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Thermolift oil recovery technologies stimulated with a resource-saving energy system

Technologie wydobycia ropy naftowej Thermolift, w których stosowany jest system energetyczny pozwalający na oszczędne wykorzystanie zasobów

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ABSTRACT: In this article, the creation of a thermal lift technology for oil wells through the use of installations with a solid oxide fuel cell has been discussed. The necessary calculations were carried out to determine the level of thermal activity in wells producing hydrocarbon resources of various compositions. Arrangements necessary to achieve this thermal activity based on solid oxide fuel cells (SOFCs) are proposed. SOFC metric characteristics are proposed that are compatible with their additional phenomena, namely, material support, shape, etc. The threshold value of the operating thermal characteristic of SOFCs is obtained depending on the structural and physical properties of their material support. The most effective ways for determination of the required thermobaric parameters of the fluid in accordance with the formation area and product, development of a resource-saving complex for the production of percussion fluid in accordance with these parameters, determination of processing periodicity to manage the thermobaric condition of the formation area, assessment of impact on the formation area and other factors generalise them. The purpose of the article is to develop a technology for management the thermobaric condition of the area through alternative resource-saving energy systems (development of Thermolift technology), substantiation of operational parameters and creation of surface equipment. The scientific idea of the presented article significantly increases the mobility of their hydrocarbon reserves on the basis of the thermobaric action of working agents, which are the product of a resource-saving surface complex (i.e. by providing Thermolift technology) and, finally increases the operational efficiency of production wells and, as a result, the production capacity of the reservoirs.

Key words: well, thermal lift, thermal activity, electrochemical generator, metric characteristic, threshold value, compatibility, electrophysical phenomena, material support.

STRESZCZENIE: W niniejszym artykule omówiono powstanie technologii wyporu termicznego dla odwiertów ropnych przez zastosowanie instalacji z ogniwem paliwowym ze stałym tlenkiem. Przeprowadzono wymagane obliczenia w celu ustalenia poziomu aktywności termicznej w odwiertach eksploatujących zasoby węglowodorów o różnym składzie ropy naftowej. Zaproponowano układy niezbędne do osiągnięcia tej aktywności termicznej oparte na ogniwach paliwowych ze stałym tlenkiem (SOFC). Zaproponowano takie parametry wskaźników SOFC, które są zgodne z ich dodatkowymi cechami, takimi jak rodzaj zastosowanego materiału, kształt itd. Wartość progowa eksploatacyjnej charakterystyki termicznej SOFC uzależniona jest od właściwości strukturalnych i fizycznych zastosowanego do ich konstrukcji materiału. Związane jest to z najbardziej efektywnymi sposobami określenia wymaganych parametrów temperaturowo-ciśnieniowych eksploatowanego płynu w zależności od obszaru występowania formacji i produktu, opracowaniem bezpiecznego dla zasobów systemu produkcji płynu udarowego zgodnego z tymi parametrami, określeniem częstotliwości przetwarzania w celu zarządzania warunkami temperaturowo-ciśnieniowymi w obrębie formacji, czy też oceną oddziaływania w obszarze występowania formacji. Celem artykułu jest przedstawienie opracowanej technologii do zarządzania warunkami temperaturowo-ciśnieniowymi obszaru złoża wykorzystującej alternatywne, pozwalające na oszczędne wykorzystanie zasobów, systemy energetyczne (technologia Thermolift), wraz z uzasadnieniem parametrów eksploatacyjnych i przedstawieniem osprzętu powierzchniowego. Naukową ideą niniejszego artykułu jest znaczące zwiększenie zakresu mobilności dostępnych zasobów węglowodorów dzięki temperaturowo-ciśnieniowemu działaniu czynników roboczych będących produktem systemu powierzchniowego pozwalającego na bardziej ekonomiczne wykorzystanie zasobów (tj. poprzez dostarczenie technologii Thermolift), a finalnie – zwiększenie wydajności operacyjnej odwiertów eksploatacyjnych, prowadzące w efekcie do wzrostu wydajności produkcyjnej złóż ropy naftowej.

Słowa kluczowe: odwiert, wypór termiczny, aktywność termiczna, generator elektrochemiczny, cechy wskaźników, wartość progowa, kompatybilność, zjawiska elektrofizyczne, wsparcie materiałowe.

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Introduction

Development of new technologies has become decisive for profit-making recovery of unconventional resources, such as heavy and ultra-heavy oil (Konoplev et al., 2002).

Hard-to-recover reserves account for more than 70% (Figure 1) of the wold's total reserves (Williams, 2003; Xin et al., 2017). Therefore, any work aimed at developing such reserves can and should be recognised as relevant in the fuel and energy sector.

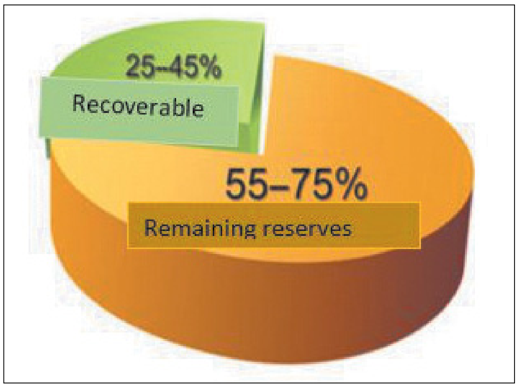

Figure 1. The ratio of residual and recoverable oil reserves

Rysunek 2. Stosunek zasobów ropy naftowej pozostających w złożu do zasobów wydobywalnych

To restore minerals with hard-to-recover reserves, various physical-chemical and mechanical-thermal methods are used, taking into account efficiency (Figure 2).

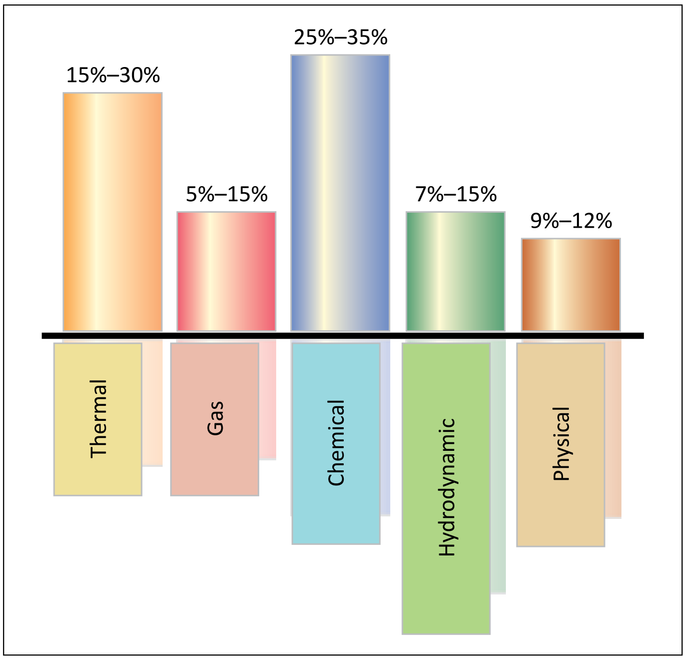

Figure 2. Potential opportunities for increasing oil recovery by various methods

Rysunek 2. Potencjalne możliwości zwiększenia wydobycia ropy naftowej różnymi metodami

As follows from Figure 2, the most effective methods for increasing oil recovery of horizons with hard-to-recover reserves are methods having thermal and chemical effects (up to 35%).

The efficiency of increasing oil recovery from reservoirs with residual reserves in the form of hard-to-recover reserves, regardless of the method used, along with other technological factors, is also significantly affected by their properties (Kudinov, 1996; Hasanov et al., 2012), which vary over a wide range, as shown in Table 1.

Table 1. Classification of crude oil according to density

Tabela 1. Klasyfikacja ropy naftowej ze względu na gęstość

Type	API gravity	Density [kg/m^3]	Viscosity [cP]
Bitumen	<<10	1,000++	>10,000
Extra heavy oil	<10	1,000+	>1,000
Heavy oil	10–22.3	920–1000	>100
Medium oil	22.3–31.1	870–920	10–100
Light oil	>31.1	<870	<10

This article contains some topics of the development of deposits with hard-to-recover reserves, which is of definite interest in the development of new technologies to improve the efficiency of the process of displacement of formation fluid displaced under appropriate conditions, namely the effect of changes in the wettability of a porous medium, the presence and influence of roughness in a porous medium on this process, achieving the required capillarity heights through the wetting of the porous medium, the presence of a sticky layer on the surface of the porous medium, the effect of the pore structure on the displacement index, etc. All these considered issues are important for improving the relevant technologies and increasing the efficiency of additional development of deposits with hard-to-recover reserves.

Problem statement

Generally, unconventional oils are considered to be oil reserves the development of which by conventional methods is ineffective either due to non-standard conditions of their occurrence (in dense and low-permeability collectors) or because the mixtures extracted from the deposits significantly differ with their physical-chemical characteristics (in particular, by the state of aggregate) from conventional oil mixtures which limits the possibility of their transportation through oil pipelines and processing at an oil refinery plant, and this requires specific ways to prepare them for refining and transport. Thus, there are two features of "unconventionality" of oil (Figure 3) (Williams, 2003).

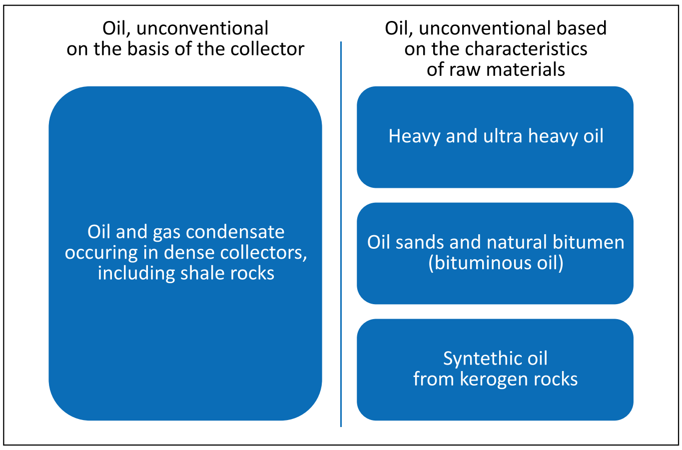

Figure 3. Classification for unconventional oil resources

Rysunek 3. Klasyfikacja niekonwencjonalnych zasobów ropy naftowej

It is known that the application of Thermolift oil recovery technologies through alternative energy devices for extension of the flowing period of oil wells operation is carried out as following cases (Abdalla et al., 2020):

- in depleted fields;
- in the significant reduction of reservoir pressure;
- when increasing the gas factor;
- when reducing the viscosity of borehole products (Kudinov, 1996; Konoplev et al., 2002).

An example of Thermolift estimates for a conventional gas condensate field (Brimble, 2004; Chen et al., 2019), which includes the following consequence, is considered:

- hoist calculation, i.e. determination of the required volume of the gas phase;
- oil temperature estimation at which the required vapor quantity of low-boiling components is provided;
- determination of energy consumption for oil heating (taking into account the various kinds of losses) and estimation of an electric heater.

The lifting hoist is carried out with the following source data by R.A. Hasanov:

- well depth – 1320 m;
- reservoir pressure – 5 MPa;
- productivity coefficient – C = 0.8 t/day × MPa;
- degree indicator – n = 1;
- permissible depression – ΔP = 0,12 MPa;
- well diameter – F = 168 mm;
- specific oil gravity – γ = 0.9 kg/m^3;
- natural gas factor – V = 30 m^3/t;
- solubility coefficient – 0.05 m^3/t MPa;
- working pressure – P – 2.75 MPa;
- absolute mouth pressure – P = 0.12 MPa.

It is assumed that there is no water in the well products if:

- the specific flow rate of the injected gas, considering its solubility, is calculated to be 125 m^3/t;
- the heating temperature has been calculated with the method of consistent approximation;
- the vapor temperature has been adjusted and the volume corresponding to this temperature has been compared with the required volume obtained as a result of calculation of the lifting hoist;
- the volume of steam generated by oil heating in the well when using single evaporation method (this methodology has been created by the Ukrainian scientists from the Scientific Research Institute of Petroleum Industry).

The calculation results are specified in Table 2:

According to Table 2, the following conclusions were reached: when oil is heated up to 100°C, the average vapor output is calculated to be 133 m³/t (533 m³/h). According to these calculations, oil lifting is achieved with a gas quantity of 125 m^3/t. The used oil heating temperature 100°C can be considered acceptable within the the accuracy of the calculations performed.

Table 2. Calculations table for the lifting hoist

Tabela 2. Tabela obliczeń dla wynoszenia

Mixture components	Molecular weight	Content	Usage	Usage	Mole content	Equilibrium constant	Vapor using	Specific volume	Vapor consumption volume	Volumetric flow rate at T = 1,000 m^3/hour	Specific usage	Heat vaporisation rate	Evaporation energy calculation
		[% weight]	[kg/hour]	[mol/hour]			[kg/hour]	[m^3/kg]	[m^3/hour]		[m^3/tone]	[cal/kg]	[kW]
CH_4	16	2	80	5.00	11.95	24,00	75.5	1.40	105.8	–	–	0	0
C_2H_6	30	4	160	5.33	12.80	6.00	130.0	9.74	96.2	–	–	0	0
C_3H_8	44	7	280	6.37	15.25	2.40	177.5	0.50	88.8	–	–	0	0
C_4H_{10}	58	7	280	4.83	11.55	1.40	141.0	0.37	62.2	–	–	60	0.8

cont. Table 2 / cd. Tabela 2

Mixture components	Molecular weight	Content	Usage	Usage	Mole content	Equilibrium constant	Vapor using	Specific volume	Vapor consumption volume	Volumetric flow rate at T = 1,000 m^3/hour	Specific usage	Heat vaporisation rate	Evaporation energy calculation
		[% weight]	[kg/hour]	[mol/hour]			[kg/hour]	[m^3/kg]	[m^3/hour]		[m^3/tone]	[cal/kg]	[kW]
C_5H_{12}	72	5	200	2.78	6.65	0.60	60.5	0.29	17.5	–	–	70	4.9
C_6H_{14}	86	10	400	4.65	11.10	0.26	63.2	0.25	15.8	–	–	74	5.4
C_7H_{16}	100	7	280	2.80	6.70	0.12	22.3	0.22	4.9	–	–	80	2.1
C_8H_{18}	114	7	280	2.45	5.90	0.06	11.6	0.20	2.3	–	–	80	1.0
C_9H_{20} etc.	270	51	2040	7.57	18.10	0.03	43.2	0.15	6.5	–	–	80	4.0
Total		100	4000	41.78			724.8		390.0	533	133	–	27.2

Formalisation of the performed calculations.

Energy consumed for oil lifting with the Thermolift method shall be used for:

- oil and vapor heating Q_1;
- evaporation of the part of oil Q_2;
- thermal losses in the rocks surrounding the well Q_3.

Then:

$$Q = Q_1 + Q_2 + Q_3 \tag{1}$$

Energy calculations for oil heating is determined with a formula (watts):

$$Q_1 = G \cdot c\,(t_{oil} - t_{fob2}) \tag{2}$$

where: c = 2,095 j/kg, °C – heat capacity of oil; t_{oil} – oil temperature at a depth of 1,300 m, which conventionally accepted equal to rocks temperature (48°C) at this depth (1300 m) in formula (2): Q_1 = 120 KW.

Evaporation energy consumption has been calculated for each component separately, and then summed up. Heat consumption for evaporation (in watts) of a component is determined with the formula:

$$Q_2 = r \cdot G \tag{3}$$

where:

r – latent heat of vaporisation in j/kg,

G – vapor quantity of a i-th component.

Total heat consumption for evaporation amounts to 27.2 kW.

Thermal losses are caused by a process of non-stationary heat exchange between the well-filling medium and rocks, and are calculated with the following formula:

$$Q_3 = F \cdot k\,(t_{ck} - t_{fob}) \tag{4}$$

where:

k – coefficient of non-stationary heat exchange,

F – surface of the well walls.

The following data sets are used to determine the coefficient of non-stationary heat exchange:

a = 0.0039 m²/s; L = 2.35 kcal/mh°C; a = 180 kcal/m²h°C.

Realisation and Results

An electrochemical battery with a solid oxide electrolyte, which is a device for energy production and storage, with a solid oxide electrolyte is considered.

It is known that electrochemical device with solid oxide electrolyte for generating the electrical energy has various modification and great advantages also suitable for heat production (Chekalyuk, 1965; Abdalla et al., 2020). This device is configured based on a module, and therefore it is possible to design them in stacks with a wide range of operational characteristics (Figure 4).

The main executive unit of the stand is a solid oxide fuel cell (3) (SOFC), designed to produce electricity and heat for pumping a hot working mixture through the injection well (2) into the in-situ space. The SOFC (3) can be designed for various capacities (Hasanov et al., 2012), modes and operating durations depending on the shape, material support and metric characteristics, as well as the type of fuel used and operating temperature and has a typical puzzle assembly (Figure 5):

To stimulate the start of the production process in the SOFC (3), air (4) is supplied to the cathode, and fuel (5) is supplied to its anode surfaces. In these compositions, various types of fuels (5) can be used, for example, natural gas, associated petroleum gas, gas from the decomposition of gas hydrates, hydrogen gas, etc. Each of the options of fuel use has a structurally different own system for supply to the anode

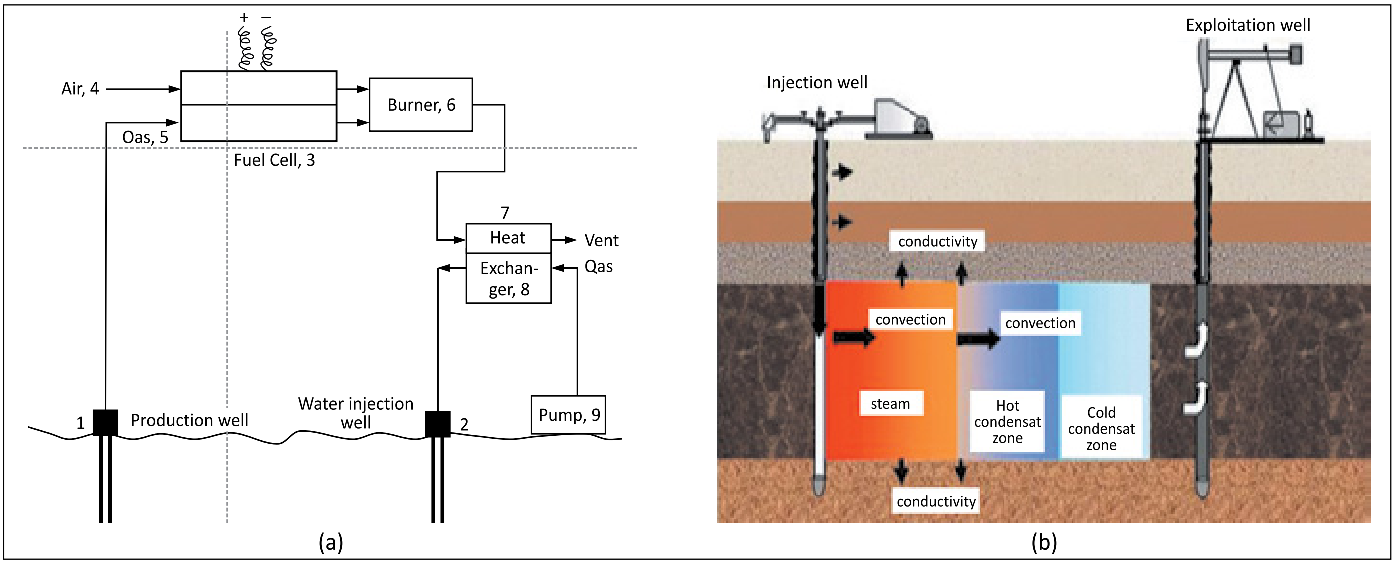

Figure 4. Scheme of fuel and energy production device using a fuel cell surface installation (a) and implementation of the Thermolift technology in the well (b)

Rysunek 4. Schemat urządzenia do produkcji paliwa i energii z wykorzystaniem instalacji powierzchniowej ogniwa paliwowego (a) oraz wdrożeniem technologii Thermolift w odwiercie (b)

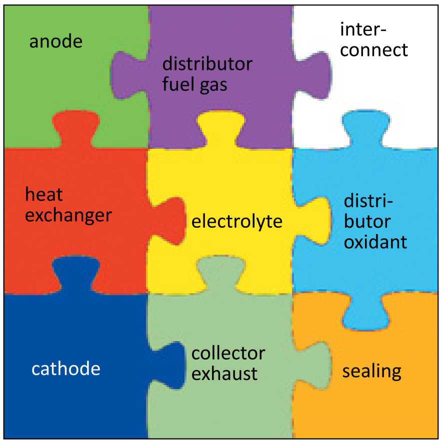

Figure 5. Puzzle of the solid oxide fuel cell (3)

Rysunek 5. Układ ogniwa paliwowego ze stałym tlenkiem (3)

surface. Due to chemical reactions on these surfaces, ionisation of air (4) and fuel (5) occurs. This ionisation process stimulates the production of electricity (which can be used for various needs) and by-products in the form of various gases and heat. In the above stand, the by-product of the reactions – the coolant – is fed through the burner (6) into the heater (7). Water is also supplied here from the sea by the pump (9). After mixing with seawater in the heat exchanger (8), the coolant is pumped into the in-situ space through the injection well (2) to warm and push up the remaining reserves to the bottom of the production well (1). Thus, the displacement of the reserves of the productive horizon due to the coolant (Figure 4b) is carried out by an installation with an SOFC.

The disadvantage of these power plants is that they require fuel and oxidation systems; therefore, the material design of their electrode system does not permit the energy storage functions by long – term recharging during the life cycle of operation.

One more disadvantage of these devices is that the metric characteristics of their electrode system are incompatible with the material provision and set without taking into account of the process intensity on the surfaces of anode and cathode on which the energy production process depends.

The closest solution to the proposed device for energy production and storage is a device presented in the form of an electrode system with an liquid electrolyte. This generator eliminates the use of fuel and oxidzing systems and allows both producing and solving the problem of storing the produced energy.

However, these devices with necessary functional opportunities to produce and store the produced energy and the advantage of using with other alternative energy sources have a number of significant shortcomings, which are summarised as follows:

1. devices using liquid electrolytes are highly volatile and have the potential to catch fire during the operational process;
2. the metric dimensions of these devices are greater than those of solid oxide electrolytes, and, therefore, they are not competitive in terms of commercial performance and are more expensive due to lack of opportunities of intercomparison of metric parameters of electrodes and volume of electrolyte contents;
3. these devices are less effective when compared to those with solid electrolytes and are inferior to them concerning quality (shorter service life and etc.).

A series of requirements are placed on modern electric power systems that determine the prospects of their application in various industries, including the oil and gas sectors. These requirements are aimed at improving the consumer quality of the applied systems and are mainly reduced to the degree of their commercialisation (1 – determines availability, a lot of functionality; 2 – affordability determines cost effectiveness; 3 – loyalty to the environment determines interaction with the environment; 4 – adaptability compliance with the conditions of the location of operation determines the requirements of the location; 5 – flexibility readiness and availability in terms of the quality and volume of fuel consumed determines the flexibility in the use of fuel). This is due to the fact that the level of global energy consumption and, accordingly, a decrease in the negative and harmful impact of production processes implemented for this purpose on the environment increases rapidly.

The specification for the power indicators of the generating system takes into consideration such indicators as efficiency, price characteristics (both purchase and installation), reliability, cycle obligation, maintainability, dimensions and weight, the list of fuels used, etc. (for instance, generation repetition, noise characteristics, quality of the produced energy) (Baybakov and Garushev, 1988).

Numerical results for solid oxide fuel cells are shown in Figures 6 and 7, in the form of graphical representations, the experimental and theoretical basis of which is contained the form of execution, metric characteristics, physical properties of the material execution and operating temperaturein (Hasanov et al., 2011):

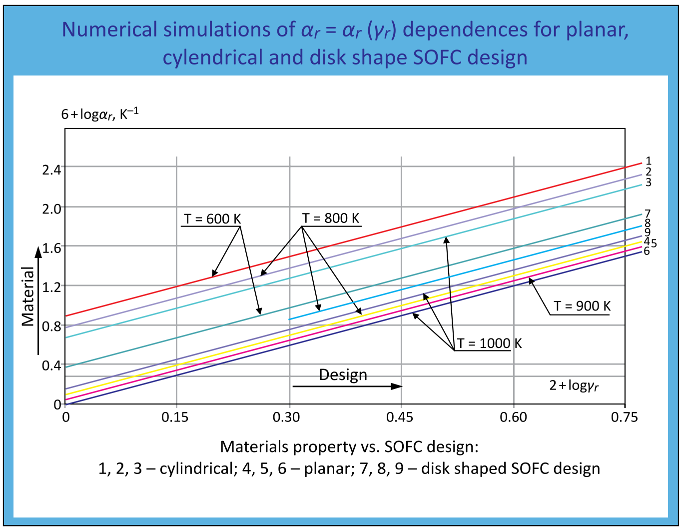

Figure 6. Dependability of metric characteristics, thermo-physical properties of the electrode system on design form and operating temperatures

Rysunek 6. Zależność cech wskaźników, właściwości termiczno-fizycznych systemu elektrody od formy konstrukcji i temperatur eksploatacji

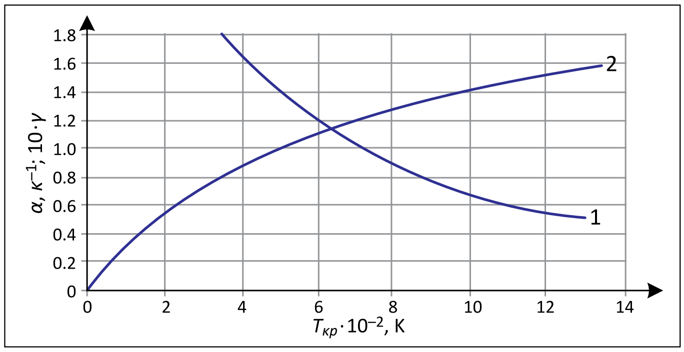

Figure 7. Optimal thermo-physical properties of the materials depending on operating temperature

Rysunek 7. Optymalne właściwości termiczno-fizyczne materiałów w zależności od temperatury eksploatacji

These dependences make it possible to synthesise acceptable combinations of parameters of the solid oxide fuel cell assembly, including its shape, material characteristics and metric parameters for various operating temperatures.

It has been established that the optimal metric characteristics with acceptable thermo-physical properties of the electrode system materialsand power of the generating device can be determined with graphs shown in Figure 7.

Conclusion

1. Studies on a specially equipped stand, and numerical simulations of the obtained analytical solutions showed that the most rational characteristics and properties of the electrode system for generating power for the device, depending on the form of design, are the parameters shown in Figure 6.
2. Thus, pursuant to own studies for the operating temperature accompanying the electrode systems of solid oxide power generating devices equal to 1000°C, the acceptable metric characteristics have been determined (by the ratio of the thickness to one of the transverse dimensions) as $10\ \gamma\ (\delta/M) = 0.34$, as well as the averaged thermo-physical property for this operating temperature, which is equal to $\alpha = 1.2\ \kappa^{-1}$. These properties and metric characteristics ensure of device efficiency for the period of its established service life without technological risks and complications.

The results of the studies were included in projects dedicated to the development and implementation of low (SFP No. G5366 dated 09.02.2017) and high and medium temperature fuel cells (EAPSFP 984580-01.01.2005-01.01.2009, G5949-10.02.22--10.02.25). The grant was funded by NATO under the Science for Peace Programme and was reported at the session of the Advanced Science Institute (ASI– 16.04.2012 NATO), researches have been carried out in a consortium with specialists from the USA, Great Britain, Turkey, Russia, Ukraine and Belarus (Hasanov et al., 2011, 2012).

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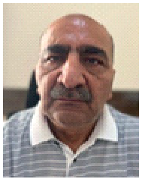

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