Improving the Efficiency of an Energy System with an Internal Combustion Engine Using a Solid Oxide Fuel Cell

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Abstract. This paper explores the possibility of using a solid oxide fuel cell as part of an energy system with an internal combustion engine running on bioethanol, incorporating thermochemical waste gas heat recovery. The main goal of the research is to determine the efficiency of energy conversion in energy systems with deep waste gas heat recovery. To achieve this goal, the following tasks were set: based on experimental studies of a spark-ignition engine running on bioethanol, determine the parameters of the process for synthesizing gas through thermochemical conversion; theoretically investigate the efficiency of using a solid oxide fuel cell in combination with a bioethanol thermochemical conversion reactor. The most significant result is the determination of the volt-ampere characteristic of the solid oxide fuel cell and the identification of the potential heat recovery capacity of the internal combustion engine exhaust gases through deep heat recovery. The significance of the obtained results lies in the theoretical and experimental validation of efficient energy conversion of synthesis gas in a solid oxide fuel cell, achieving a high thermodynamic efficiency of the cell (0.95–0.75). The proposed energy system configuration, based on an internal combustion engine running on bioethanol with thermochemical waste heat recovery, allows for a 6.5% increase in the overall system power output. This contributes to reduced fuel consumption and improved environmental performance. The research findings can be applied in the design and development of highly efficient energy systems with internal combustion engines for various applications.
***Keywords*:** solid oxide fuel cell, internal combustion engine, energy system, alternative fuel, synthesis gas, heat recovery.

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Îmbunătățirea eficienței unei centrale electrice cu un motor cu ardere internă prin utilizarea unei celule de combustibil cu oxid solid

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***Rezumat*.** Această lucrare explorează posibilitatea utilizării unei celule de combustibil cu oxid solid ca parte a unui sistem energetic cu un motor cu ardere internă care funcționează pe bioetanol, care încorporează recuperarea termochimică a căldurii gazelor reziduale. Scopul principal al cercetării este de a determina eficiența conversiei energiei în sistemele energetice cu recuperare adâncă a căldurii gazelor reziduale. Pentru atingerea acestui scop, au fost stabilite următoarele sarcini: pe baza studiilor experimentale ale unui motor cu aprindere prin scânteie care funcționează pe bioetanol, determinarea parametrilor procesului de sintetizare a gazului prin conversie termochimică; teoretic investigați eficiența utilizării unei celule de combustie cu oxid solid în combinație cu un reactor de conversie termochimică a bioetanolului. Rezultatul cel mai semnificativ este determinarea caracteristicii volt-amperi a celulei de combustie cu oxid solid și identificarea capacității potențiale de recuperare a căldurii a gazelor de eșapament ale motorului cu ardere internă prin recuperarea profundă a căldurii. Semnificația rezultatelor obținute constă în validarea teoretică și experimentală a conversiei eficiente a energiei gazului de sinteză într-o pilă de combustie cu oxid solid, realizând o eficiență termodinamică ridicată a celulei (0,95–0,75). Configurația propusă a sistemului energetic, bazată pe un motor cu ardere internă care funcționează cu bioetanol cu recuperare termochimică a căldurii reziduale, permite o creștere cu 6,5% a puterii totale a sistemului. Acest lucru contribuie la reducerea consumului de combustibil și la îmbunătățirea performanței de mediu. Rezultatele cercetării pot fi aplicate în proiectarea și dezvoltarea de sisteme energetice extrem de eficiente cu motoare cu ardere internă pentru diverse aplicații.

***Cuvinte-cheie*: celulă de combustie cu oxid solid, motor cu ardere internă, centrală electrică, combustibil alternativ, gaz de sinteză, utilizarea căldurii.**

Повышение эффективности энергоустановки с двигателем внутреннего сгорания путем применения твердооксидного топливного элемента

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Аннотация. В статье рассмотрена возможность применения твердооксидного топливного элемента в составе энергетической установки с двигателем внутреннего сгорания, работающим на биоэтаноле с термохимической утилизацией тепла отходящих газов. Основной целью исследования является определение эффективности энергопреобразования в энергетических установках с глубокой утилизацией тепла отходящих газов. Для достижения цели поставлены следующие задачи: на базе экспериментальных исследований двигателя с искровым зажиганием, работающего на биоэтаноле определить параметры процесса получение синтез-газа термохимическим преобразованием; теоретически исследовать эффективность применения твердооксидного топливного элемента в комплексе с реактором термохимической конверсии биоэтанола. В процессе исследований были подробно рассмотрены различные режимы работы двигателя, а также проведен детальный анализ температуры отходящих газов и синтез-газа, полученного в реакторе конверсии. Наиболее существенным результатом является получение вольтамперной характеристики твердооксидного топливного элемента и установление возможной величины утилизации тепла отходящих газов двигателя внутреннего сгорания за счёт глубокой утилизации. Установлено, что температура синтез-газа достаточна для эффективной работы топливного элемента без необходимости дополнительного подогрева, что является важным фактором повышения общей энергетической эффективности системы. Значимость полученных результатов состоит в теоретическом и экспериментальном обосновании эффективного энергопреобразования синтез-газа в твердооксидном топливном элементе с достижением высокого термодинамического КПД элемента (0,95...0,75). Предложенная схема энергетической установки на базе ДВС, работающей на биоэтаноле с термохимической утилизацией тепла отходящих газов, позволяет увеличить общую мощность энергоустановки на 6,5 %, что способствует снижению расхода топлива и повышению экологичности. Полученные результаты исследований могут быть использованы при проектировании и конструировании высокоэффективных энергетических установок с двигателями внутреннего сгорания различного целевого назначения, включая стационарные и транспортные применения, что демонстрирует широкие перспективы их использования.

***Ключевые слова*:** твердооксидный топливный элемент, двигатель внутреннего сгорания, энергетическая установка, альтернативное топливо, синтез-газ, утилизация тепла.

I. INTRODUCTION

Currently, there is a strong global trend toward research in the development and application of fuel cells [1–3].

Fuel cells enable the conversion of the energy contained in fuel into electrical and, partially, thermal energy, bypassing the combustion process.

The interest in fuel cells is primarily driven by several advantages, including high energy conversion efficiency and environmental friendliness, the ability to use various types of fuel (methane, hydrogen, synthesis gas, alcohols), modular design, silent operation, and more. Among the wide variety of existing fuel cells, solid oxide fuel cells (SOFCs) stand out as particularly promising.

This type of fuel cell offers several advantages over other types.

Notably, SOFCs do not require an expensive platinum-based catalyst and can utilize any hydrocarbon fuel that has undergone gasification (conversion into a combustible hydrogen-containing gas) [4–7].

Recently, there has been a growing trend toward integrating fuel cells into energy systems with heat engines. Since SOFCs operate at high temperatures and their exhaust gases have significant energy potential, several researchers have proposed developing combined power systems based on gas and steam turbines [8–10]. Such combined energy systems can achieve relatively high efficiency levels of 58–68% [11–13].

Research is also being conducted on the use of SOFCs in energy systems with internal combustion engines (ICEs) [14–18]. These combined energy systems with ICEs can also achieve high efficiency levels of up to 60% or more [19–22].

One of the promising directions for SOFC application is their use in marine power systems [5, 17, 23]. In particular, study [17] proposes employing SOFCs for electricity generation on large ocean-going vessels, with the anode gas (the gas exiting the fuel cell) being utilized in a spark-ignition gas engine for additional power generation. The study demonstrated that this energy system configuration increases efficiency by 8.3% compared to a conventional marine engine running on natural gas [17]. Furthermore, integrating SOFCs into marine power systems significantly reduces emissions of harmful pollutants and greenhouse gases from ICE exhaust gases, with NOx emissions reduced by 30% and CO_2 emissions by 12% [17].

Methanol [14] and methane [17] are the primary feedstocks used for fuel cells in energy systems with internal combustion engines. Thus, there is particular interest in research focused on the use of alternative fuels, specifically bioethanol, which has a widely available raw material base and is considered a promising alternative fuel for spark-ignition internal combustion engines.

Based on this, research on the application of fuel cells in energy systems with internal combustion engines running on bioethanol, incorporating thermochemical waste heat recovery, is both relevant and promising. The objective of this study is to analyze the efficiency of energy conversion in such systems.

II. RESEARCH METHODS

The analysis of energy conversion efficiency in a spark-ignition internal combustion engine (ICE) system operating on bioethanol with thermochemical waste heat recovery and an SOFC is carried out using mathematical and physical modeling methods.

The data used in this study, related to the thermochemical waste heat recovery of ICE exhaust gases and the production of hydrogen-rich synthesis gas in a conversion reactor, are based on the results of long-term experimental research, which have been published in numerous scientific articles. (Examples include: Characteristics of an Experimental Bioethanol Conversion System for the 2Ch 7.2/6 ICE]. *Dvigateli vnutrennego sgoraniya*, 2013, Analysis of the Piston Engine Operation on Ethanol with Synthesis-Gas Additives. *Eastern-European Journal of Enterprise Technologies*, 2018, Determining the Influence of Synthesis Gas Additives on the Environmental Performance of an Internal Combustion Engine. Mathematical modeling was used in this study to determine the characteristics and operational parameters of the SOFC.

Mathematical modeling is one of the key components in the design of SOFCs.

The processes occurring in the fuel cell, taking into account various factors (such as the geometry of the fuel cell surface, flow directions, internal transformations, etc.), are well described in the existing literature [24–31]. Most of the studies focus on steady-state models of SOFCs, though some authors also address dynamic models [32–36].

Conditionally, the mathematical model of an SOFC can be represented as mass and energy balances, as well as a model of electrochemical processes that links the composition and temperature of the fuel and oxidizer streams with the output voltage and current density.

When using synthesis gas in an SOFC, the main total current-generating reactions will be:

$$2H_2 + O_2 = 2H_2O\ ;$$
$$2CO + O_2 = 2CO_2\ ,$$

The voltage generated by the SOFC can be represented as [14, 32, 39]:

$$U = E - \left(\eta_{Ohm} + \eta_{conc} + \eta_{act}\right);$$

where E – is the electromotive force of the reaction in the SOFC; η_{Ohm} – is the ohmic losses; η_{conc} – is the concentration losses (resulting from the formation of concentration gradients of reactants in the reaction zone and supply channels); η_{act} – is the activation losses (reflecting the kinetics of the electrochemical reaction and described by the Butler-Volmer equation).

The electromotive force of the reaction in the fuel cell, taking into account the local temperature and partial pressure, is determined through the Nernst equation [32, 37–39]:

$$E = E_0 - \frac{T \cdot R_\mu}{n \cdot F} \ln\left(\frac{p_{H_2O}}{p_{O_2}^{0,5} \cdot p_{H_2}}\right);$$

where E_0 – is the standard EMF, V; R_μ – is the universal gas constant (8.314 J/(mol·K)); T – is the reaction temperature, K; F – is Faraday's constant (F = 96 485 C·mol⁻ ¹); p_{H_2O} , $p_{O_2}^{0,5}$, p_{H_2} – are the partial pressures, Pa; n – is the number of electrons involved in the reaction.

Ohmic losses η_{Ohm} in the fuel cell are primarily related to the resistance of ion and electron conductivity, as well as the contact resistance of the fuel cell components.

Since the ion flow in the fuel cell electrolyte and the electron flow in the electrodes essentially obey Ohm's law, the ohmic losses of the SOFC can be represented as [14, 32, 39]:

$$\eta_{Ohm} = jR_{Ohm} \ ;$$

where j – is the current density, A/m²; R_{Ohm} – is the internal resistance of the fuel cell (including both ionic and electronic resistances), Ω·m².

The internal resistance can be determined by measuring the resistance of the fuel cell or, with certain assumptions (neglecting contact resistances), theoretically (by knowing the distance between the elements and the conductance values) using the following formula [14, 32, 40]:

$$R_{Ohm} = \frac{\tau_{anode}}{\sigma_{anode}} + \frac{\tau_{electrolyte}}{\sigma_{electrolyte}} + \frac{\tau_{cathode}}{\sigma_{cathode}} \ ;$$

where $\tau_{cathode}$, τ_{anode} , $\tau_{electrolyte}$ – are the thicknesses of the cathode, anode, and electrolyte, respectively; $\sigma_{cathode}$, σ_{anode} – are the specific electronic conductivities of the cathode and anode, respectively; $\sigma_{electrolyte}$ – is the ionic conductivity of the electrolyte [40].

Concentration losses occur when the supply of reactant components and the removal of products from the reaction zone happen too slowly and do not match the given current density. Concentration losses can be estimated as follows [14, 32, 41–43]:

$$\eta_{conc} = \eta_{conc}^{anode} + \eta_{conc}^{cathode} \ ;$$

$$\eta_{conc}^{anode} = \frac{T \cdot R_\mu}{n \cdot F} \ln\left(\frac{p_{H_2O}^{TPB} \cdot p_{H_2}^{f}}{p_{H_2O}^{f} \cdot p_{H_2}^{TPB}}\right);$$

$$\eta_{conc}^{cathode} = \frac{T \cdot R_\mu}{n \cdot F} \ln\left(\frac{p_{O_2}^{a}}{p_{O_2}^{TPB}}\right);$$

where $p_{\mathrm{H_2}O}^{TPB}$, $p_{\mathrm{H_2}O}^{f}$, $p_{\mathrm{H_2}}^{f}$, $p_{\mathrm{H_2}}^{TPB}$, $p_{O_2}^{a}$, $p_{O_2}^{TPB}$ – are the partial pressures of the components at the three-phase boundaries.

Activation losses are significantly influenced by temperature. At high temperatures, the electrode reactions occur quickly, resulting in minimal activation losses, whereas lower temperatures lead to an increase in these losses and, consequently, a decrease in voltage.

Activation losses, reflecting the kinetics of the electrochemical reaction, can be estimated using the Butler-Volmer equation [14, 32, 39]:

$$j = j_0^{electrode}\left[\begin{array}{l}\exp\left(\dfrac{\alpha \cdot n \cdot F}{T \cdot R_\mu}\eta_{act}^{electrode}\right) - \ldots \\ \ldots \exp\left(-\dfrac{(1-\alpha)\cdot n \cdot F}{T \cdot R_\mu}\eta_{act}^{electrode}\right)\end{array}\right]$$

$$j_0^{electrode} = \frac{T \cdot R_\mu}{n \cdot F} k^{electrode} \exp\left(\frac{E^{electrode}}{T \cdot R_\mu}\right);$$

where $j_0^{electrode}$ – is the current exchange density; α – is the charge transfer coefficient; n – is the number of electrons transferred in one elementary step of the reaction; $k^{electrode}$ – is the pre-exponential factor of the current exchange density; $E^{electrode}$ – is the activation energy of the current exchange density.

III. RESEARCH RESULTS

To evaluate the efficiency of using a solid oxide fuel cell in an energy system with an internal combustion engine, experimental studies were conducted on the operation of a 1Ch 6.8/5.4 engine (gasoline power station with the factory marking TE 200) with spark ignition, operating on bioethanol. This is a four-stroke gasoline engine that drives an electric current generator. The main characteristics of the engine are presented in Table 1.

Table 1

№ п/п	Parameter	Value
1	Number of cylinders	1
2	Displacement, cm³	196
3	Cylinder diameter, mm	68
4	Stroke length, mm	54
5	Compression ratio	8,5
6	Rotational speed, rpm	3000
7	Effective power, kW	4,8
8	Specific effective fuel consumption, kg/(kW·h)	0,412

The experimental energy system is equipped with a thermochemical conversion reactor (Mytrofanov O., Poznanskyi A., Proskurin A., Shabalin Yu. Research into the Recovery of

Exhaust Gases from ICE Using an Expansion Machine and Fuel Conversion), which allows the recovery of exhaust gas heat from the ICE to produce synthesis gas for the fuel cell.

The average operating temperature of SOFCs is 800–1000 °C; however, recently there has been a global trend towards lowering the operating temperature to nearly 500 °C. These types of fuel cells are called medium-temperature fuel cells (operating range 500–700 °C) [14, 44]. This temperature reduction allows the use of SOFCs in energy systems with internal combustion engines without additional heating of the components before the fuel cell or with partial heating using the exhaust gas from the fuel cell combustion (Fig. 1).

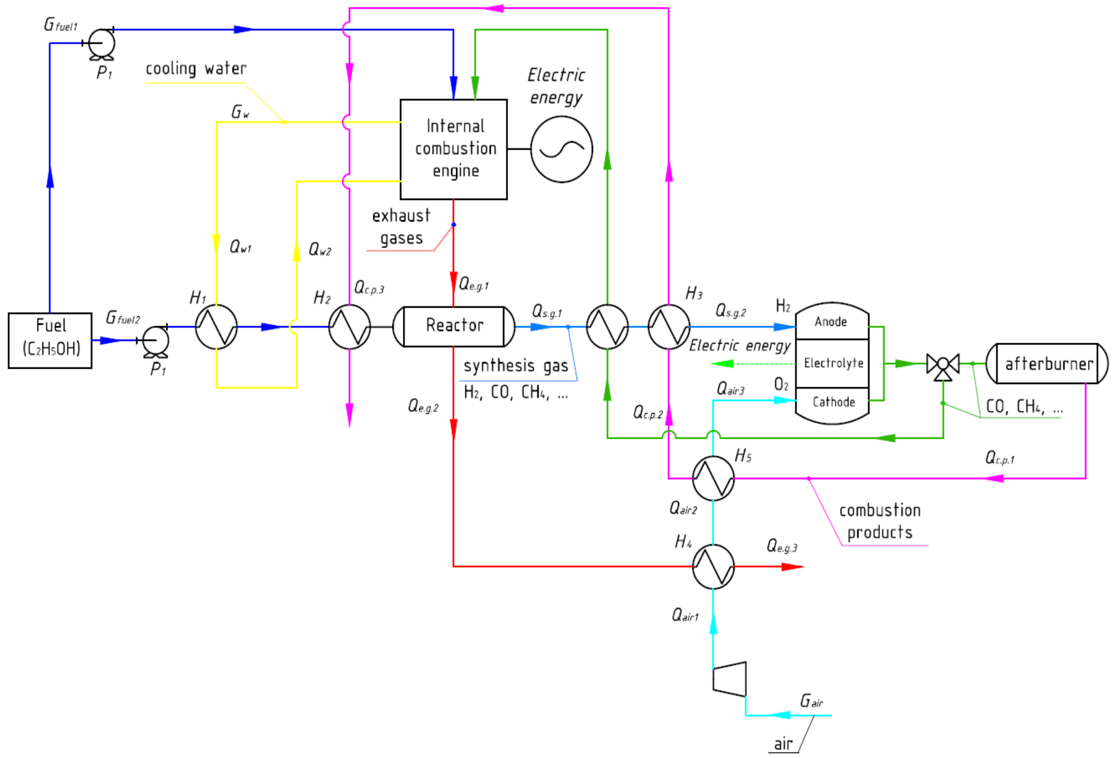


Fig. 1. Schematic diagram of an energy system based on an internal combustion engine with spark ignition and a deep exhaust gas heat recovery system.

Experimental studies showed that the exhaust gas temperature at the outlet of the combustion chamber of the internal combustion engine with spark ignition, depending on the load, ranges from 688 to 800 °C, which is sufficient for bioethanol conversion in the reactor (Fig. 2).

At the same time, the synthesis gas obtained from the bioethanol conversion in the thermochemical reactor has a sufficiently high temperature of 552–673 °C (Fig. 3). This temperature level is adequate for the effective operation of medium-temperature SOFCs. If an increase in the operating temperature of the fuel cell is required, the energy system with the internal combustion engine can be supplemented with a post-combustion unit (Fig. 1), in which additional energy will be generated through the combustion of residual synthesis gas.

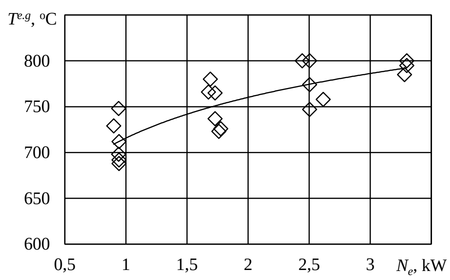


Fig. 2. Dependence of exhaust gas temperature on the load mode of the internal combustion engine.

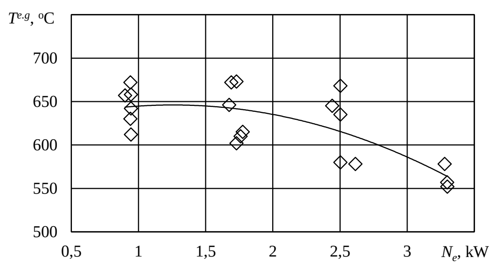
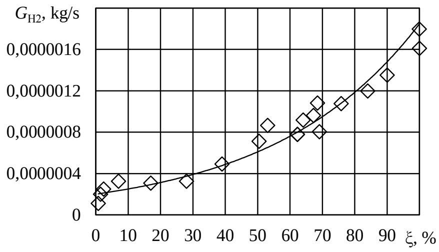
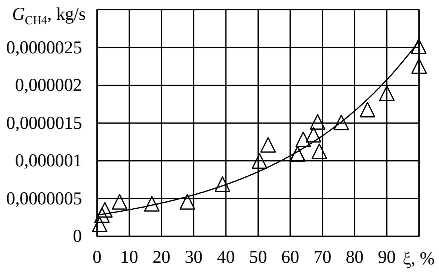


Fig. 3. Dependence of synthesis gas temperature at the reactor outlet on the load mode of the internal combustion engine.

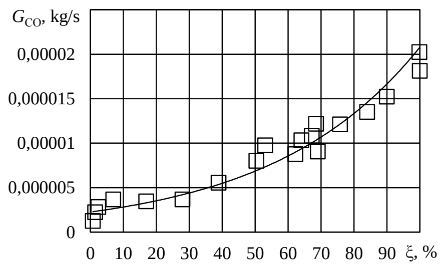
The composition of the synthesis gas obtained in the thermochemical conversion reactor is as follows: 43 % H_2, 34 % CO, 23 % CH_4 by volume. Fig. 4 shows the experimentally obtained flow rates of the synthesis gas components as a function of the conversion degree.



a



b



c

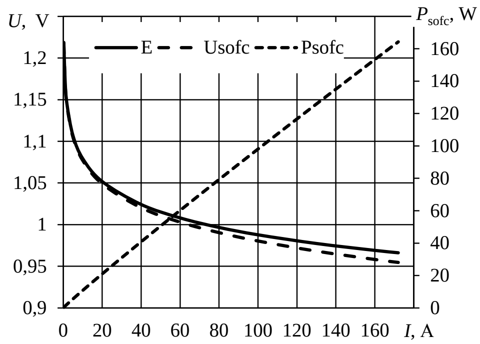
a **–** H_2 **;** ***b*** **–** CH_4 **;** ***c*** **–** CO **.**

Fig. 4. Mass flow rate of synthesis gas components as a function of the conversion degree in the thermochemical reactor.

The main parameters of the solid oxide fuel cell used in the analysis of energy conversion efficiency were taken from existing literature sources [26, 28, 29, 31, 32, 37].

Figure 5 shows the calculated volt-ampere characteristic of the fuel cell at the maximum hydrogen flow rate (G_{H_2} = 1,798·10^{-6} kg/s), which corresponds to the complete conversion of bioethanol in the thermochemical reactor. The operating temperature of the synthesis gas at the fuel cell inlet was 923 K (without additional heating). The maximum power of the SOFC under these conditions is P_{SOFC} = 164,3 W at a voltage of U_{SOFC} = 0,955 V (the EMF of the fuel cell is E = 0,966 V). The total voltage losses in the fuel cell range from 0.0016 to 0.01157 V.

The theoretical dependence of the thermodynamic efficiency of the SOFC on the current is shown in Fig. 6. The thermodynamic efficiency varies in the range of 0.95 to 0.75.



——— – EMF (Electromotive Force); - - - - – Voltage of the SOFC; ········ – Power of the SOFC

Fig. 5. Volt-ampere characteristic of the fuel cell.

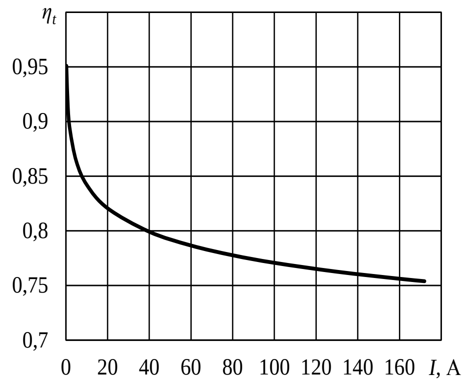
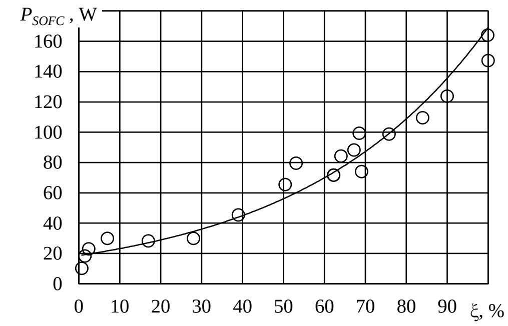


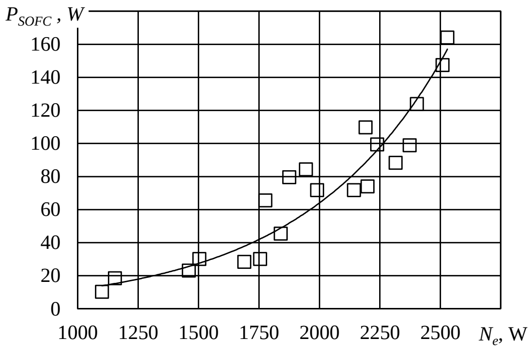
Fig. 6. Thermodynamic efficiency of the SOFC.

The power of the SOFC (Fig. 7, a) directly depends on the efficiency of the thermochemical conversion reactor of bioethanol (conversion degree) and, accordingly, on the load of the internal combustion engine (ICE) (Fig. 7, b). The power range of the SOFC in such an energy system varies from 10.2 to 164.3 W.

The data shown in Fig. 7 are the results of mathematical modeling of the output power of the SOFC for different experimentally obtained modes of combined operation of the thermochemical reactor and the ICE.



a



b

a – depending on the conversion degree of bioethanol in the thermochemical conversion reactor; b – depending on the ICE load.

Fig. 7. Output power of the SOFC.

The application of SOFCs in an energy system based on ICEs running on bioethanol with thermochemical heat recovery of exhaust gases allows for an overall increase in electrical power from 1.6% to 6.5%, depending on the load mode. Unused components of the synthesis gas (methane and carbon monoxide) that are not utilized in the fuel cell are directed to the ICE, which also contributes to the reduction of the specific effective fuel consumption by the engine itself.

IV. CONCLUSION

The analysis of the potential application of a solid oxide fuel cell (SOFC) in an energy system based on an internal combustion engine (ICE) running on bioethanol with thermochemical waste heat recovery has allowed for the assessment of changes in energy conversion and its efficiency.

Experimental studies and mathematical modeling have established that:

– the temperature of the synthesis gas, obtained through bioethanol conversion in the thermochemical reactor, is sufficient for the effective operation of medium-temperature SOFCs and ranges from 825 to 946 K;

– the maximum power of the SOFC at a hydrogen flow rate of $1.798 \cdot 10^{-6}$ kg/s and a working temperature of 923 K is 164.3 W;

– the EMF at maximum load of the SOFC is 0.966 V, while the voltage considering all losses is 0.955 V;

– the increase in the total power of the energy system due to deep waste heat recovery from the ICE's exhaust gases is up to 6.5%.

Based on the obtained results, it can be concluded that further in-depth theoretical and experimental research into the application of fuel cells in energy systems with internal combustion engines (ICEs), running on both fossil and alternative fuels, is promising.

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