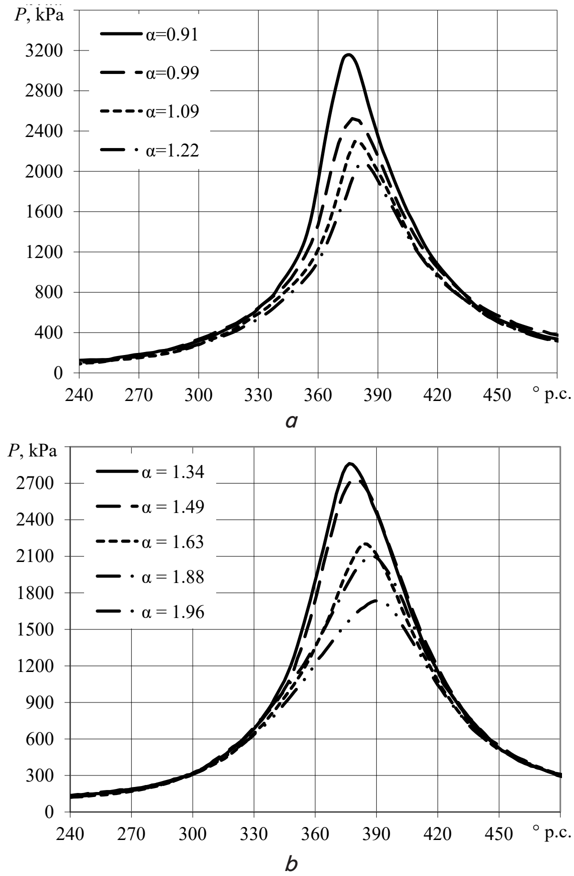

Fig. 5. Experimental indicator diagrams of the 2Ch 7.2/6 engine: *a* – gasoline; *b* – synthesis gas

Due to the significant hydrogen content of syngas (43% by volume), the ignition limits of the fuel-air mixture are significantly expanded. Reducing α to 1.25 or lower results in harsher engine operation (Fig. 6).

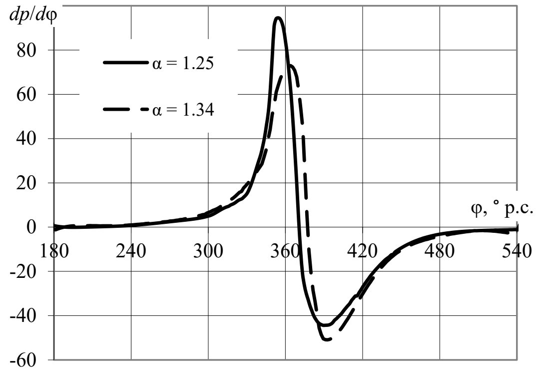

Fig. 6. Dependence of the rate of pressure increase during operation of the 2Ch 7.2/6 engine on synthesis gas

Normal operation of the 2Ch 7.2/6 engine on synthesis gas is ensured by using α in the range of 1.35...1.75. With this value of α, the maximum value of the indicated efficiency of the engine is also ensured.

5. 2. Analyzing the probability distribution law of random variables of maximum combustion pressure for normality

Confidence estimates of experimental results are based on the hypothesis about a normal distribution of random measurement errors. Therefore, they can be used as long as the experimental results obtained do not contradict this hypothesis.

Due to the non-identity of subsequent engine operating cycles, especially under partial load conditions, before conducting a statistical analysis of the obtained indicator diagrams, it is necessary to evaluate the probability distribution law of random variables P_z^i for normality.

To test the probability distribution law of random variables P_z^i for normality, the χ^2 (chi-square) test is used

$$\chi^2 = \sum_{i=1}^{l} \left(\frac{m_i - np_i}{np_i} \right)^2, \tag{1}$$

where l is the number of intervals covering the entire axis $(-\infty; x_1)$, $(x_1; x_2)$,..., $(x_{l-1}; +\infty)$; n is the total number of measurement results ($n = m_1 + m_2 + \ldots + m_l$); m_i is the number of measurement results falling within the corresponding interval; p_i is the probability of falling within the corresponding interval under the normal probability distribution.

The probability of the maximum combustion pressure value of the i-th indicator diagram falling within the corresponding interval under the normal probability distribution is determined as

$$p_i = \Phi(t_i) - \Phi(t_{i-1}),$$

or

$$p_i = \Phi\left(\frac{P_z^i - \overline{P}_z}{s} \right) - \Phi\left(\frac{P_z^{i-1} - \overline{P}_z}{s} \right), \tag{2}$$

where $\overline{P}_z$ is the arithmetic mean of the maximum combustion pressure; P_z^i is the maximum combustion pressure of the i-th indicator diagram; s is the root mean square error (empirical standard); $\Phi(t) = \frac{1}{\sqrt{2\pi}} \int_0^t e^{-0.5t^2} \mathrm{d}t$ is the probability integral.

Before testing the probability distribution law of random variables P_z^i for normality, the measured values of maximum combustion pressure were grouped into intervals covering the entire $(-\infty; +\infty)$ axis. The number of maximum combustion pressure values in each selected interval was approximately equal. The number of intervals was $l = 8$.

The results of testing the probability distribution law of random variables P_z^i for normality using the χ^2 goodness-of-fit test are shown in Fig. 7.

The resulting χ^2 goodness-of-fit test value, even in the worst case, is significantly less than the critical value ($\chi^2 = 11.07$) with a confidence level of $P = 0.95$ and degrees of freedom of $k = l - 3 = 5$.

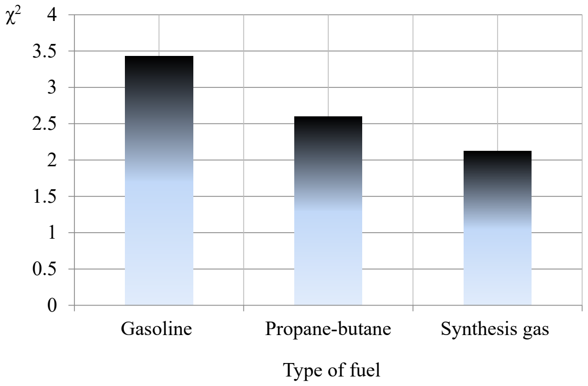

Fig. 7. Testing the probability distribution law of random variables P_z^i for normality when using different types of fuel by a 2Ch 7.2/6 engine

Furthermore, it is advisable to estimate the minimum required number of measurements of subsequent operating cycles of a 2Ch 7.2/6 engine using different types of fuel.

Since the reliability of confidence estimates and the value of the confidence interval for the true combustion pressure value directly depend on the total number of measurements n_{meas}, the minimum number of measurements required to achieve the required reliability and accuracy ε can be estimated using the following expression

$$n \geq \left[\frac{t(P)}{\varepsilon} \right]^2 \sigma^2, \tag{3}$$

where $t = t(P)$ is determined in accordance with the equality of the probability integral $2\Phi(t) = P$.

The minimum required number of measured sequential indicator diagrams of the 2Ch 7.2/6 engine using different types of fuel with a confidence level of $P = 0.95$ and a measurement accuracy of $\varepsilon = \pm 4\%$ is shown in Fig. 8.

Under the experimental conditions, the minimum number of sequentially measured indicator diagrams under all operating modes of the 2CH 7.2/6 engine was $n_{meas} = 100$.

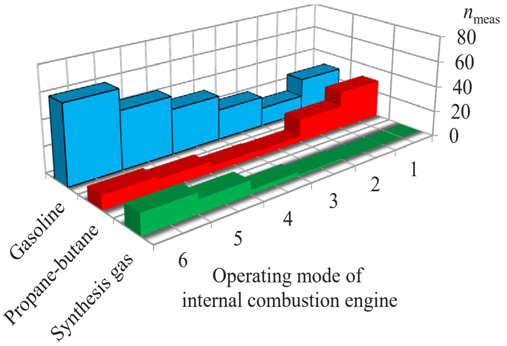

Fig. 8. The minimum required number of engine indicator diagrams for 2Ch 7.2/6 engine when using different types of fuel ($P = 0.95$; $\varepsilon = \pm 4\%$)

5. 3. Assessing the impact of the fuel used and the fuel-air mixture ratio on the degree of unevenness of the operating cycle

The degree of unevenness of the operating cycle is determined as

$$\delta = \frac{\sum_{i=1}^{n_{meas}} \left| P_z^i - \overline{P_z} \right|}{n_{meas} \overline{P_z}}. \qquad (4)$$

As a result of processing a significant number of consecutive working cycles of a 2Ch 7.2/6 spark-ignition engine operating on different types of fuel, dependences of the degree of unevenness on the composition of the fuel-air mixture were obtained (Fig. 9).

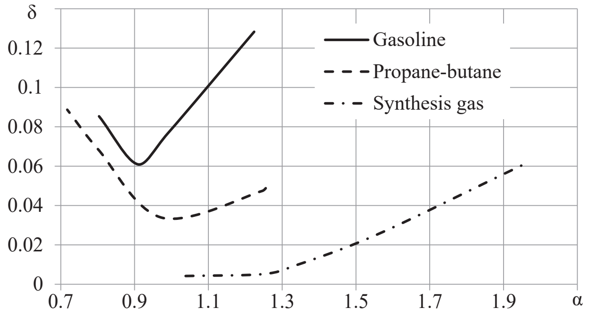

Fig. 9. Dependence of the degree of unevenness in the working cycle of the 2Ch 7.2/6 engine when operating on different types of fuel on the excess air coefficient

When the 2Ch 7.2/6 engine operates on syngas, the degree of unevenness in the operating cycle is significantly reduced. The minimum degree of unevenness in the operating cycle is in the range of $\alpha = 1.05–1.25$. As α increases (the mixture becomes leaner), the degree of unevenness in operation on syngas increases and reaches the minimum value of unevenness in operation when running on gasoline with an excess air ratio of 0.9–1.0. In fact, the greater uniformity of the engine's operating cycle when operating on syngas allows the maximum indicated efficiency to be shifted toward leaner fuel-air mixtures.

6. Discussion of results based on investigating the degree of unevenness of the engine cycle when operating on different fuels

In contrast to [1, 4, 6], in which hydrogen is considered an additive to methane, and [5, 8–10], in which it is considered an additive to gasoline, our study presents syngas as a fully-fledged alternative fuel. The results of the studies show that the excess air ratio and the presence of free hydrogen in the fuel significantly affect the operating cycle roughness of a spark-ignition engine. The presence of free hydrogen (in this case, in syngas) significantly alters the physicochemical properties of the air-fuel mixture. Compared to gasoline, the presence of 43% hydrogen by volume in syngas significantly increases the normal combustion velocity (0.96 m/s at $\alpha = 1$) and also significantly expands the ignition concentration limits of the air-fuel mixture (Fig. 5, 9).

When operating the 2Ch 7.2/6 engine on standard fuels, a significant increase in the degree of unevenness in the operating cycle is observed in the lean-mixture region. In some cases, even isolated misfires were observed during processing of the experimental diagrams. However, when operating on syngas, misfires were absent in all measurements. This is explained, first of all, by the relatively wide ignition limits of the air-fuel mixture, as well as the high values of the normal hydrogen combustion rate, which is almost an order of magnitude higher than that of other motor fuels. Furthermore, this is explained by the value of the minimum required ignition energy (0.02 MJ versus 0.26...0.28 for standard fuels).

When operating the 2Ch 7.2/6 engine on syngas, slight non-identity of subsequent operating cycles (Fig. 9) within the range of $\alpha = 1.05...1.25$ is explained, first of all, by minor deviations in the ignition spark delivery relative to the top dead center. An assessment of the minimum required number of measured sequential indicator diagrams (Fig. 8) and low δ values (Fig. 9) when operating on synthesis gas showed that when processing experimental diagrams from n_{meas}, it will be sufficient to take several of them, in which $P_z \approx \overline{P}_z$. This significantly simplifies and speeds up the process of treating a large array of engine operating cycle indexing results.

Our experimental results on the degree of unevenness in the operating cycle of a spark-ignition engine allow us to evaluate and analyze the factors influencing the variability of the operating process when operating on different fuel types. However, the study is limited by the use of only three fuel types and a constant syngas composition (especially hydrogen).

A drawback of the research results is the lack of comprehensive studies under an idle mode, which, for example, accounts for a significant portion of the operating time of an automobile internal combustion engine.

A further development of this research could be the study on the degree of unevenness in the operating cycle of an engine when syngas is added to different types of liquid and gaseous fuels, as well as similar studies on a diesel engine.

7. Conclusions

1. We have acquired experimental indicator diagrams of partial operating modes of a spark-ignition internal combustion engine (ICE) using gasoline, propane-butane, and syngas with a hydrogen content of 43% (by volume). It was found that normal engine operation on syngas is ensured with α in the range of 1.35–1.75, while a decrease to 1.25 and below leads to more severe operation.

2. It was established that the maximum combustion pressure values P_z^i of the obtained sequential experimental indicator diagrams, according to the χ^2 criterion, correspond to the law of normal distribution of random errors. Moreover, the χ^2 criterion value in the most unstable case (when operating

on gasoline with $\delta = 0.128$) was 3.427, which is 3.23 times lower than the critical value for a confidence level of 0.95 and a degree of freedom of 5.

3. It was determined that when the engine is operating on syngas, the degree of unevenness in the operating cycle is the lowest compared to the other tested fuels. Moreover, the minimum value of δ is observed in the range of $\alpha = 1.05...1.25$. As the mixture becomes leaner, δ for syngas increases and, within the range of $\alpha \approx 2$, it reaches the minimum value of unevenness in the operating cycle of the engine on gasoline with $\alpha = 0.9...1.0$.

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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The study was conducted without financial support.

Data availability

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

Use of artificial intelligence

The authors state that generative models served only as an additional tool for editing, grammar, and formatting, exclusively under human control. AI was not involved in working with scientific data, interpreting it, drawing conclusions, or creating other meaningful elements of the paper. ChatGPT (OpenAI GPT-5.3, version 2026) was used. All responsibility for the content and accuracy lies with the authors.

Authors' contributions

Oleksandr Mytrofanov: Conceptualization, Methodology, Writing – original draft, Visualization; **Arkadii Proskurin**: Validation, Formal analysis, Writing – review & editing, Project administration.

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