Analysis of Syngas Combustion Process in Piston Engines

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Abstract. The article examines the features of the combustion process of hydrogen-containing gas (syngas) in the working cylinder of a spark-ignition internal combustion engine. The main objective of the study is to evaluate the heat release parameters of syngas. To achieve this goal, an experimental investigation was conducted to assess the nature of syngas combustion and establish its regularity. The most significant result is the derivation of dependencies for determining the current value of the combustion characteristic index m and the combustion duration φz in Professor I.I.Vibe's heat release model for spark-ignition engines operating on syngas, with an air excess ratio α ranging from 1.0 to 2.2 and hydrogen content in the fuel composition varying between 30% and 100% by volume. The significance of the obtained results lies in the establishment of the variability of the combustion index m (ranging from 1.6 to 5.5) in Professor I.I.Vibe's semi-empirical heat release model, which more closely corresponds to the actual heat release law observed in experimental studies. The proposed dependencies for determining m and φz allow for accounting the specific features of the syngas combustion process in spark-ignition engines, thereby significantly improving the accuracy of determining the indicated pressure in the working cylinder (the relative root-mean-square error does not exceed 4.5%), which, in turn, enhances the accuracy of assessing the engine's energy and economic parameters. The results of this study can be applied in the design and construction of new spark-ignition engines running on alternative fuel.
Keywords**:** alternative fuel, syngas, combustion heat release characteristics, working process, combustion index, combustion duration.

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Analiza procesului de ardere a gazului de sinteză în motoarele cu piston

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Rezumat. Articolul ia în considerare caracteristicile procesului de ardere a gazului de sinteză în cilindrul de lucru al unui motor cu ardere internă cu aprindere prin scânteie. Scopul principal al studiului din lucrare este de a estima parametrii degajării de căldură a gazului de sinteză. Pentru atingerea acestui scop au fost stabilite următoarele sarcini: pe baza unor studii experimentale, să se evalueze natura modificărilor în procesul de ardere a gazului de sinteză și să se stabilească regularitatea acestuia. Rezultatul cel mai semnificativ este obținerea de dependențe pentru determinarea valorii curente a indicelui caracteristic de ardere m și a duratei de ardere φz în modelul de degajare de căldură al profesorului I.I.Vibe pentru motoarele cu aprindere prin scânteie care funcționează pe gaz de sinteză cu intervalul de variație a excesului de aer. raportul α 1,0...2,2 și conținutul de hidrogen din combustibil între 30...100 % în volum. Semnificația rezultatelor obținute constă în faptul că a fost stabilită variabilitatea indicelui de ardere m (interval de modificare 1,6...5,5) în modelul semiempiric de degajare de căldură al Prof. I.I.Vibe, ceea ce este mai în concordanță cu legea reală a degajării căldurii în studiile experimentale. Dependența propusă pentru determinarea m și φz permit luarea în considerare a particularităților procesului de ardere a gazului de sinteză în motoarele cu aprindere prin scânteie și astfel crește semnificativ precizia determinării presiunii indicatorului în cilindrul de lucru (eroarea relativă medie pătrată nu depășește 4,5 %), ceea ce afectează, la rândul său, acuratețea estimarii parametrilor de funcționare a motorului.
Cuvinte-cheie: combustibil alternativ, gaz de sinteză, caracteristici de eliberare a căldurii de ardere, proces de lucru, indice caracteristic de ardere, durata arderii.

Анализ процесса сгорания синтез-газа в поршневых двигателях

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Аннотация. В статье рассмотрены особенности процесса сгорания водородосодержащего газа (синтез-газа) в рабочем цилиндре двигателя внутреннего сгорания с искровым зажиганием. **Основной целью** исследования в работе является оценка параметров тепловыделения синтез-газа. **Для достижения** поставленной цели были поставлена задача – на базе экспериментальных исследований оценить характер изменения процесса сгорания синтез-газа и установить его закономерность. **Наиболее существенным результатом** является получение зависимостей для определения текущего значения показателя характера сгорания m и продолжительности сгорания φ_z в модели тепловыделения профессора И. И. Вибе для двигателей с искровым зажиганием, работающих на синтез-газе с диапазоном изменения коэффициенте избытка воздуха α 1.0...2.2 и содержания водорода в составе топлива в пределах 30...100 % по объему. **Значимость полученных результатов** состоит в том, что установлено переменность показателя сгорания m (диапазон изменения 1.6…5.5) в полуэмпирической модели тепловыделения профессора И. И. Вибе, что в большей степени соответствует реальному закону тепловыделения при экспериментальных исследованиях. Предложенные зависимости для определения m и φ_z позволяют учесть особенности процесса сгорания синтез-газа в двигателях с искровым зажиганием и тем самым значительно повысить точность определения индикаторного давления в рабочем цилиндре (относительная среднеквадратичная погрешность не превышает 4.5 %), что в свою очередь отображается на точности оценки энергетических и экономических параметров работы двигателя. Полученные результаты исследований могут быть использованы при проектировании и конструировании новых двигателей с искровым зажиганием, работающих на альтернативном топливе, или конвертации уже существующих, а также для уточнения математической модели процесса сгорания таких программ как Lotus engineering software, Siemens, AVL Boost, Ricardo WAVE и GT-Power.

***Ключевые слова*:** альтернативное топливо, синтез-газ, характеристики тепловыделения при сгорании, рабочий процесс, показатель характера сгорания, продолжительность сгорания.

I. INTRODUCTION

Interest in the issue of fuel economy in thermal engines is growing every year in all industrially developed countries worldwide. The use of non-renewable energy sources has several negative factors, with the most significant being economic and environmental. From an economic perspective, the cost of generating 1 kW of energy from non-renewable organic fuel increases yearly due to the depletion of reserves and the increasing complexity of extraction. From an environmental point of view, the use of non-renewable organic fuel leads to environmental pollution from the combustion products of thermal engines and various energy installations, as well as to an increase in greenhouse gases, the concentration of which in the atmosphere has been rapidly rising in recent years. These and many other factors are driving the growing popularity of alternative fuels in energy and transportation sectors.

Promising types of liquid alternative fuels include alcohols (methanol, ethanol) and biodiesel, while gaseous alternatives include hydrogen and hydrogen-containing gas (syngas) [1–6]. The use of these types of fuels in transportation energy systems with internal combustion engines (ICE) requires certain design modifications to the energy system, as well as changes in the organization of the working cycle. This is especially true for the use of hydrogen and syngas in energy systems. Despite the challenges associated with hydrogen use, its potential as a fuel for ICE is confirmed by numerous studies and implemented energy system projects [7–13].

Hydrogen possesses specific physicochemical properties that directly affect the combustion process in the cylinder of an internal combustion engine (ICE). Even small additions of hydrogen to other types of fuel significantly influence the mixture properties, the combustion process, and engine performance parameters [14–22]. In particular, hydrogen has a low density (which greatly affects the energy capacity of the fuel-air charge), a high combustion speed (100–115 m/s), wide flammability limits, and low ignition energy. These and other properties result in differences in heat release characteristics, and consequently, in its mathematical model, compared to a gasoline engine.

In Professor A. P. Marchenko's work [23], the features of the hydrogen combustion process were analyzed, and one of the methods for mathematically describing the heat release characteristics in spark-ignition ICEs was proposed. In studies [14, 17, 19, 24], the heat release characteristics of diesel engines with hydrogen additives were investigated, while in [25], syngas additives were examined.

Most existing publications and studies focus on the use of hydrogen as a fuel or its additives to the main fuel. However, the combustion process of syngas, the effect of its composition (mainly a mixture of gases such as H_2, CO, CO_2, CH_4 [26–29]), as well as the air excess ratio α on the heat release characteristics in spark-ignition engines, has not been fully explored. The available data can only be used as an initial assessment of the heat release process when modeling the working cycle of an internal combustion engine.

Thus, the aim of this study is to analyze the heat release dynamics when using hydrogen-containing gas and to develop an adequate mathematical model that takes into account the specific features of this process.

II. RESEARCH METHODS

The analysis of heat release dynamics for spark-ignition internal combustion engines operating on syngas is carried out using methods of mathematical and physical modeling. A well-organized experiment allows for obtaining a real picture of the processes occurring in the engine cylinder, while mathematical modeling significantly speeds up and reduces the cost of designing and developing a new engine. However, due to the complexity of describing the combustion process, in order to ensure the accuracy and reliability of the results obtained through mathematical modeling, the model must be supplemented with empirical dependencies and coefficients.

The research is based on the authors' own experimental results from various sizes of four-stroke spark-ignition engines – 4Ch 8.2/7 (Eastern-European Journal of Enterprise Technologies. 2018. Vol. 4/1 (94). P. 14-19.); 2Ch 7.2/6 (Internal Combustion Engines: All-Ukrainian Scientific and Technical Journal. 2011. No. 2. P. 3–8); 1Ch 6.8/5.4 (Internal Combustion Engines: All-Ukrainian Scientific and Technical Journal. 2013. No. 2. P. 13–17.), as well as known data from other authors [4, 5]. This will allow for providing more generalized recommendations regarding the description of the heat release dynamics in spark-ignition internal combustion engines operating on syngas.

Currently, a significant number of models have been developed for calculating the heat release curve. For instance, several researchers (N. V. Inozemtsev, V. K. Koshkin, N. M. Glagolev, V. I. Soroko-Novitsky, and others) propose using the flame front propagation speed to calculate the combustion rate in spark-ignition engines [30, 31]. The model is based on M. Gyu's postulate that the amount of combustible gas mixture ignited by a unit surface area of the flame front per unit time is a constant value ($V/F = const$, where V is the volumetric flow rate of the combustible mixture per unit time; F is the area of the flame front), as well as the assumption that the flame front surface has a spherical shape (experimental data indicate that the front has an irregular shape and its propagation speed is not constant across different combustion areas) [34]. It is important to note that, in reality, the combustion reaction in the working cylinder of an internal combustion engine does not conclude in a very narrow flame zone (as occurs in laminar flow); therefore, representing the flame front surface as a reaction surface leads to inaccuracies in calculating the heat release characteristics. Additionally, determining the change in the size of the reaction surface with the movement of the flame front and the normal speed of the flame front itself (which affects the mass burning rate) is also challenging [32]. Another factor influencing the accuracy of determining the heat release characteristics is the proper consideration of the effect of mixture turbulence depending on the engine's rotational speed, which poses a rather complex challenge [32–34].

Additionally, empirical and semi-empirical models developed in the 20th century (by B. M. Gonchar, B. P. Pugachev, K. Neiman, I. I. Vibe, and others) are widely used to describe the combustion process in piston engines, characterizing the change in the heat release curve in the working cylinder of an internal combustion engine (ICE) [32, 35, 36]. Such models are relatively simple to describe and universal, making them suitable for analyzing the dynamics and calculating heat release in the cylinder of spark-ignition engines operating on syngas. Among the known models, the one developed by Professor I. I. Vibe is the most widely used, in which the relative combustion rate and the fraction of burned fuel are described by the following semi-empirical relationships [30]:

$$\frac{dx}{d(\varphi)} = -C\frac{(m+1)}{\varphi_z}\left(\frac{\varphi}{\varphi_z}\right)^{m} \exp\left(C\left(\frac{\varphi}{\varphi_z}\right)^{m+1}\right);$$

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

where φ is the current crankshaft angle of the engine; φ_z is the angle of the combustion duration process; m is the empirical combustion characteristic coefficient (which defines the combustion dynamics); C is a constant ($C = \ln\left[1-x_z\right]$, x_z is the fraction of burned fuel at the end of the combustion process).

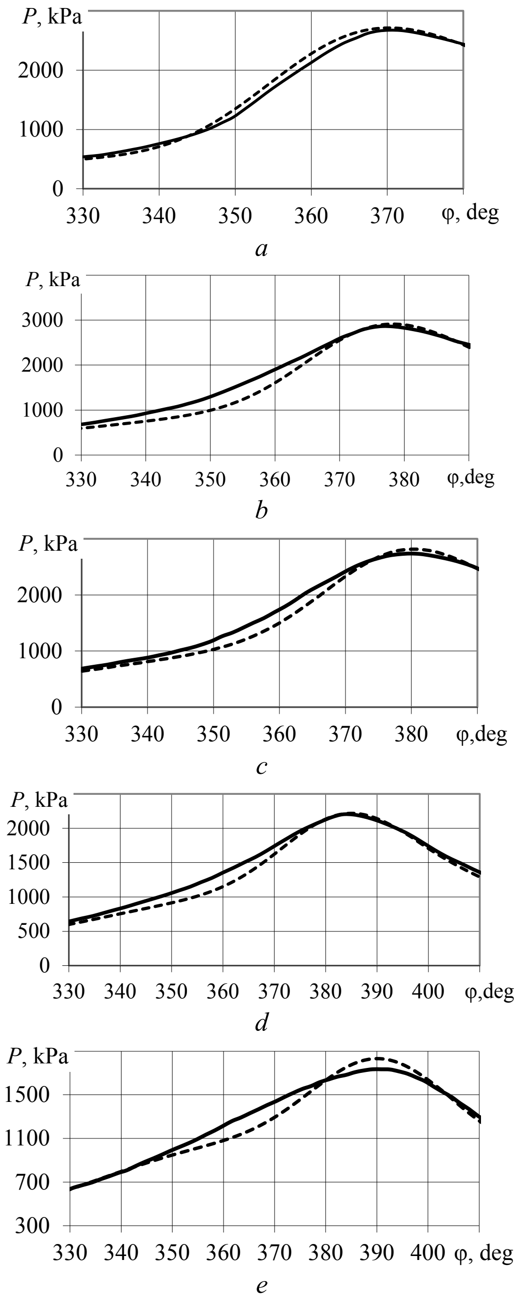
Due to its universality, simplicity, and sufficient accuracy in describing the combustion process, Professor I. I. Vibe's model has found widespread application in globally renowned commercial simulation programs such as Lotus Engineering Software [37, 38]; Siemens AMEsim [39]; AVL Boost [40]; Ricardo WAVE [41, 42]; and GT-Power [43, 44].

III. RESEARCH RESULTS

To analyze the dynamics of heat release and to construct its mathematical model for the spark-ignition internal combustion engines operating on syngas, experimental studies were conducted on various engine sizes under different operating conditions, and indicator diagrams were obtained.

To ensure the correspondence between the calculated and experimental indicator diagrams, the values of the parameters m and φ_z are selected depending on the type of engine and its operating conditions. These parameters in I. I. Vibe's model for diesel and gasoline engines are chosen from a known range and set as constant values.

In mathematical modeling, the combustion characteristic coefficient is of particular interest, as it reflects the change over time in the relative density of effective centers during the combustion process. When using syngas, applying a constant value of m leads to significant deviations between the experimental and calculated curves, which can be clearly observed, for example, when comparing experimental and calculated indicator diagrams (Fig. 1) for different operating modes of the spark-ignition engine 2Ch 7.2/6 (a two-cylinder four-stroke engine with a cylinder diameter of 72 mm and a piston stroke of 60 mm) with 43% hydrogen content by volume.



——— – experiment; - - - - – calculation

***a** – α = 1.25 (Ne=1.16 kW); **b** – α = 1.34 (Ne=1.8 kW); **c** – α = 1.49 (Ne=1.71 kW); **d** – α = 1.63 (Ne=1.87 kW); **e** – α = 1.96 (Ne=1.93 kW).*

Fig. 1. Comparison of experimental and calculated fragments of indicator diagrams corresponding to the combustion process of syngas with different values of the air excess coefficient α.

The values of the combustion characteristic coefficient and duration (in the mathematical modeling shown in Fig. 1) were selected based on achieving the minimum value of the root mean square deviation of the indicator pressure.

The maximum relative root mean square error in determining the pressure in the cylinder, depending on the air excess coefficient and the operating mode of the internal combustion engine, reached up to 12.5%, while the value of the root mean square deviation was 80.2 kPa. The confidence interval at a probability of 0.95 was ± 157.1 kPa.

The range from which the value of the coefficient m was selected was 1.6…5.5. When using the minimum values of the range, there is a coincidence of the pressure curve in the first half of combustion and a significant deviation in the second half; when using the maximum values, there is a deviation in the initial phase of combustion and a coincidence in the final phase. This means that, in fact, the combustion of syngas in the engine cylinder occurs more intensively in the initial period and less intensively in the final period, indicating that the combustion law (or relative heat release rate) is close to a triangular shape.

Thus, it can be concluded that the combustion characteristic coefficient m for engines operating on syngas has a clearly variable nature and changes in the range of 1.6…5.5 throughout the combustion of the fuel-air mixture. A solution to the problem of increasing the accuracy of the mathematical model could be the application of a variable value for the combustion characteristic coefficient m. It is also necessary to consider that the value of m depends on several factors, such as the type of fuel used, the ignition method for the fuel-air mixture, the air excess coefficient, the operating mode, and many others. For spark-ignition engines running on syngas, the factors determining the dynamics of heat release are the air excess coefficient α and the gas composition (primarily the hydrogen content, which has a high combustion speed). Therefore, when developing a mathematical model, the influence of these factors must be taken into account.

Based on the analysis and processing of a significant number of experimental indicator diagrams from different engines operating on syngas with a hydrogen content of 30...100% by volume, it is proposed to use the equation of a straight line to find the variable value of m during combustion (Fig. 2):

$$m_i = a \cdot \varphi_i \cdot \frac{\varphi_z'}{\varphi_z} + b \, ;$$

where φ_i is the current value of the combustion period angle; a and b are coefficients of the straight line equation, which depend on the air excess coefficient α (for the range of 1.0...2.2):

$$a = 0.2532 \cdot \alpha^3 - 1.2593 \cdot \alpha^2 + 2.0906 \cdot \alpha - 1.1149 \, ;$$
$$b = 0.659 \cdot \alpha^3 - 3.4831 \cdot \alpha^2 + 6.3403 \cdot \alpha - 2.1937 \, .$$

To determine the duration of combustion φ_z in the model of I.I. Vibe based on experimental data for various hydrogen concentration values, the following equations are proposed:

$$\varphi_z = \varphi_z' + \Delta\varphi \, ;$$
$$\varphi_z' = -10.186 \cdot \alpha^2 + 59.464 \cdot \alpha - 4.1447 \, ;$$
$$\Delta\varphi = -434.6 \cdot C_{H_2}^3 + 1080.2 \cdot C_{H_2}^2 - 907.85 \cdot C_{H_2} + 225.19$$

where C_{H_2} is the hydrogen concentration in the composition of syngas (hydrogen content for the range of 30...100% by volume).

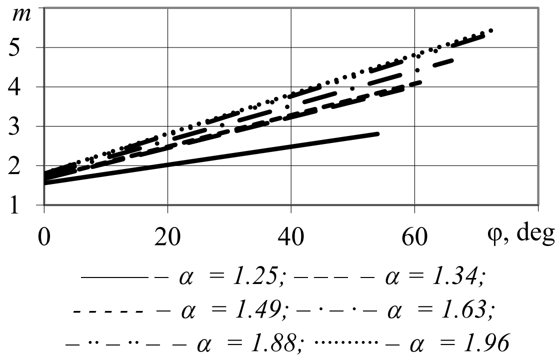
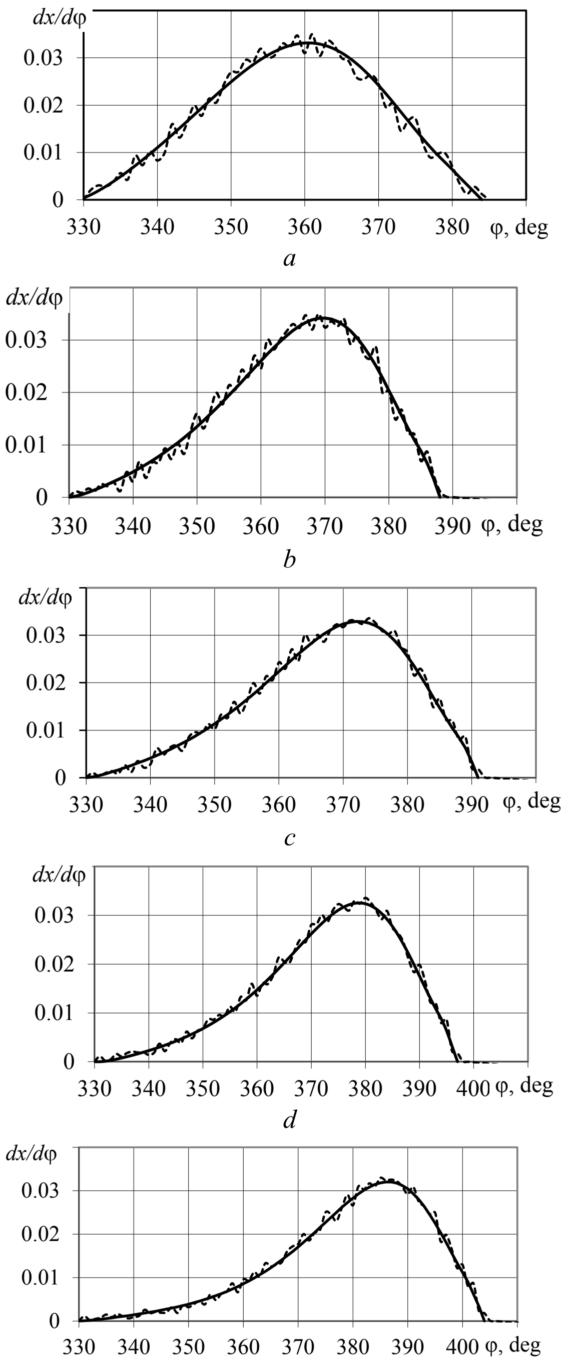


Fig. 2. Change in the combustion characteristic indicator m during combustion at different values of the air excess coefficient.

Based on the obtained equations for determining m and φ_z, the dimensionless combustion rate for spark-ignition engines running on syngas is defined as follows:

$$\frac{dx}{d\varphi} = -\frac{C}{\varphi_z}\left(\frac{\varphi_i}{\varphi_z}\right)^{a\varphi_i + b} \cdot \exp C\left(\frac{\varphi_i}{\varphi_z}\right)^{a\varphi_i + b + 1} \cdot$$
$$\cdot \left(a\varphi_i \ln\left(\frac{\varphi_i}{\varphi_z}\right) + a\varphi_i + b + 1 \right)$$

The adequacy check of the proposed model for the heat release process can be performed by comparing the experimental characteristics of the relative combustion rate with the calculated values, using the example of the engine 2Ch 7.2/6 (Fig. 3).



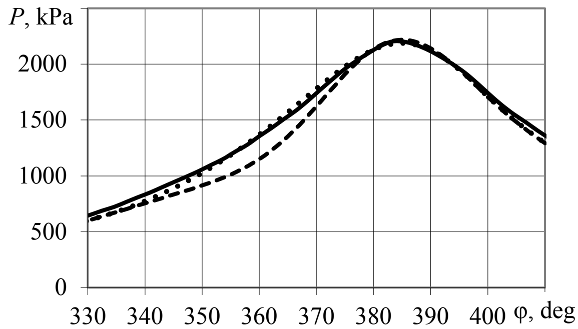
––––– – *calculation;* - - - - - - – *experiment*

a **– α = 1.25 (N_e=1.16 kW);** ***b*** **– α = 1.34 (N_e=1.8 kW);** ***c*** **– α = 1.49 (N_e=1.71 kW);** ***d*** **– α = 1.63 (N_e=1.87 kW);** ***e*** **– α = 1.96 (N_e=1.93 kW).**

Fig. 3. Comparison of experimental and calculated relative combustion rate characteristics when using syngas with different values of the air excess coefficient α

The use of a variable combustion characteristic indicator *m* and the consideration of the influence of the air excess coefficient, as well as the hydrogen content in the syngas, has led to a high correlation between the experimental and calculated curves of the relative combustion rate of the fuel-air mixture.

This, in turn, results in a more accurate match of the indicator pressure in the working cylinder of the 2Ch 7.2/6 engine (Fig. 4).



––––– – *experiment;* - - - - – *calculation at m = const;* ········ – *calculation at m = var*

Fig. 4. Comparison of experimental and calculated fragments of indicator diagrams corresponding to the combustion process of syngas with an air excess coefficient of α = 1.63 (Ne=1.87 kW).

When using the proposed relationships, the maximum relative root mean square error in determining the indicator pressure in the cylinder decreases to 4.5%, the maximum value of the root mean square deviation is 27.6 kPa, and the confidence interval with a probability of 0.95 does not exceed ± 54 kPa.

IV. CONCLUSION

The assessment of the heat release parameters when using synthesis gas in spark-ignition engines allowed for an evaluation of the nature of the combustion process and established its variable regularity (intense combustion at the beginning of the process and slowed down at the end). It was found that for spark-ignition engines operating on synthesis gas, the combustion characteristic parameter *m* in the semi-empirical heat release model of Professor I. I. Vibe exhibits variable behavior, which aligns more closely with the actual law of heat release in experimental studies.

Experimental research and mathematical modeling of various engine sizes enabled the determination of the possible range of variation for the combustion characteristic parameter m in Professor I. I. Vibe's model, which is 1.6 to 5.5.

Dependencies have been obtained to determine the current values of m and the duration of combustion φ_z for engines operating on synthesis gas with a range of air excess coefficients from 1.0 to 2.2 and varying hydrogen content in the fuel composition from 30% to 100% by volume.

Considering the specifics of the combustion process of synthesis gas in spark-ignition engines significantly improved the accuracy of determining the indicator pressure in the cylinder (the relative root mean square error was 4.5%), thereby enabling an adequate assessment of the energy and economic parameters of engine operation.

Based on the presented results, a promising direction for further deeper theoretical and experimental research is the study of heat release dynamics in engines operating with various additives of synthesis gas to the main fuels – gasoline, diesel, alcohol fuels, and gas.

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