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DEVELOPMENT AND CREATION OF RESEARCH CELLS FOR SOLID OXIDE FUEL CELLS

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The article is devoted to the development and creation of research cells for solid oxide fuel cells (SOFCs) designed to study their characteristics at various temperatures. The primary focus is on the use of high-temperature glass sealants that ensure the hermeticity of the structure. The paper describes the materials and methods for fabricating model fuel cells, including various combinations of electrolytes (YSZ, ScSZ, GDC) and electrodes (NiO, LSM). The design of the research cells incorporates electrochemical sensors, providing precise control over the composition of the gas mixture entering the active zone, with deviations not exceeding 0.5%. The results of current-voltage characteristics of the model SOFCs in the temperature range of 700–950 °C showed that an increase in temperature leads to a reduction in ohmic losses and improved kinetics of electrochemical reactions. The maximum power density is achieved at higher current densities with increasing temperature, which is attributed to enhanced material conductivity and improved electrode activity. At lower temperatures, limited cell efficiency is observed due to increased electrolyte resistance and reduced electrode activity. The developed research cells demonstrated high reliability and reproducibility of data, enabling their use in optimizing the material composition and structure of SOFCs. The obtained results confirm the potential of the proposed methodology for the development of highly efficient fuel cells.

Keywords: *solid oxide fuel cells (SOFCs), model fuel cells, research cells, high-temperature glass sealants, electrochemical sensors, current-voltage characteristics, power density, ohmic losses, kinetics of electrochemical reactions.*

INTRODUCTION

Energy is a cornerstone of modern society. The anticipated surge in global energy consumption by 2050 necessitates prompt and decisive measures. In light of the growing depletion of natural energy resources, the development and enhancement of highly efficient electrochemical systems for energy storage and conversion have become increasingly critical. At present, hydrogen energy (or the hydrogen economy) is widely regarded as a key solution to addressing environmental, economic, and social challenges, as well as ensuring sustainable development and long-term energy security. Hydrogen energy is recognized as a priority field (a critical technology) in nearly all developed nations. However, significant challenges impede the successful commercialization of hydrogen energy technologies. A fundamental requirement for the transition to a hydrogen economy is the establishment of a hydrogen infrastructure, effective methods for hydrogen storage and transportation, and a reduction in associated costs [1, 2].

Fuel cells are advanced electrochemical systems that directly convert the chemical energy of fuels into electrical energy with high efficiency. Unlike conventional energy sources, such as internal combustion engines, fuel cells produce minimal carbon dioxide emissions and significantly reduce environmental pollution. One of the defining characteristics of fuel cells is their ability to utilize a wide range of fuels, including hydrogen, methane, and other hydrocarbons, making them adaptable for various energy and transportation applications [3–5]. Fuel cells are categorized based on the type of electrolyte they employ, such as proton exchange membrane fuel cells (PEMFC), phosphoric acid fuel cells (PAFC), alkaline fuel cells (AFC), and solid oxide fuel cells (SOFC). Among these, SOFCs stand out due to their distinctive advantages [6, 7]. These cells operate at elevated temperatures (450–1000 °C), enabling the direct use of diverse fuels, including hydrocarbons, without requiring pretreatment. Furthermore, SOFCs exhibit high energy conversion efficiency, extended operational life, structural adaptability, and low greenhouse gas emissions [8, 9].

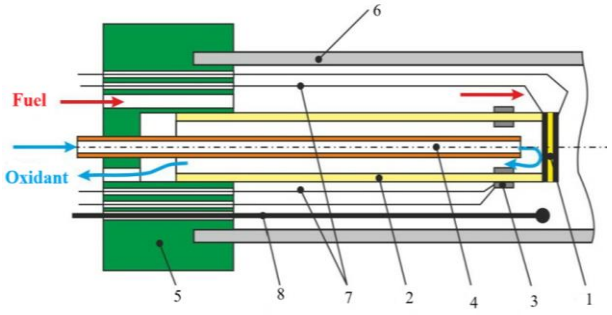
The working mechanism of SOFCs relies on the electrochemical conversion of fuel facilitated by a solid oxide electrolyte that conducts oxygen ions. The cell comprises three main components: the anode, cathode, and electrolyte. The anode functions as the oxidation electrode, the cathode as the reduction electrode, and the electrolyte facilitates oxygen ion transfer from the cathode to the anode. The electrochemical reactions occurring at the anode and cathode generate electrons, which flow through an external circuit, producing an electric current. These processes position SOFCs as a promising energy solution for both stationary and mobile applications [10–12].

This article aims to develop the design and fabrication techniques for experimental SOFCs, including model elements utilizing various material combinations. It also seeks to perform a comprehensive analysis of their voltage-current characteristics across a broad temperature spectrum. The research emphasizes optimizing material compositions and SOFC structures to improve their efficiency, power density, and operational reliability. Additionally, it focuses on creating reliable electrochemical

sensors for precise monitoring of the gas atmosphere in the operating zone.

MATERIALS AND METHODS

Figure 1 shows a schematic representation of the design of the research cell. The main components of the cell include the holder (5), the tailpiece (2), and the model SOFC (1). In addition to these elements, the research cell contains another crucial component — the electrochemical sensor (3), which allows for monitoring the composition of the fuel mixture at the cell inlet.



1 – model SOFC; 2 – tail (ceramic tube); 3 – electrochemical sensor; 4 – gas inlet; 5 – sealed holder with gas and current inlets (leads); 6 – furnace chamber (ceramic tube); 7 – probe wire leads; 8 – control thermocouple

Figure 1. Research cell diagram

In the design shown in Figure 1, one end of the tailpiece (2) is hermetically connected to the holder (5), while the opposite end houses the disc-shaped model SOFC (1). The hermetic attachment of the model SOFC to the tailpiece is achieved using high-temperature glass sealants, which must exhibit good wettability and a coefficient of thermal expansion (CTE) closely matching that of the SOFC components. The design of the holder (5) includes spatially separated openings for gas flow and electrical connections, as well as provisions for mounting the tailpiece and a seat for the centered and hermetic installation of the cell into the tubular furnace chamber (6). The length of the thermal compensation tailpiece (2), combined with the length of the ceramic tube of the furnace (6), is selected based on the following conditions: heat dissipation at the end (near the holder), the extent of the thermal zone of the furnace (with the sample positioned in the middle), and ensuring the required temperature gradient.

Manufacturing of Research Cells

Source materials

The following powders were used to fabricate model fuel cells (hereinafter referred to as cells): YSZ, ScSZ, GDC, NiO, and LSM, the characteristics of which are presented in Table 1. The YSZ and ScSZ electrolyte powders were synthesized using the laser evaporation method [13], while the NiO powder was produced by the wire explosion method [14]. The GDC powder is a commercial product from Kceracell Co., Ltd. The LSM powder was synthesized through the pyrolysis of a polymer-salt composition.

Table 1. Nomenclature and characteristics of the original powders

Designation	Compound	S_{BET}, m^2/g	d_{BET}, nm	γ_{theor}, g/cm^3
YSZ	$Zr_{0,84}Y_{0,16}O_{2-\delta}$	4,7	216	5,92
ScSZ	$Zr_{0,8}Sc_{0,2}O_{2-\delta}$	52	20	5,67
GDC	$Ce_{0,9}Gd_{0,1}O_{2-\delta}$	34,2	24,3	7,21
NiO	NiO	28,4	31	6,80
LSM	$La_{0,7}Sr_{0,3}MnO_{3-\delta}$	0,79	1200	6,51

Manufacturing of elements

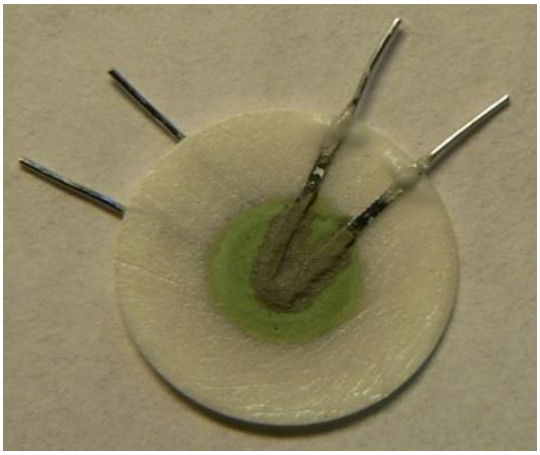
The fabricated planar model cells had different structures (supporting components, electrolyte, and electrode compositions). A description of the cells is provided in Table 2.

Table 2. Structure of model elements

Cell	Supporting component	Cathode, (mass%)	Electrolyte	Anode (mass%)
No 1	Electrolyte	60LSM+40YSZ	YSZ	50Ni+50YSZ
No 2	Electrolyte	60LSM+40YSZ	YSZ	50Ni+50GDC
No 3	Electrolyte	60LSM+40YSZ	ScSZ	50Ni+50YSZ
No 4	Cathode	50LSM+50YSZ	YSZ	50Ni+50GDC
No 5	Anode	60LSM+40YSZ	YSZ	50Ni+50GDC

Supporting electrolyte samples in the form of discs were fabricated from films of the corresponding electrolyte material using uniaxial pressing. The film composition included 84.6 wt.% powder, 12 wt.% polyvinyl butyral (PVB), and 3.4 wt.% triethylene glycol dimethyl ether (TEGDME). The pressed samples were sintered at 1350 °C for 5 hours. The resulting discs had a diameter of approximately 11 mm, a thickness of 300 μm, and a density exceeding 97% of the theoretical value. Electrode slurries with the following composition were applied to the supporting electrolyte samples using the painting method: 87.2 wt.% powder mixture, 10 wt.% PVB, and 2.8 wt.% TEGDME. Isopropyl alcohol served as the solvent. The electrodes were sintered in an air atmosphere at 1200 °C for 4 hours. The electrode thickness after sintering was approximately 30 μm. It should be noted that fibers from ashless filter paper (5 wt.%) were used as pore formers during the fabrication of both the supporting anode and the supporting cathode. Platinum wire with a diameter of 0.3 mm was used as probes (current collectors) for all cells. To improve electrical contact, the probes were coated with platinum paste, which was sintered at 1000 °C. Figure 2 shows the cells with the supporting electrolyte.

The cathodes and anodes of all cells were impregnated (activated) three times with solutions of $Pr(NO_3)_3$ and $Ce(NO_3)_3$, respectively. The prepared cells were hermetically attached to the end of a tubular stem made of industrial YSZ ceramics using SG2 glass sealant. Figure 3 shows the appearance of the fully assembled Cell No. 1. The only difference between Cell No. 1 and the other cells is the model fuel cell.



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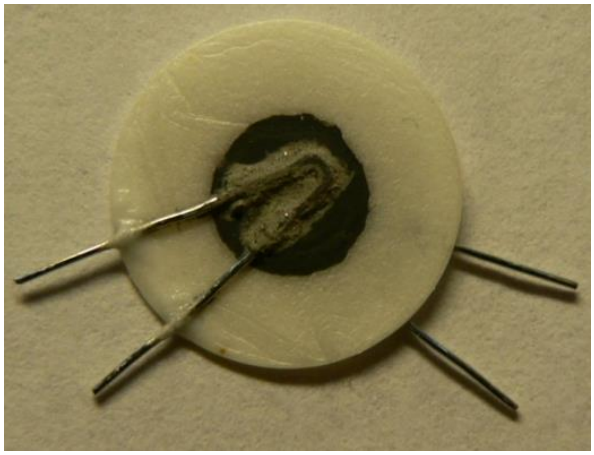

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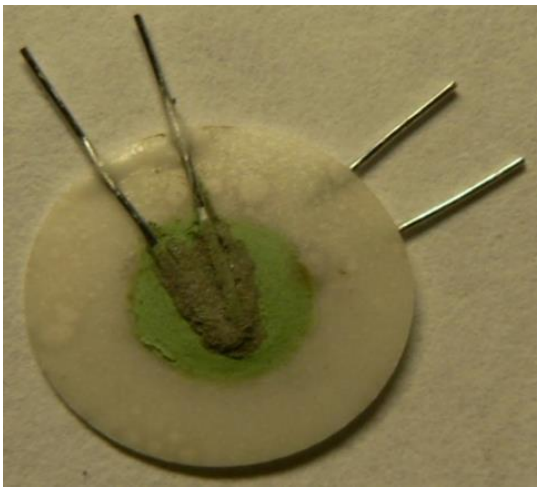
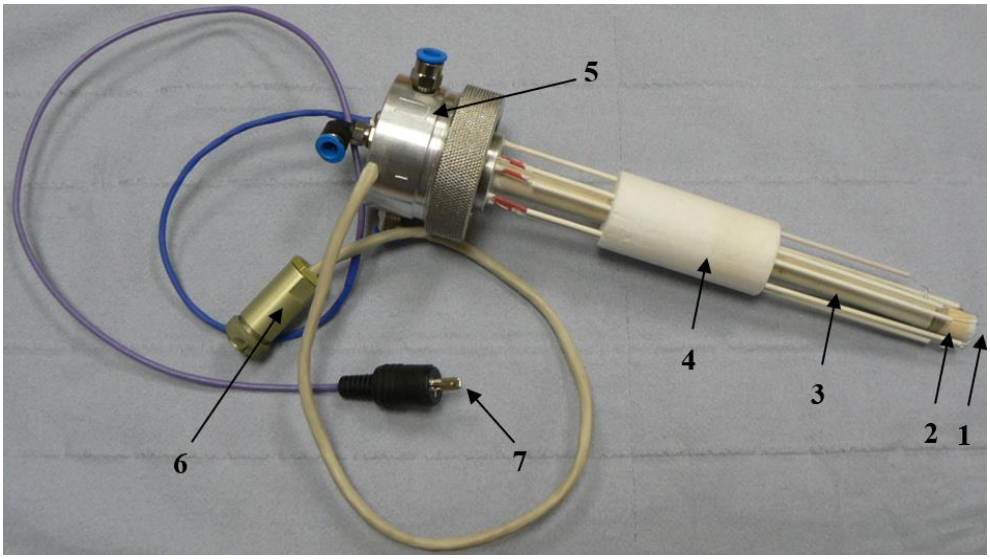


c)

Figure 2. Appearance of planar cells for: Cell No. 1 (a), Cell No. 2 (b) and Cell No. 3 (c)

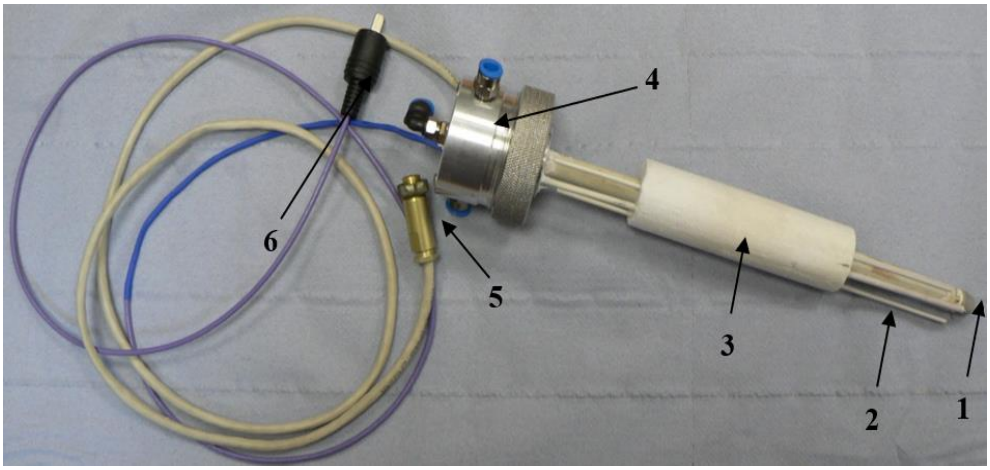
Manufacturing of the Sensor

It was proposed to simplify the terminology by referring to the electrochemical sensor, manufactured as a separate device and installed in a tubular furnace opposite the end where the research cell is mounted, simply as a "sensor". The working part of the sensor was made from an industrially produced YSZ test tube. Platinum electrodes were applied to the inner and outer surfaces of the test tube using the painting method and sintered at 1200 °C. Platinum wire with a diameter of 0.3 mm served as probes. In other aspects, the design of the sensor does not differ from the design of the research cell. The working part of the sensor was attached to the end of the tubular stem using SG3 glass sealant. The appearance of the sensor is shown in Figure 4.



1 – model fuel cell; 2 – electrochemical sensor; 3 – tail; 4 – thermal insulation;
5 – cell holder; 6 – probe terminals; 7 – terminals of the control thermocouple

Figure 3. Appearance of research cell No. 1



1 – electrochemical sensor; 2 – tail; 3 – thermal insulation; 4 – sensor holder;
5 – probe terminals; 6 – terminals of the control thermocouple

Figure 4. Appearance of the Sensor

RESULTS AND DISCUSSIONS

Characteristics of Research Cells

Electrochemical sensor readings

Table 3 presents the test results of the electrochemical sensors for all research cells and the sensor at various temperatures. Measurements were conducted under identical gas flow conditions: hydrogen – 100 ml/min, air – 100 ml/min.

Table 3. Readings of electrochemical sensors of research cells and the sensor

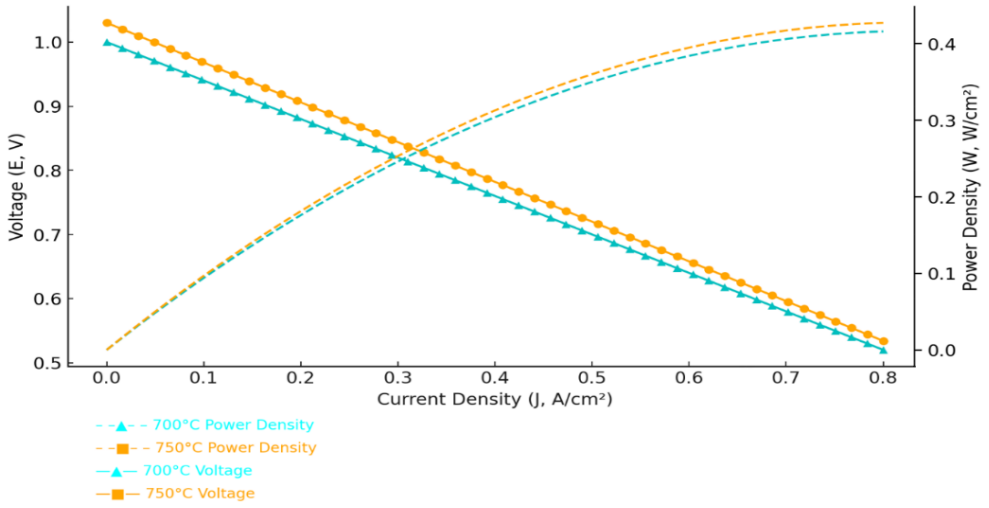
T, ℃	C1, B	C2, B	C3, B	C4, B	C5, B	Sensor, B
900	1.100	1.101	1.106	1.103	1.102	1.091
850	1.109	1.112	1.116	1.111	1.110	1.100
800	1.119	1.122	1.125	1.122	1.119	1.109
750	1.127	1.131	1.135	1.129	1.124	1.117
700	1.134	1.135	1.141	1.133	1.130	1.124

It is evident that the data variation for all electrochemical sensors does not exceed 0.5%. Thus, the fabricated electrochemical sensors enable highly accurate monitoring of the gas atmosphere in the working zone and, consequently, allow for effective control of the hermeticity of the research cells.

Characteristics of model fuel cells

Figure 5 shows graphs of the dependence of voltage (E) and power density (W) on current density (J) for model fuel cells at various temperatures (700 ℃, 750 ℃, 800 ℃, 850 ℃, 900 ℃, and 950 ℃).

The voltage decreases linearly with increasing current density for all temperatures. This is due to the growth of ohmic losses and polarization caused by the increase in the rate of electrochemical reactions. Higher temperatures (e.g., 900 ℃ and 950 ℃) show slightly higher initial voltage compared to lower temperatures (700 ℃ and 750 ℃), which is attributed to the reduction in the internal resistance of the cell. Power density increases with current density until it reaches a maximum, after which it begins to decrease due to a sharp drop in voltage. At higher temperatures, the maximum power density is higher, reflecting improved electrochemical reaction kinetics and increased material conductivity. At lower temperatures, the initial voltage is lower than at higher temperatures, and the maximum power density is reached at a lower current density (approximately 0.4–0.5 A/cm²). This lower performance is explained by increased electrolyte resistance and reduced electrode activity. At intermediate temperatures, there is a balance between good electrolyte conductivity and sufficient reaction kinetics. The maximum power density is achieved at a higher current density (approximately 0.5–0.6 A/cm²) compared to 700 ℃ and 750 ℃. Higher temperatures demonstrate better performance: voltage drops more slowly with increasing current density, and the power density reaches its maximum at even higher current densities (0.6–0.7 A/cm²). This is due to minimal ohmic losses and high activity of cathodic and anodic reactions.



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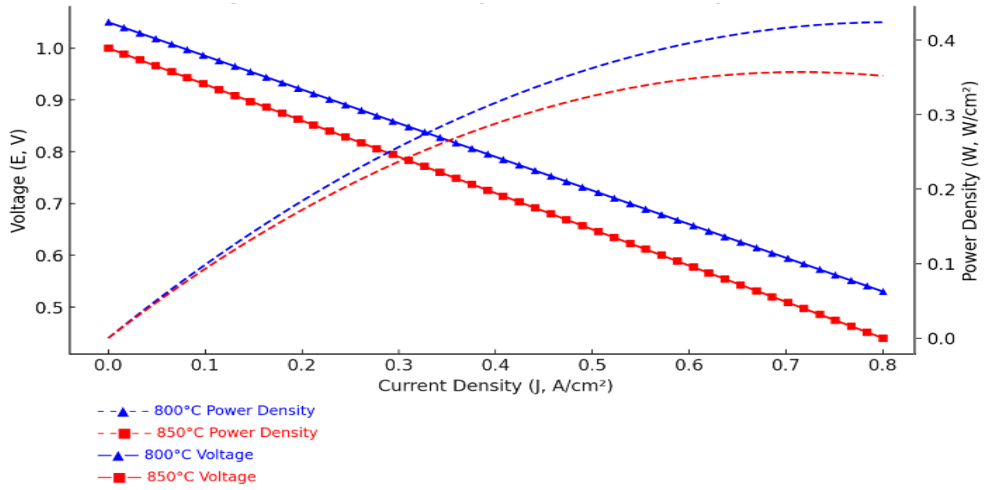

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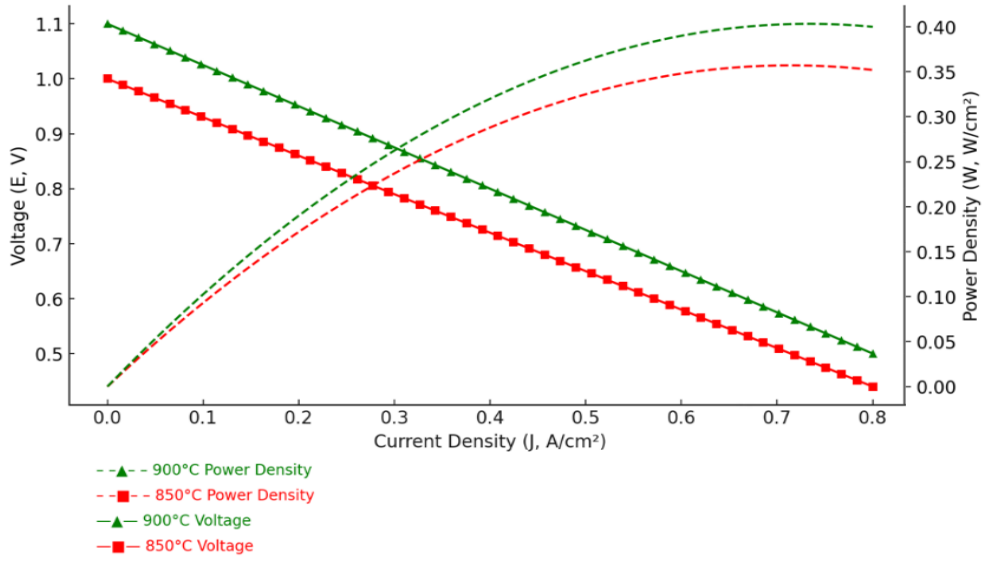

c)

Figure 5. Volt-Ampere characteristics of the cell taken at: 700 and 750 ℃ (a), 800 and 850 ℃ (b), 900 and 950 ℃ (c)

CONCLUSIONS

Research cells for solid oxide fuel cells (SOFCs) were developed and fabricated using high-temperature glass sealants to ensure the hermeticity of the structure. The cell design includes electrochemical sensors that demonstrated high accuracy in measuring the gas atmosphere in the working zone, with deviations not exceeding 0.5%. This allows for effective control of experimental conditions and cell hermeticity. The results of the voltage-current characteristics of the model SOFCs revealed a linear decrease in voltage with increasing current density, attributed to growing ohmic losses and polarization. It was found that increasing the temperature (up to 950 °C) reduces the internal resistance of the cells, enhances the kinetics of electrochemical reactions, and improves material conductivity, resulting in higher power density. The maximum power density is achieved at higher current densities with increasing temperature, indicating improved performance. At lower temperatures, limited electrode activity and increased electrolyte resistance were observed, reducing the efficiency of the cells. Thus, the developed research cells and their fabrication methodology enable the study of SOFC characteristics over a wide temperature range, ensuring high data reproducibility and applicability for optimizing material composition and cell structure.

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ҚАТТЫ ОКСИДТІ ОТЫН ЭЛЕМЕНТТЕРІНЕ АРНАЛҒАН ЗЕРТТЕУ ҰЯШЫҚТАРЫН ӘЗІРЛЕУ ЖӘНЕ ЖАСАУ

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Бұл мақала әртүрлі температураларда қатты оксидті отын элементтерінің (ҚООЭ) сипаттамаларын зерттеуге арналған зерттеу ұяшықтарын әзірлеу мен жасауға арналған. Негізгі назар құрылымның тығыздығын қамтамасыз ететін жоғары температуралы шыны герметиктерді қолдануға аударылған. Мақалада үлгілік отын ұяшықтарын жасауға арналған материалдар мен әдістер сипатталған, соның ішінде электролиттердің (YSZ, ScSZ, GDC) және электродтардың (NiO, LSM) әртүрлі комбинациялары қарастырылады. Зерттеу ұяшықтарының құрылымында белсенді аймаққа түсетін газ қоспасының құрамын 0,5%-дан аспайтын ауытқулармен дәл бақылауды қамтамасыз ететін электрохимиялық сенсорлар бар. 700–950 °C температура диапазонында үлгілік ҚООЭ вольт-амперлік сипаттамаларын зерттеу нәтижелері температураның жоғарылауы омикалық шығындардың азаюына және электрохимиялық реакциялардың кинетикасының жақсаруына әкелетінін көрсетті. Материалдардың өткізгіштігі артып, электродтардың белсенділігі жақсарған сайын, жоғары температурада максималды қуат тығыздығы жоғары ток тығыздығымен қол жеткізілді. Төмен температураларда электролиттің қарсылығының артуы мен электродтардың белсенділігінің төмендеуіне байланысты ұяшықтардың тиімділігі шектелген. Әзірленген зерттеу ұяшықтары деректердің жоғары сенімділігі мен қайталанғыштығын көрсетті, бұл оларды ҚООЭ материалдары мен құрылымдарының құрамын оңтайландыру үшін пайдалануға мүмкіндік береді. Алынған нәтижелер ұсынылған әдістеменің жоғары тиімді отын элементтерін әзірлеудегі әлеуетін растайды.

Түйін сөздер: *қатты оксидті отын элементтері, үлгілік отын ұяшықтары, зерттеу ұяшықтары, жоғары температуралы шыны герметиктер, электрохимиялық сенсорлар, вольт-амперлік сипаттамалар, қуат тығыздығы, омикалық шығындар, электрохимиялық реакциялардың кинетикасы.*

РАЗРАБОТКА И СОЗДАНИЕ ИССЛЕДОВАТЕЛЬСКИХ ЯЧЕЕК ДЛЯ ТВЕРДООКСИДНЫХ ТОПЛИВНЫХ ЭЛЕМЕНТОВ

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Статья посвящена разработке и созданию исследовательских ячеек для твердооксидных топливных элементов (ТОТЭ), предназначенных для изучения их характеристик при различных температурах. Основное внимание уделено использованию высокотемпературных стеклянных герметиков, обеспечивающих герметичность конструкции. В статье описаны материалы и методы изготовления модельных топливных ячеек, включая различные комбинации электролитов (YSZ, ScSZ, GDC) и электродов (NiO, LSM). Конструкция исследовательских ячеек включает электрохимические сенсоры, обеспечивающие точный контроль состава газовой смеси, поступающей в активную зону, с отклонениями, не превышающими 0,5%. Результаты исследований вольт-амперных характеристик модельных ТОТЭ в температурном диапазоне 700–950 °C показали, что повышение температуры приводит к снижению омических потерь и улучшению кинетики электрохимических реакций. Максимальная плотность мощности достигается при более высоких плотностях тока с увеличением температуры, что объясняется повышенной проводимостью материалов и улучшенной активностью электродов. При более низких температурах наблюдается ограниченная эффективность ячеек из-за увеличенного сопротивления электролита и сниженной активности электродов. Разработанные исследовательские ячейки продемонстрировали высокую надежность и воспроизводимость данных, что позволяет использовать их для оптимизации состава материалов и структуры ТОТЭ. Полученные результаты подтверждают потенциал предложенной методологии для разработки высокоэффективных топливных элементов.

Ключевые слова: *твердооксидные топливные элементы (ТОТЭ), модельные топливные ячейки, исследовательские ячейки, высокотемпературные стеклянные герметики, электрохимические сенсоры, вольт-амперные характеристики, плотность мощности, омические потери, кинетика электрохимических реакций.*