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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

İMPROVEMENT OF PERFORMANCE İNDİCATORS AND QUALİTY OF FUEL ELEMENTS OF PLANAR EXECUTİON

Specialty: 2004.01– “Dynamics, strength of machines, devices and apparatus”.

Field of science: Technical sciences

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Baku – 2022

Dissertation work was carried out at the Research Institute "Geotechnological Problems of Oil, Gas and Chemistry" at the Azerbaijan State Oil and Industry University

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GENERAL CHARACTERİSTİCS OF WORK

The actuality and study degree of the topic. The growth of the total population in the world has led to an enormous consumption of various energy resources. The current situation with the development of the population has forced scientists to take an increased interest in the development of new energy resources. By improving the resources used, an advantage over fossil fuels can be achieved and the problems associated with this can be overcome.

In addition, there are now increased demands for environmental problems due to global warming on the earth. Consequently, the world community, including scientists, must take responsibility for finding a sustainable solution to reduce the use of fossil fuels in order to counteract the problems of future resource depletion. Thus, by proposing alternatives to the use of resources, it is possible to achieve this goal with safe and effective solutions. Therefore, at the present stage of technological progress, the use of fuel cells has increased very rapidly and found application in various industries and households. According to the current level of development, fuel cells (FC) can provide environmentally friendly, efficient and reliable energy production for almost any electric power device. In addition, widespread use of fuel cells in portable, stationary and transport applications is planned.

Offering new and effective solutions that can help overcome the current serious problems, especially for solid oxide fuel cells (SOFC) (electrodes and interconnects) must be actively researched and developed to meet the industrial and societal needs. Furthermore, research has been conducted on the specification and material support of fuel cell devices in order to optimize their technological performance and to meet the challenges of ensuring efficient use in various applications. By developing inexpensive, easily sinterable materials (Ni, Fe, Cu, Al, Sr); and by developing a solid-state ceramic anode or cathode for SOTC applications at various scales (from macro to nano scale), the current level of commercialization of SOFC's in various fields of technology has been achieved. It should be noted that the solid oxide fuel cell power generation technologies meet all the requirements, i.e. they can use various fuel resources (have flexibility), minimize the environmental impact (have Compatibility), are designed for commercial attractiveness (Affordability), have a wide range of practical application (Adoptability) and can operate for power generation as well as for chemical production (Capability).

To solve these problems, i.e. to increase the level of commercialization of existing SOFC's a necessary condition is to carry out a set of mechanical researches with relevant results, which are compatible with the results of other problems of their development.

In the present dissertation we consider SOFC's in planar design and their development in recent decades, as well as their importance for the production of environmentally clean energy.

Object and subject of the research. The object of the study is one of the types of SOFC developments, which have found application in various fields of technology, namely fuel cells in the planar design. The subject of research is performance and quality of fuel elements of planar design by solving mechanical problems of their component composition to bring them into compatibility with the results of solving other problems of SOFC development.

The purpose and objectives of the study. The purpose of the study is to development of design methodology for high-temperature solid oxide fuel cells of flat layered macrocomposite design to improve their performance and quality.

The research task is to develop, investigate and design models of solid layered macro-composite structure with different physical, rheological and structural-mechanical properties of material execution.

Methods of research. Constructive and physical modeling, mathematical modeling and solution of boundary value problems, optimization methods, development of conducting and generalization of experimental studies.

The main provisions brought to the defense.

1. Justification and characterization of mechanical problems of high-temperature layered structures of solid oxide fuel elements with different structural-material design taking into account operating conditions.

2. Assessment of influence of changes in rheophysical and structural-mechanical properties of material support on serviceability properties of structural design pairs of individual fuel elements, and in stacks.

3. Study to determine the essence of the influence of the phenomenon of “form of structural design” on the load-carrying capacity of both individual solid oxide fuel elements and in stacks.

4. Development of criteria for evaluation of quality indexes of solid oxide fuel elements, operating under high operating temperatures and jumping modes of operation.

5. Determination of survivability life of high-temperature fuel cells with different material design and deformation behavior models.

Scientific novelty of the study. Modeling and study of the stress-strain state and ensuring efficiency of the multilayer structure of individual solid oxide fuel cells and their packs, taking into account the phenomena determining their design and operating conditions.

Theoretical and practical significance of the study.

1. The range of mechanical problems of macrocomposite fuel cell designs for conditions of operating temperatures and modes of their operation has been determined and justified.

2. A methodology has been developed to determine the shape, order and parameters of creep and relaxation nuclei to assess the deformation behavior of macrocomposite structures with different material design at operating temperatures under various modes of operation.

3. A methodology has been developed for calculating the long-term strength and stability of individual planar design fuel element

structures and their packs operating at high operating temperatures, taking into account the mode of operation.

4. The results of the conducted research are included in the projects devoted to the development and implementation of low (SFP #G5366 (09.02.2017)) and high (EAP SFP 984580) temperature fuel cells and funded by NATO within the program "Science for Peace and Security" and reported at the session of the NATO Advanced Study Institute (ASI-Advanced Science Institute).

Approbation and implementation: The results of the dissertation work were presented at:

- XVI scientific conference of doctoral candidates and young researchers (Baku, 2012);
- XVII scientific conference of doctoral students and young researchers (Baku, 2013);
- Scientific-practical conference "Azerbaijan-2020: Prospects of development of the oil and gas industry", dedicated to the 90th anniversary of Heydar Aliyev (Baku, 2013);
- XV International Youth Scientific Conference "Severge-oekoteh-2014" (Ukhta, 2014);
- International scientific conference dedicated to scientific-technical and applied problems of modern energetics (Sumgait, 2015);
- XX Republican Scientific Conference of doctoral students and young specialists devoted to the Year of Multiculturalism in Azerbaijan (Baku, 2016);
- XXV International Scientific and Practical Conference (Penza, 2019);
- XXVI International Scientific Symposium: "Shusha: Triumph of Victory" (Eskishehir/Turkey, 2022);
- Scientific seminars of the department "Mechanics" of ASOİU and Research Institute "Geotechnological Problems of Oil, Gas and Chemistry" (2016-2017).

On the topic of the dissertation work 19 scientific papers have been published.

Name of the organization in which the thesis was carried out. Research Institute "Geotechnological Problems of Oil, Gas and Chemistry" under the Azerbaijan State of Oil and Industry University.

The total volume of the dissertation in symbols, with the indication of the volume of each structural element of the dissertation separately. The thesis consists of an Introduction, 4 chapters, 156 pages of text, 28 figures, 16 diagrams, 8 tables, a list of 99 references. A title page and a table of contents (2951 symbols), an introduction (8295 symbols), Chapter I (76355 symbols), Chapter II (29537 symbols), Chapter III (64288 symbols), Chapter IV (14168 symbols), conclusions (3050 symbols) and a list of the used literature (18946 symbols). The volume of the dissertation is 198640 characters, not counting figures, tables, diagrams and references.

MAİN CONTENT OF WORK

The introduction analyzes the existing designs of fuel cells based on the experience of developments in various European and Asian countries. The study of the principle of their operation, as well as the kinetic processes occurring in them, confirms the fact that these indicators depend on many factors of a physicochemical nature, activated in the temperature range (600-1200)^{0}C.

It is argued that predictive models for determining performance and quality indicators should be built on the basis of studies of models of solid layered macrocomposite structure with different physical, rheological and structural-mechanical properties of its elements.

The combination of these properties determines the deformation model and failure mechanisms of SOFC macro-composite construction and their materials.

And the destructions of different nature, manifested in the form of delamination, loss of stability, cracking, accumulation of damages at the stage of manufacturing, etc., and reducing the quality indicators of SOFC is determined by the form of structural design and is a consequence of their loading during the period of operation.

It is shown that while many electrochemical and material science issues of SOFC design and operation for their existing structural designs have found solutions, the issues of mechanical behavior at the generated high temperatures of both individual assemblies, represented by solid composites with different deformation behavior of elements, and their use in stack, and stack in assembly, require clarification.

The first chapter of the dissertation work is devoted to the review of fuel cells and the evaluation of the prospects of their application as alternative sources of electric power generation, as well as the formulation of problems.

In this chapter, fuel cells are analyzed chronologically in terms of their design, as well as in terms of efficiency, existing capacities, fields of application, etc.

An analysis is given of the positive and negative properties of fuel cells in comparison with other power generating facilities and ways to make them commercially attractive [7][1].

The following modifications of fuel cells and the level of their development in different countries of the world for application in various industries are given.

Further in this chapter the tasks necessary for research and their importance in providing the required efficiency of operation are substantiated.

Modern electric power systems have a number of requirements defining for their application in the future in the oil and gas and other industries. These requirements contribute to the consumer quality of the applied systems and are designed mainly to ensure their commercialization (determines accessibility), loyalty to the environment (interaction with the environment), multiple functionality (determines the ability to use in different layouts), compliance with site conditions of operation (site requirements), readiness and availability of fuel consumption quality and volume of

[1]Modern electrochemical generators and their fuels. Musavi S.A.

consumption (flexibility in fuel use). This is due to the fact that the level of energy consumption in the world and, consequently, the negative impact of the production processes implemented for this purpose on the environment is rapidly growing.

Solid oxide fuel cell power generation technologies meet all of the above requirements, i.e. they can use various fuel resources, their environmental impact is minimized (have Compatibility), are designed with commercial attractiveness in mind, have a wide range of practical applications, and can operate both for power generation and chemical production (Capability). Solid oxide fuel cells are structurally composed of the following elements.

The conversion of the energy of the starting fuels (coal, oil, natural gas) into electricity is a multi-step process. Indeed, the energy utilization factor of such conversion is determined by the second law of thermodynamics, which limits the possibility of its significant increase above the current level. The fuel energy utilization factor in the most modern steam-turbine power plants does not exceed 40%. Fuel cells convert 60 to 70% of fuel energy directly into electricity and the efficiency factor of power plants using hydrogen from hydrocarbon fuel in fuel cells reaches the level of 40-45%.

The existing design and technological capabilities of both individual and packaged fuel cells allow us to recommend them for widespread use in the foreseeable future as energy sources in various sectors of the economy. The anticipated applications of fuel cells, despite their high cost, allow their use for various needs in near-Earth space research facilities. For example, the metric and mass advantages of fuel cells have allowed their use in manned aerospace missions. The location-loyalty of fuel cells also allows their use as power supply equipment for various industries and technologies. When combined with a DC motor, the fuel cell will be an effective source of driving power for the vehicle.. For the widespread use of fuel cells, research on their commercialization is necessary, including reducing their cost and expanding the possibilities of efficient use of cheap fuel. If these conditions are met, fuel cells around the world will facilitate the affordable introduction of electrical and mechanical energy. There are two areas of TE application: off-grid and large-scale energy. For off-grid applications, specific characteristics and ease of operation are the main ones for fuel cells, while efficiency is the decisive factor for big energy. In addition, the plants must not be made of expensive materials and use inexpensive technologies of natural fuel preparation and be durable.

The second chapter of the dissertation work is devoted to the fuels used in fuel cell fuel systems, their analysis and determination of existing ones, as well as the problems of creating new sources of resources.

Perfection of the mechanical model of FC, including significantly depends on the type of fuel fed to the anode surface by the fuel supply system, which poses the problem of determining the fuels with low commercial characteristics and compliance with the necessary volumes to ensure the functionality of the FC.

The type of fuel fed and the structural and mechanical properties of the anode material of the FC design, determines the intensity of the reaction on its surface, ionization, fed fuel, and ultimately the output of the density and quality of electrical energy, and thus the efficiency of the unit.

In addition, the type of fuel fed can also significantly affect the degradation processes occurring on the surface of the anode, both spontaneously and during operation and contributing to the interruption of the operating process. Usually hydrogen gas, gas hydrates and OGP (oil and gas product) are used as FC fuel.

OGP utilization technologies are used to process gas from an oil field and turn it into electricity and heat. Mini SOFC's are designed with different capacities (from 1 to 50 MW) on the basis of gas turbine (GTU) and gas piston (GPU) units, including those operating on associated gas. It is reasonable to use GTU for large power units (from 3 MW and above) and uniform power consumption, in other cases it is more appropriate to use GTUs. Conversion into electric power and provision of priority access to the wholesale energy market of capacities produced by utilization of OGP at gas turbine and gas piston power plants, which use OGP or products of its processing as the main fuel, are promising technologies with significant economic effect [4][2].

Taking into account the great economic and environmental benefits, as well as the availability of appropriate resources for the utilization of OGP by combining GTU or GPU with electrochemical generators of SOFC type, recently developed and implemented electric generating plants. It can also be explained by the fact that OGP is one of the most important fuels for use in the fuel system of solid oxide fuel cells. The process of generation of different values of thermal power, determining the requirements for materials and properties of solid electrolytes significantly depends on the physical and chemical processes on the anode-cathode surfaces of SOFC.

Thus, the associated gas separated from oil during oil well operation and directed to the flare unit for combustion is used as a source of environmentally clean power supply for the offshore fixed platform (OFP). In addition, there is an opportunity to use the separated hot water for domestic needs of the operating personnel.

Taking into account the fact that the combustion products of associated gas released from oil during the operation of oil wells at OFP's intensively pollutes the environment and OGP is a source of fuel for SOFC hybrid designs with GTU for disposal is advisable:

A) prevention of environmental pollution by combustion products of associated gas;

B) to generate electricity of hot water for use in industrial and domestic needs;

C) hot water from the use and combustion of associated gas in fuel cells can be directed for use by service personnel of the offshore fixed platform.

A possible list of existing fuels, their types and phase states and sources of generation is given in Table.

The main focus, taking into account the environmental friendliness and the possibility of achieving these resources, is on associated petroleum gas, gas hydrates and hydrogen fuel. For all

[2] To the question of the utilization of associated petroleum gas. Musavi S.A.

types of fuel an analysis of the possibilities of their utilization in fuel cells is carried out.

Table

Fuel cell fuel resources

Origin of fuels	Phase state of fuels		
natural	gaseous natural gas synthesis gas coal gas hydrogen	liquid gasoline diesel methanol	solid coal
renewables	biogas	ethanol	biomass residual materials
secondary sources		waste of food oils and fats	minerals plastics

The third chapter is devoted to the statement, interpretation and solution of the mechanical problems of solid oxide fuel cells and contains studies on the classification of the mechanical problems of SOFC's, for the statement and solution of strength and stability problems for their various structural embodiments, including packaged ones [9][3].

It is noted that SOFC technologies are at the initial stage of development and many of their problems, including mechanical ones, are waiting to be solved. Undoubtedly, the solution of these and other problems will make it possible to develop and implement commercially attractive electric power plants (EPP) based on SOFC technologies with the required reliability, long service life and high

[3] On the issue of solving SOFC mechanical problems. Musavi S.A.

performance characteristics. The existence of a set of performance indicators for EPP based on SOFC technologies impose certain requirements on the processes of their development and operation.

Each structural embodiment of SOFC's at all stages of their manufacture and operation is characterized by the corresponding forms of performance, geometric characteristics, initial imperfect-tions, permanent regime loads, intensity and efficiency of electrophysical and electrochemical, etc. processes determined by their design. Predictive models for determining the performance and quality parameters of a single FC should be based on studies of models of solid layered macro-composite structure with different physical, rheological and structural-mechanical properties of its elements (presence of two porous electrodes - anode and cathode, as well as dense electrolyte). The combination of these properties determines the deformation model and fracture mechanisms of the macrocomposite structure of SOFC's and their fabrication materials.

Fractures of different nature, manifested in the form of delamination, loss of stability, cracking, accumulation of damages at the stage of manufacturing, etc., and reducing the quality indicators of SOFC's is determined by the form of structural design and is a consequence of their loading in and during operation. It should be noted that in all cases the type of loading is thermal, the action of which determines the deformability and, as a consequence, the survivability of the electrode system design.

Moreover, the action of thermal loads accompanies the entire period of operation of the fuel cell and has a jump-like character of action in the start-up and shutdown modes of the system.

It should be noted that the issues of mechanical behavior at the generated high temperatures of both individual selves, represented by solid composites with different deformation behavior of elements, and their use in stack, and stack in assembly, require clarification [10][4].

[4] Thermomechanical stability of solid-oxide fuel elements (SOFC) of planar execution. Hasanov R.A., Gulgazli A.S., Musavi S.A.

SOFC's, as the most practical and efficient class of fuel cells, along with the main problems require the elaboration of many mechanical issues of their development and operation.

It is known that any deformation behavior is characterized by geometrical relations of the equilibrium (or motion) kind $u = u(\varepsilon)$ and physical relations of the kind $\sigma = \sigma(u)$, where $\sigma, u, \varepsilon -$ stress, displacement and deformation respectively. This behaviour is evaluated by the strength condition, which is associated with the existence of a yield surface in the form of a convex surface in the stress space and its location in relation to the loading path.

Moreover, if the continuation of the loading path leads to new deformations, the process is called active loading, otherwise, it is called unloading. The line of active loading and its location in relation to the yield surface classifies the type of deformation.

Analysis of existing studies shows that mechanical models studied in various loading schemes and modes must incorporate both mechanical (Young's modulus-E, Poisson's coefficient-μ, limit of proportionality- σ_{pr}, limit of fluidity - σ_f, limit of strength - σ_s), and rheological (constants included in the kernels of creep and relaxation) properties, functions $\sigma_{pr} = \sigma_{pr}(\theta)$, $\sigma_f = \sigma_f(t)$, $\sigma_s = \sigma_s(t)$) determined by experimental studies (mechanical properties can also be determined by studies in the literature).

The complexity of modeling the deformation behavior of macrocomposite structures such as fuel cells contributed to the development of a theory for adequate modeling of the deformation behavior of FC and strength conditions to assess the performance and quality of their structures, which allowed to solve the problems of designing compatible combinations of structural parameters, their material and regime support within the specified quality indicators, taking into account certain phenomena of SOFC structures (Figure 1).

Further in this chapter, problems are set and solved for fuel cells having disk-shaped (for comparison) and planar design, taking into account the phenomena determining them.

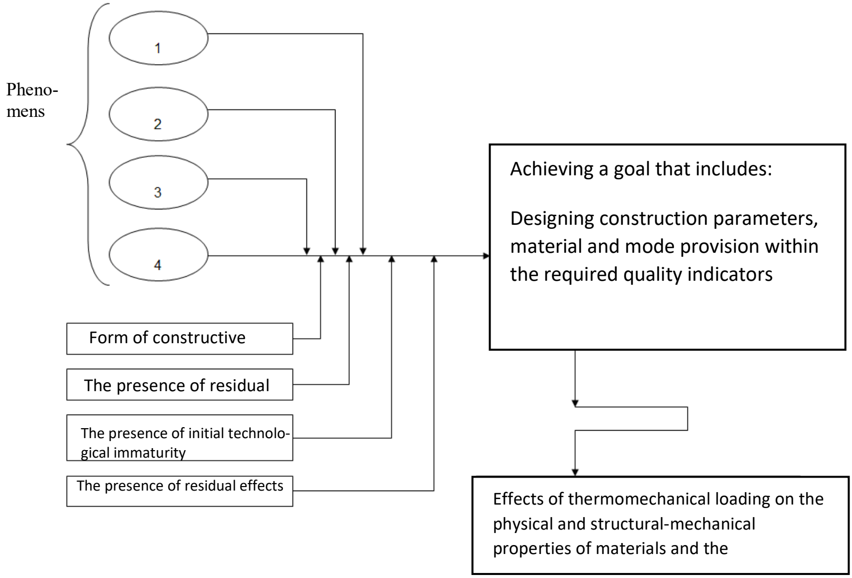

Figure 1. Mechanical problems of SOFC and methodology of their solution

The following hypotheses were adopted to solve the mathematical models of the problems formulated with regard to the mechanical phenomena and the structural design of SOFC's:

- materials of structural layers behave as visco-elastic bodies under the influence of high temperature;

- the loss of structural stability occurs beyond viscoelastic deformations, i.e. creep deformations take place at the loss of stability;

- the deformation behavior of the structural-multilayer plate is investigated taking into account geometric nonlinearity. This is explained by the fact that the loss of bearing capacity of a multilayer plate occurs at deflections that have metric values comparable to the order of its thickness.

As a result of solving the mathematical model, the strength condition for the disk-shaped structure is obtained in the form:

$$\frac{3}{32}\frac{\alpha_1+\alpha_2}{2}\Delta T=\frac{8}{35}\alpha^2+\frac{1}{3}\gamma^2 \quad (1)$$

Individual layers of the layered structure as well as the planar SOFC structure as a whole react to thermal loading in a peculiar and different way. The difference in the mechanical behavior of the layers of the multilayer structure contributes to various kinds of deformation complications during its operation. Deformation complications are characterized by the properties of reversibility and residuality.

They manifest themselves as:

- formation and sprouting of cracks of various sizes, orientations and lengths on anode and cathode surfaces;
- formation of caverns, due to violation of cohesion of the SOFC multilayer structure layers (pairs, respectively, anode-electrolyte, electrolyte-cathode);
- formation of distortions and swellings due to outstripping mechanical vulnerability of separate layers and the structure as a whole.

As a result, we can conclude that the manifestation of deformation type complications in multilayer planar SOFC-type structures mainly depends on:

- structural-mechanical and thermal-physical properties of the materials of the layers, as well as the presence of initial defects in their structure (heterogeneity, cellularity, overdamping, cracking, etc.);
- the stressed state of the multilayer macro-composite structure, caused by thermal loading and related factors;
- physical and chemical properties and kinetic characteristics of supply and circulation of working agents in the fuel and air supply systems, etc;

An important role in the manifestation of complications of deformation character is also the form of the design of SOFC and the combination of its geometric characteristics.

Consequently, the right choice and rational combination of geometric characteristics with the form of structural design, as well as the conditions and mode of operation are the directions of prevention of various kinds of complications of deformation type [13][5].

In this regard, the task is set, the mechanical model of which is presented in Figure 2.

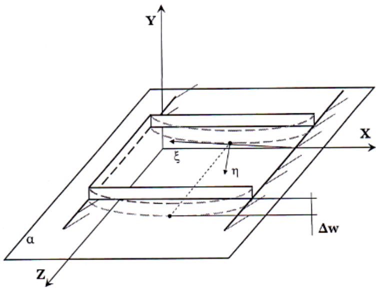

Figure 2. A mechanical model of the deformation behavior of a planar SOFC in the form of a multilayer composite plate

Taking into account the boundary conditions, the equations of equilibrium of the deformable macrocomposite plate, the maximum axial displacements of the outer sections of the outer layers are represented by the dependences:

- for the first layer - $w\left(\frac{l}{2}\right) = (h_1\alpha_1 + h_2\alpha_2)T$; (2)
- for the third layer - $w\left(\frac{l}{2}\right) = (h_2\alpha_2 + h_3\alpha_3)T$,

where is the plate length; $2h_1, 2h_2, 2h_3$ – thickness of the macro-composite structure layers.

The shape of the SOFC structural design and the combination of its geometrical characteristics are also of great importance in the manifestation of deformation complications.

Consequently, a correct choice and rational combination of geometric characteristics with the form of structural design, as well

[5] Determination of interlayer loads in layered constructions exposed to high temperatures. Musavi S.A., Kheyrabadi G.S.

as the conditions and mode of operation are the directions of prevention of various kinds of deformation complications.

As a result, it has been established that the values of critical temperatures depend on the value of the roots of the cubic equation below:

- for an articulated fixed plate:

$$A_1C_1^3 + A_2C_1^2 - A_3 = O; \qquad (3)$$

- for a rigidly fixed plate

$$A_4C_1^3 + A_5C_1^2 - A_6C_1 + A_7 = O, \qquad (4)$$

where

$$\begin{aligned}
&A_1 = \frac{\pi}{4}\frac{b}{a};\\
&A_2 = \frac{3}{4}\left(1 - \frac{h_2\alpha_2}{h_1\alpha_1}\right)\frac{9{,}6(1+v_1)(1-2v_1)}{2\pi(1-v_1)};\\
&A_3 = \frac{1}{6}\left(\frac{h_1\pi}{a}\right)^2\left(1 - \frac{h_2\alpha_2}{h_1\alpha_1}\right)\frac{9{,}6(1+v_1)(1-2v_1)}{2\pi(1-v_1)};\\
&A_4 = 3\left[4\left(1 + \frac{h_2\alpha_2}{h_1\alpha_1}\right)\frac{h_1\pi}{a}\frac{9{,}6(1+v_1)(1-2v_1)}{2\pi(1-v_1)}\right];
\end{aligned} \qquad (5)$$

$$\begin{aligned}
&A_5 = 4\left[1 + \left(1 + \frac{h_2\alpha_2}{h_1\alpha_1}\right)1 - \frac{h_2\pi}{a}\frac{9{,}6(1+v_1)(1-2v_1)}{2\pi(1-v_1)}\right];\\
&A_6 = 16\left(\frac{h_1\pi}{a}\right)^2\left[\frac{h_1\pi}{a}\frac{9{,}6(1+v_1)(1-2v_1)}{2\pi(1-v_1)}\right];\\
&A_7 = 43\left[\left(1 + \frac{h_2\alpha_2}{h_1\alpha_1}\right)\left(\frac{h_1\pi}{a}\right)^3\frac{9{,}6(1+v_1)(1-2v_1)}{2\pi(1-v_1)}\right].
\end{aligned}$$

Numerical interpretation of obtained solutions for initial data: longitudinal size, respectively, layers-a1(anode)=a2(electrolyte)=3.8

mm; coefficient of thermal expansion (CTE), respectively, anode)=1,22·$10^{-5}k^{-1}$; a2 (electrolyte)=1,08·$10^{-5}k^{-1}$;thickness, respectively, h_1(anode)=0,04 mm; h2(electrolyte)=0,15 mm; Poisson's coefficient, respectively, ν_1 (anode)=0,32 (Diagram 1):

$$H_1 = \frac{\alpha_2 h_2}{\alpha_1 h_1};\quad b_1 = \frac{h}{a}\cdot\pi = 1177{,}5$$

Diagram 1 shows the dependence of critical temperature of planar SOFC's on geometrical characteristics, allowing to carry out calculations in direct (when sizes are given and operating temperature is determined) and inverse (when operating temperature is limited and rational ratios of layer sizes are determined) formulations.

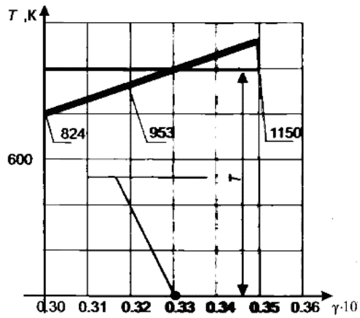

Diagram 1. Dependence of critical temperature of planar SOFC's on geometric characteristics

Calculations for comparative assessment of temperature stability of mono- and poly-layered structures were also performed. It has been established that:

- poly-layered structures are stable under temperature effects compared to monolayer structures by ≈ (52÷58)%;

- for monolayer construction stability at the operating temperature equal to 1000K, is provided at the size ratios $\gamma = \frac{a}{h} \le 28$;

For a multilayer structure, the dependence of the operating temperature and dimensional ratios is shown in diagram 2.

The strength and stability problems are considered and their results are analyzed for the SOFC in a package design, containing "n" number of single cells (Diagram 2). For this variant of the package design of SOFC's the limiting value of operating temperature, at which achievement of which loss of stability of separate plates in a package is possible is determined.

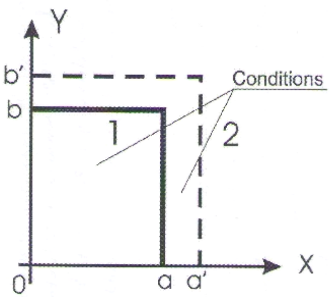

Diagram 2. Package design of the SOFC

Applying the method of sections and the principle of independence of the forces were determined their values acting on the surfaces of the plates:

$$\left.\begin{aligned} P_{xi} = E_i \varepsilon_{xi} S_x = E_i\left(1 + V_i \frac{b}{a}\right)\alpha_i T b h_i \\ P_{yi} = E_i \varepsilon_{yi} S_y = E_i\left(1 + V_i \frac{b}{a}\right)\alpha_i T b h_i \end{aligned}\right\} \quad (6)$$

where h – the thickness of the i-th plate in the package.

The critical value of the operating temperature for the investigated design of the package SOFC is defined as:

$$T_{kr} = \frac{\pi^2 h_i^2}{12b(b+v_i a)\alpha_i}, \text{ where } J_{x\min} = \frac{\alpha h_i^3}{12}. \quad (7)$$

A result, the dependence of CTE on critical temperature (curve 1) and allowable temperature loads on metric characteristics (curve 2) for three element package of SOFC's has been determined and presented in diagram 3, which allows to create package designs in SOFC's with acceptable metric characteristics and thermophysical properties of individual plates [15][6].

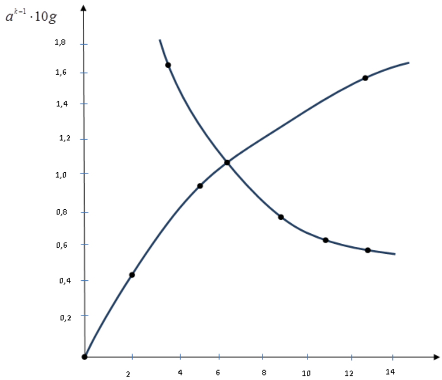

Diagram 3. Dependence of temperature of the heat-resistant plate package on their material design coefficient of thermal expansion (curve 1) and metric characteristics (curve 2) (curve 2 was calculated at $\alpha = 1{,}2 \cdot 10^{-5} k^{-1}$).

The results obtained allow us to make the following generalizations for the practice of designing SOFC packages and managing their deformation behavior:

- at the same metric dimensions and thermal-physical properties of manufacturing materials, the extreme structural elements of the package design of planar SOFC's are more vulnerable in the deformation behavior;

- the thicknesses of its structural elements are more sensitive in determining the value of temperatures, corresponding to the critical deformation behavior of the package design of planar SOFC's from the metric characteristics.

[6] Experimental installation and its constructive features. Musavi S.A.

- at the same metric dimensions to increase thermal stability of planar SOFC's in a package it is necessary in their design to use separate elements of SOFC's with relatively low coefficients of thermal expansion;

- reduction of the metric sizes (length and width) of planar SOFC's in the package design promotes increase of thermal stability of the design, and mechanical characteristics of materials of individual SOFC's do not reflect on this dependence in any way.

The fourth chapter is devoted to the experimental study of the material design of SOFC's.

In order to classify the strain behavior of planar SOFC's under operating temperature conditions on samples of their layer materials, the experimental studies below were performed:

- to determine the mechanical characteristics of fabrication materials of SOFC layers (i.e. Young's modulus-*E*, Poisson's coefficient- μ, limit of proportionality- σ_{pr}, limit of fluidity - σ_f, limit of strength - σ_s), by tensile (compression) tests the characteristics of these materials $\sigma = \sigma(\varepsilon)$ were taken;

- to determine the rheological properties of the materials for manufacturing SOFC layers (i.e. $\sigma_{pr} = \sigma_{pr}(\theta)$, $\sigma_f = \sigma_f(t)$, $\sigma_s = \sigma_s(t)$) necessary to study in them the relaxation phenomena and the phenomenon of creep were taken the dependences $\sigma = \sigma(\varepsilon)$ under long actions of applied loads.

Experiments were carried out on the АМИА 5-2 unit, on which electrolyte samples were tested; these samples were manufactured in the Institute of Applied Mechanics of Ukraine and delivered to us for testing under the NATO grant under the "Science for Peace and Security" Program. To carry out experimental studies, special fixtures were developed, taking into account the cross-sections of the tested specimens.

According to the theoretical studies we can conclude that the stability of composite structures mainly depends on factors:

- strength and rheological properties of materials of layers and defects of their structure (presence of cracks, heterogeneities, overdamping, etc.);

- the stress state of the multilayer composite caused by thermomechanical loading and related factors;

- electrochemical and physical-mechanical effects on the surface and contact layers of the structure, depending on the physical properties of the materials;

- the amplitude and frequency of oscillation of thermomechanical effects on the structure;

- the duration of operation;

- uneven loading of the composite structure, caused by the uneven ohmic resistance of its elements due to the redistribution of the structural characteristics of materials under the influence of the operating temperature.

In all cases, therefore, the main criteria for sustainable operation of SOFC are:

- time factor, because it determines the reduction of strength and other related processes.

- mode of operation, because it determines the degree and nature of loading of the structure and adequate behavior of materials.

There are (or are allowed to be) the following main categories of mechanical damage of SOFC:

- formation and sprouting of cracks of various sizes, orientations and extents on SOFC structural elements;

- as a result of spasmodic (pulsatile, jump-like) fluctuations of temperature impact, instant damage to the integrity of a macro-composite element with the opening of cracks and with the disruption of the electrical network;

- loss of stability of the SOFC structure up to the destruction of its elements;

- due to aggressive media in fuel and air preparation systems corrosion formation of materials of SOFC structural elements.

Complications resulting from the deformation behavior of SOFC structures under the influence of operational thermomechanical loading are peculiar to all without exception (subject to specification and requiring appropriate generalizations):

- modifications of the SOFC structural design;
- types of deformation-type complications;
- causal manifestation of complications and their signs;
- consequences of the deformation manifestation.

All this contributes to:

- deterioration of physical and chemical properties and characteristics of material support of SOFC design;
- reduction of efficiency of electro-physical and qualitative indicators of SOFC design.

In diagrams 4-7 creep curves of tested samples, obtained under different temperature and constant mechanical loading modes are shown.

Analysis of curves shows that development of creep deformations irrespective of temperature mode of loading occurs in two stages: in the unsteady creep stage, the rate of which decreases with time, and in the decaying creep stage with a constant strain rate. However, in all cases, due to the porous structure of the samples, their viscous creep deformation takes place.

The loading modes of the experimental specimens are shown in diagrams 4 и 5.

As a result, rheological characteristics of materials in the form of creep curves at different temperature regimes were determined.

It was found that the development of creep deformations regardless of the temperature mode of loading occurs in two stages:

- the unsteady creep stage, the rate of which decreases with time;
- the stage of decaying creep with constant strain rate.

It was found that under the same conditions, an increase in the temperature index of 7-8 times increases the strain by 2,5-3 times.

Because of the rather large porosity of the material and its relatively low mechanical strength and, as a consequence, the presence of strong relaxation of thermal stresses will contribute to a decrease in the resistance of structural elements made of this material and their thermomechanical fatigue failure.

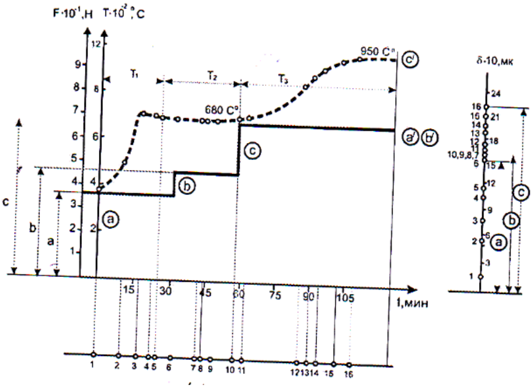

Diagram 4. Mode factors of the test program of specimens with square cross-section: a,b,c-mechanical loading at 3,5; 4,5; 6,5 N, respectively:
a',b',c'-appropriate thermomechanical loading at changes: for 350<a'<680°C; for b' 680°C=const; for 680<c'<1000°C.

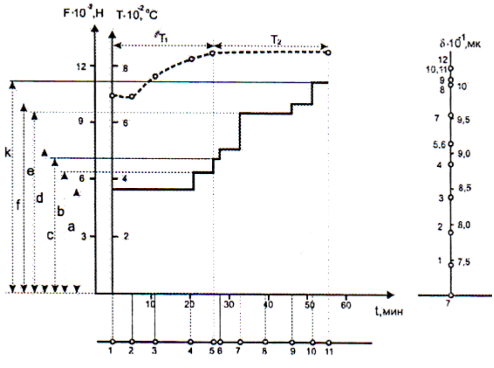

Diagram 5. Mode factors of testing program with specimens of circular section: a, b, c, d, e, k-levels of mechanical, T_1 and T_2 modes of thermal loading.

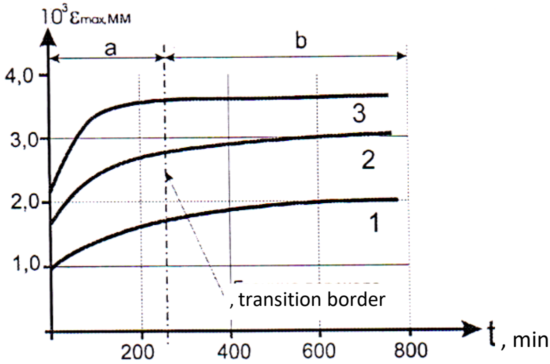

Diagram 6. Creep curves at different temperature regimes: 1-100°C; 2-400°C; 3-800°C. a-area of unsteady creep; b-area of fading creep.

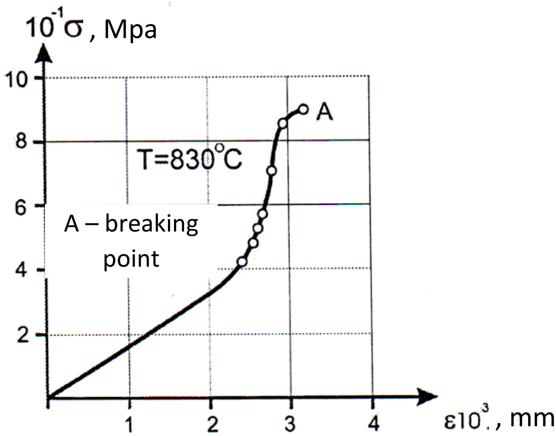

Diagram 7. Dependence $\sigma = f(\varepsilon, t)$

CONCLUSİONS

1.The analysis of the existing class of fuels was performed and the possibility of effective utilization of a number of hydrocarbon compounds, including associated gas, gas hydrates and hydrogen in the fuel system of low- and high-temperature fuel cells was confirmed [3][7].

2.The mechanical problems of low- and high-temperature solid oxide fuel cells were studied and characteristic phenomena affecting their consumer quality indicators were determined [9][8].

3.To determine mechanical and rheological characteristics, a method of high-temperature loading under short- and long-time action of loads, which allows evaluating the long-term strength and stability of fuel cell structures operating under the influence of high temperatures, has been developed.

4.The classification is given and the reasons of mechanical damages of anode and cathode surfaces, which influence the fuel elements efficiency, are revealed and recommendations for design of material design of their multilayer macro-composite structures, exposed to depressive thermomechanical influence in the process of operation, are given [13][9].

5.A mathematical model of the mechanical behavior of fuel elements with various forms of structural design has been developed and solved, and recommendations for the choice of a rational combination of their geometric characteristics with regard to the form of design and operating modes have been given.

6.Mechanical behavior of individual fuel elements in packaged design under thermomechanical loads has been studied and recommendations for prevention of deformation complication and design of structural and technological parameters of packs and

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[7] Electroenergetic object on the basis of non-traditional hydrocarbon resources. Musavi S.A.

[8] On the issue of solving SOFC mechanical problems. Musavi S.A.

[9]Determination of interlayer loads in layered constructions exposed to high temperatures. Musavi S.A., Kheyrabadi G.S.

increase of efficiency in operation process of electric power unit-fuel element have been developed.

7. It is established, that at $\alpha_i = 1{,}2 \cdot 10^{-5} k^{-1}$ rational geometrical characteristic for planar SOFC in a package design is value $\gamma_i = 6 \cdot 10^{-2}$, it means, that if the relative thickness of an edge element of a package SOFC in a planar design $\gamma_i > 6 \cdot 10^{-2}$, the occurred deformation complication will be characterized by loss of stability of a design. Otherwise, i.e. in the case of $\gamma_i < 6 \cdot 10^{-2}$ SOFC elements of the package design, they may lose stability before the appearance of plasticity in their materials.

8.The threshold values of metric dimensions that allow the full potential of stability and strength of planar FC structures to be exploited and recommendations for implementation and funding in various programs to be applied in design practice have been determined.

9. Proposals based on the thesis results are included in the development, for implementation in consortia of international level projects to create low (SFP № G5366), medium (SFP № G5949) and high (SFP № G987898) temperature fuel cells accepted for funding under the NATO program "Science for Peace and Security", as well as reported at a session of the Advanced Science Institute (ASI).

The main content of the thesis was published in the following works:

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Author's personal participation in published works in co-authorship:

[3,4,6,7,9,11,15,16,17,19] – supplied by the author himself;

[1,2,5,8,10,12,13,14,18] – study, analysis, processing of results.

The defense will be held on 18 October 2022 at 11^{00} at the meeting of the Dissertation council ED 2.09 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Azerbaijan Technical University.

Address: 25, H. Javid avenue, Baku city, AZ1073

Dissertation is accessible at the Library of Azerbaijan Technical University.

Electronic versions of dissertation and its abstract are available on the official website of the Azerbaijan Technical University (www.aztu.edu.az).

Abstract was sent to the required addresses on 16 September 2022.

Signed for print: 15 september 2022

Paper format: A5

Volume: 34951

Number of hard copies: 20