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Technological Scheme of a Solid Oxide Fuel Cell – Microturbine Hybrid Power Plant for Electricity Production

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Abstract: Researchers from all over the world are studying environmentally friendly, resource-saving, efficient technologies. Hydrogen fuel is recognized as one of the most promising energy resources in the near future. Hybrid power plants make it possible to use hydrogen fuel in the most efficient way. The structure of hybrid power plants includes an electrochemical plant and a mechanical generator. Thus, the solid oxide fuel cell (SOFC) works in conjunction with the gas microturbine. Hybrid power plants have high efficiency of about 60-70%. Another important advantage is the possibility of recycling hydrogen-containing gases (gaseous waste from industrial enterprises) instead of burning in the atmosphere. The purpose of the article is to develop a technological scheme of a hybrid power plant, including a 1 kW SOFC and a 30 kW gas turbine, and to calculate its technological parameters, flows and connections. The hybrid power plant is equipped with additional carbon dioxide capture technologies to achieve decarbonization of the energy production process.

Keywords**—** *hybrid power plant, solid oxide fuel cell (SOFC), gas turbine, hydrogen energy*

1. Introduction

The global trend today is to reduce the use of fossil fuels. At the same time, due to the growth of the world's population and the development of industrial enterprises, the consumption and demand for electricity is growing. Therefore, researchers all around the world are making efforts to develop efficient and cost-effective ways to produce electricity. At the same time, many government organizations and large industrial enterprises stimulate to support research in this area. The use of fuel cells to produce electricity is a modern and energy efficient technology. Fuel cells have a relatively high efficiency and minimal emissions of environmentally harmful gases. Solid oxide fuel cell (SOFC) is suitable for use in hybrid power plants due to its performance [1]. SOFC operates at high temperatures and can be used as a heat source for various purposes. For example, SOFC can be used in the energy sector: at a thermal power plant, for heat and power supply of housing and communal facilities, etc. [2]. The next stage in the development of SOFC technology was the use of fuel cells in hybrid power plants with a gas turbine, steam turbine, gas-piston unit. This made it possible to ensure higher efficiency of electricity production [3].

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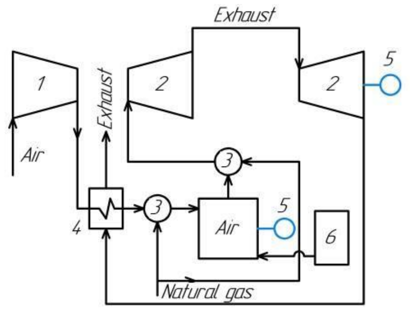
SOFC/gas turbine hybrid power plants are recognized as a very promising way to generate energy and a large number of scientific papers and studies are related to this topic [4].

The scientific community has accumulated extensive experience in the design, theoretical research, modeling and optimization of hybrid power plants [5]. Experimental pilot samples of hybrid power plants with SOFC are presented by such industrial companies as Rolls-Royce Fuel Cell Systems, Mitsubishi Heavy Industries, Siemens Westinghouse, etc. (Fig. 1) [6].



1 – compressor; 2 – mgt; 3 – dust burner; 4 – recuperator; 5 – electric generator; 6 – high-pressure auxillary air.

Fig. 1. Technological scheme of a pilot industrial hybrid power plant designed by Siemens Westinghouse

In scientific studies, hybrid power plants show excellent efficiency of about 60-70%. However, the economic viability is strongly affected by the high cost of the fuel cell. In fact, despite the successful research efforts of the last decades, SOFCs are still far from real commercial availability. The cost of high temperature SOFCs is still much higher than the cost of gas turbines, piston engines and alternative fuel cells (low temperature fuel cells) [7].

In a hybrid power plant SOFC and a gas turbine are interconnected by heat flows. Thus, the heat generated by both units is effectively used for fuel and air heating, for fuel reforming, etc. Another advantage of hybrid power plants is the ability to use natural gas, methane, propane-butane and other hydrocarbons as fuel. There are a number of studies on the use of gaseous wastes (biogas, industrial wastes), ammonia as a fuel [8].

A lot of technical difficulties must be overcome in order to develop an efficient industrial scale SOFC/GT hybrid energy system. Most of the difficulties are associated with the connection of a large number of installations and auxiliary equipment into a single stable system. An important problem is how to organize the coordinated operation of SOFC with a gas turbine and ensure the safety and stability of the system. The operation mode of an autonomous gas turbine is usually dynamic. At the same time, the operating mode of the SOFC power generation system is static. Many technological difficulties are associated with the fact that microturbines in hybrid power plants are not optimized for operation with SOFC. Adapting a commercial gas turbine for use with SOFCs introduces severe restrictions on stack size and heat flow direction [9].

The problems of equipment layout, the chemical composition of the fuel used, the need to maintain a stable amount of hydrogen in the anode chamber, slow kinetics of electrochemical reactions, and the control and management of a hybrid power plant remain unresolved [10].

The idea of using a hybrid power plant is most relevant for industrial and energy complexes, for example, a thermal power plant - a petrochemical enterprise. At refineries or chemical plants with hydrogen production, one of the waste products is hydrogen-containing gases, which can be used as fuel in a hybrid power plant. In the Republic of Tatarstan, there are several hydrogen production units at oil refineries (JSC TANECO, JSC TAIF-NK) and chemical enterprises (PJSC Nizhnekamskneftekhim, PJSC Kazanorgsintez, JSC Ammoni, JSC Nefis Cosmetics). The main areas of hydrogen use in the Republic of Tatarstan are the purification of motor fuels, the processes of hydrogenation of hydrocarbons and the use of hydrogen in the cooling systems of electric generators at thermal power plants. All these enterprises produce hydrogen-containing gaseous waste. The hydrogen content in the gaseous waste can reach 63%.

Nowadays, hydrogen-containing waste is burned in flares or mixed with natural gas in small quantities (2-10%) and burned in gas turbines. But it is possible to use the gaseous waste more rationally, for example, to produce electricity in a hybrid power plant with a fuel cell.

Thus, the purpose of this article is to develop a technological scheme for an SOFC/GT hybrid power plant based on calculations of electrochemical and heat and mass transfer processes. The developed hybrid power plant is environmentally friendly and allows efficient disposal of hydrogen-containing waste from oil refineries and chemical plants. Gaseous wastes containing hydrocarbons, carbon oxides can be used as fuel for electrochemical transformations in a fuel cell with pre-reforming to produce electricity with high efficiency.

Материалы и методы

To conduct research, we have designed and calculated a technological scheme of a hybrid power plant with 30 kW microturbine and 1 kW SOFC, with a fuel gas pre-reformer and internal fuel reforming. A simplified technological scheme of a hybrid power plant is shown in Fig. 2.

Characteristics of the main equipment are presented in Table 1.

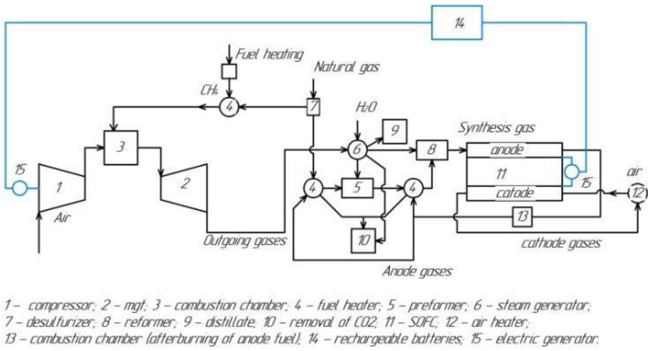


Fig. 2. Technological scheme of hybrid power plant with SOFC and microturbine

A. *Technological units of the experimental hybrid power plant*

- Gas microturbine, heat exchanger (recuperator) with power electronics and controls.
- Pre-reformer (operating by steam reforming method) of methane, natural gas, gaseous hydrocarbons with hydrogen buffer tank.
- SOFC unit with internal reformer, power electronics and controls.
- Distillation unit (steam generator) with chemically treated water tank and distillate storage tank.
- Battery unit with controller.
- Fuel preparation system (desulfurizer).
- CO_2 separation and capture unit (gas emission calciner).
- Fuel storage unit.

TABLE I. TECHNICAL PARAMETERS OF SOFC AND GAS TURBINE

Parameters	Installation	
	SOFC	***GT***
Power output	1 kW	28 kW
Fuel consumption	0.24 m^3/h	12 m^3/h
Air temperature	15 – 25 ºC	15 – 25 ºC
Fuel temperature	15 – 50 ºC	15 – 50 ºC
Temperature in the reformer	800 ºC	-
Temperature in SOFC	900 ºC	-
Pressure	3.5 atm	3.6 atm
Fuel type	methane, methanol	methane/propane, natural gas, kerosene, diesel

2. Results

B. Qualitative and quantitative analysis of the gas mixture at the outlet of the installations

At the first stage, it is necessary to carry out a preliminary purification of the fuel from sulfur-containing gases. These gases adversely affect the catalyst and fuel cell electrodes, interacting with them, thereby changing the physical and chemical properties. After desulfurization, the fuel is fed to the pre-reformer. Also, part of the fuel can be fed to the gas microturbine. For example, petrochemical production wastes meet the requirements for the content of the main components for use as a gas microturbine fuel (except for the sulfur content).

A mixture of propane/butane (75/25) was used as a fuel simulating petrochemical production waste.

Steam reforming reactions of propane (C_3H_8) 75% / butane (C_4H_{10}) 25% proceed as follows:

$C_3H_8 + 3H_2O \leftrightarrow 3CO + 7H_2$ ΔH = 677,8 kJ/mol (1)

$C_4H_{10} + 4H_2O \leftrightarrow 4CO + 9H_2$ ΔH = 610,35 kJ/mol (2)

At a temperature of 450 - 700°C, alkanes decompose due to the breaking of C–C bonds. Alkanes and alkenes with fewer carbon atoms are formed.

$$C_4H_{10} \rightarrow C_3H_6 + CH_4 \quad (3)$$

$$C_3H_8 \rightarrow C_2H_4 + CH_4 \quad (4)$$

As a result of the vapor shift reaction, additional hydrogen is released.

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (5)$$

The CO is assumed to be converted through a vapor shift reaction that is in equilibrium.

The resulting hydrogen is partially spent on interaction with unsaturated hydrocarbons.

$$C_3H_6 + H_2 \rightarrow C_3H_8 \quad (6)$$

$$C_2H_4 + H_2 \rightarrow C_2H_6 \quad (7)$$

A mixture of propane, butane, ethane, methane, carbon monoxide, hydrogen, carbon dioxide and water vapor is fed to the second stage of reforming.

The products of the second stage are mainly CO, H_2, H_2O, CO_2. The remaining components (hydrocarbons) contain up to 1% in total. The total reaction of the second stage:

$CH_4 + 2H_2O \leftrightarrow CO + 4H_2$ ΔH = 165 kJ/mol (8)

We accept the percentage of fuel processing in the reformer as 0.8.

The steam consumption for two stages of steam reforming, taking into account the necessary excess of steam and the ratio of steam to carbon 2.5/1 - 3/1, is 850 g/h.

At the SOFC outlet with a fuel utilization index of 0.85, we obtain a mixture of CO_2, H_2, CO, H_2O.

The following reactions take place in SOFC:

$$2H_2 + O_2 \rightarrow 2H_2O \quad (9)$$

$$2CO + O_2 \rightarrow 2CO_2 \quad (10)$$

The required air flow rate (with an oxygen content of 21%) is 2 m^3/h. This value was obtained under the condition that air is needed only for chemical processes in SOFC.

With a specific air mass (at 20°C) of 1.2 kg/m^3, the mass flow will be 2.37 kg/h. The composition of the gas mixture was calculated by the analytical method. The system of reaction equations was compiled in terms of the equilibrium constants of gas mixtures. The calculations took into account the reactions occurring at different stages of the SOFC pre-reforming system. The temperature in the reformer is assumed to be 800 ºC, the temperature in SOFC is 900 ºC (Table 2) [11].

TABLE II. Gases composition after passing through the units of a hybrid power plant

fuel components	**exit of the pre-reformer**	**exit of the reformer**	**exit from SOFC anode**
H_2	46	53	7
CO	10	13	3
CO_2	4	7	18
H_2O	19	26	72
CnHm	21	1	-

The efficiency of a hybrid power plant with SOFC was calculated, taking into account the heat of combustion of hydrogen. 1 kW is equal to 3.6 MJ/h, and the calorific value of hydrogen is 140 MJ/kg. Then the total efficiency of the hybrid power plant, for the case of propane/butane supply to SOFC with reforming, is 34-35%.

Fuel consumption (propane/butane) for SOFC with a capacity of 1 kW at a propane-butane density of 0.577 kg/m^3 (-25ºC) will be 0.416 m^3/h. The efficiency of steam reforming in the calculations is assumed to be 80% according to the literature data. The mass fractions of the components of the gas mixture and the number of moles of hydrogen in the reaction were also taken into account.

C. Calculation of the heat balance of the fuel reforming process

The reforming reaction involves 4 moles of propane and 1 mole of butane from the ratio of propane/butane in the fuel mixture and fuel consumption. The enthalpies of steam reforming reactions and steam shift reactions are also taken into account. The amount of heat required to reform propane can be calculated as:

Q = 4 mol/h * 677.8 kJ/mol = - 2.71 MJ/h

The amount of heat required to reform butane can be calculated as:

Q = 1 mol/h * 610.35 kJ/mol = - 0,61 MJ/h

Taking into account the 0.06 kg/h of produced hydrogen during reforming and its calorific value of 140 MJ/kg, the heat balance of the process of propane/butane conversion to hydrogen and the conversion of hydrogen itself in SOFC can be calculated as:– 2.71 MJ/h – 0.61 MJ/h + 10.5 MJ/h = 7.18 MJ/h
where 10.5 MJ/h is the heat of combustion of hydrogen according to the reaction.
The specific heat of combustion of the propane-butane mixture is 36 MJ/kg (according to literature data). Thus, if we carry out a simple combustion of propane / butane mixture, taking into account the fuel consumption of 0.24 kg/h, we will get the following amount of energy:

0,24 kg/h * 36 MJ/kg = 8,64 MJ/h

Thus, we can obtain 7.18 MJ/h of useful energy in SOFC, taking into account the losses for fuel reforming. With direct combustion of the propane/butane mixture, we get 8.64 MJ/h of energy. We come to the conclusion that the energy effect of obtaining energy in SOFC is comparable to traditional energy production by combustion.
The temperature of exhaust gases from SOFC is 900 ºC. SOFC consumes 0.24 kg/h of fuel, 2.37 kg/h of air and 0.85 kg/h of steam. The exhaust gases flow rate is 3.46 kg/h. Thus, the total heat release from SOFC is:

1173 K * 3,46 kg/h * 0,717 kJ/kg*K = 2,9 MJ/h

where 0.717 kJ*K/kg is the heat capacity of air.

It is necessary to supply 3.32 MJ/h of energy for reforming process according to the above calculations.
In addition, SOFC heat is spent on cathode gases heating. Therefore, it is necessary to install a combustion chamber at the anode outlet for afterburning the gases leaving the anode. The combustion chamber will allow complete processing of the fuel and the use of heat from SOFC for the reforming process.

D. Gas microturbine energy balance calculation

Gas microturbine has nominal capacity of 30 kW.

The operating voltage range is 380-480 V, the maximum phase current is 58 A. Thus, the operating power is 22 - 27.84 kW due to loss for fuel heating and converting DC into AC.

In the combustion chamber of a gas microturbine, the pressure is supposed to be constant. The heat exchange process in a turbine is non-adiabatic.

The calorific value of natural gas supplied to the turbogenerator is 30.7 – 47.5 MJ/m^3. Possible impurities in the composition of the fuel gas: N_2 – $up\ to$ 22%, CO_2 – 11%, $O_2 - 6\%$, $CO - 0 \div 5\%$, $H_2 - 0 \div 10\%$, $H_2O - 0 \div 5\%$. The hydrogen sulfide content must be less than 5 ppm.

The fuel temperature at the turbine inlet is 15°C - 50°C, the inlet pressure is 3.6 atm. According to the instructions, the fuel consumption is 10 m^3/h in the "on-line" mode and 12 m^3/h in the "stand alone" mode.

Taking into account the density of natural gas 0.7 kg/m^3, its mass flow rate is 7 - 8.4 kg/h.

The air temperature at the air filter inlet should be 15°C. The air is involved in cooling the turbogenerator and is heated up to 205 °C (Fig. 3).

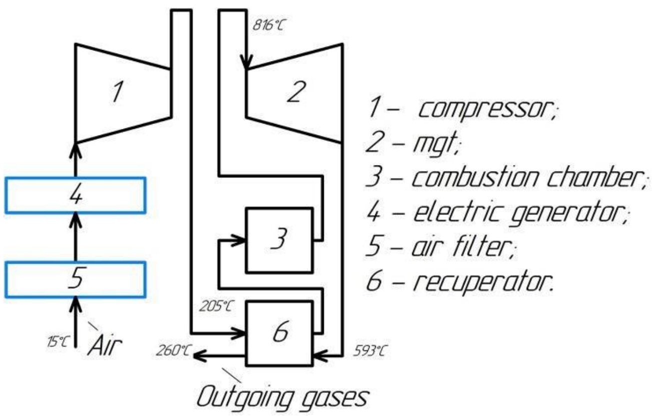


Fig. 3. Schematic diagram of a microturbine with gas flow temperatures

The theoretical air consumption for burning 1 m^3 of natural gas is 9.52 m^3. Taking into account the excess air of 20%, the air consumption will be 11.4 m^3\m^3. Therefore, when the turbine is operating in the "on-line" mode $10\frac{m^3}{h} * 11{,}4\frac{m^3}{m^3} = 114\frac{m^3}{h}$ of air is required. When the turbine is operating in the «stand alone» mode the air consumption will be $12\frac{m^3}{h} * 11{,}4\frac{m^3}{m^3} = 137\ \frac{m^3}{h}$.

To reduce the temperature in the combustion chamber in order to reduce toxic emissions of oxides of sulfur, nitrogen, vanadium, we take a tenfold excess of air.

According to the specifications of the gas microturbine, the inlet air flow is 15,291 l/min (917.5 m^3/h).

Thus, the mass flow rate of air, taking into account its density, is equal to:

$$917{,}6 * 1{,}2\ kg = 1101\ kg/h$$

Exhaust mass flow rate is 0.31 kg/s (1116 kg/h) $0.31\frac{kg}{s}$ $(1116\frac{kg}{h})$. We assume that the mass of flows at the output is equal to the mass of flows at the input.

The temperature of exhaust gases from turbine is 275 ºC The total heat release from the gas turbine, taking into account the heat capacity of air (0.717 kJ/kg*K), will be:

$$548\ \text{К} * 1108\frac{kg}{h} * 0.717 = 435\frac{MJ}{h}$$

According to the specifications of the gas microturbine, the specific heat release is 13.8 kJ/kWh. Thus, the heat released from the turbine will be equal to:13,8 kJ/kWh * 30 kW = 414 kJ/h

The exhaust gases heat can be used to produce steam and sent to, for example, a fuel cell steam reformer.

The difference between the exhaust gas temperature (275ºC) and the vaporization temperature (110ºC) is 165ºC and it can be used to heat and evaporate water.

Therefore, the amount of exhaust gas heat that can be used will be equal to:

$$1108\ \frac{kg}{h} * 165\text{К} * 0.717\ \frac{kJ}{kg * \text{К}} = 131\ \frac{MJ}{h}$$

It takes 2500 kJ to produce 1 kg of steam. Therefore, 52.4 kg of steam per hour can be produced.

So, we can produce enough steam to supply the pre-reformer and reformer. According to the calculations obtained, no more than 1 kg/h of steam is required for two stages of fuel reforming. The remaining amount of steam can be condensed or used in a thermal power plant during the transition of hybrid energy production technology to an industrial level.

E. Gaseous emissions decarbonization unit of a hybrid power plant

We can use in SOFC not only pure hydrogen as fuel, but also hydrocarbons that have previously undergone a reforming process. However, in this case, carbon is converted into carbon dioxide, which is a greenhouse gas and has a negative impact on the environment. CO2 emissions from a SOFC/gas turbine hybrid power plant should be captured in order to achieve decarbonization of the electricity production process.

The addition of a carbon dioxide capture unit to the scheme affects the final cost and energy efficiency of the hybrid power plant. Therefore, it is proposed to use cheap, accessible and non-toxic reagents as part of the technology for capturing the released carbon dioxide.

For a hybrid power plant, two technological schemes for decarburization of the energy production process are proposed: using absorbents and subsequent regeneration of working solutions, and using solid sorbents.

A series of experiments was carried out to select the most efficient absorbent. During laboratory experiments, the following absorbents were used: 10% sodium hydroxide solution, 10% aqueous ammonia solution, 1% chelamine, calcium hydroxide solution, 6% calcium hydroxide solution, 25% sodium carbonate solution, 6% quicklime solution, 6% calcium chloride solution, 6% pre-treatment sludge solution. The choice of these absorbents is justified by their availability and low cost. Since the method of carbon dioxide capturing is relevant for energy enterprises, all reagents are available at thermal power plants. The absorption capacity of the reagents was analyzed at 95 ºC and 25 ºC.

Sodium hydroxide 6% and calcium oxide 6% showed the best absorption capacity compared to other absorbents. Based on the experimental data, a technological scheme for CO2 absorption by sodium alkali is proposed. The resulting solution is fed to interact with a freshly prepared calcium oxide suspension. At the next stage, the regenerated alkali is separated and returned to the cycle. The precipitated calcium carbonate is dehydrated and can be used in the construction industry.

According to the second technology, we proposed to use solid adsorbents to capture CO_2: activated carbon (natural and calcined at 150 ºC), bentonite, silica gel, natural zeolite, CaO, $Ca(OH)_2$, highly basic anion exchange resin, soda lime (a mixture of NaOH and $Ca(OH)_2$). Additionally, each adsorbent was kept in 10% sodium alkali for 10 minutes, dried and examined.

Among the studied adsorbents, CaO, $Ca(OH)_2$, as well as zeolite kept in sodium hydroxide solution showed the best adsorption capacity in terms of specific surface area. Based on the calculations performed, a technological scheme is proposed for the absorption of released CO2 by a mixture of calcium oxide with natural zeolite. As a result, natural non-toxic products are formed, suitable for recycling in the construction industry. The reagents proposed for use are cheap and readily available.

3. Conclusion

The article presents the technological scheme of a solid oxide fuel cell – microturbine hybrid power plant for electricity production. SOFC operates at high temperature and atmospheric or elevated pressure. Hydrogen, carbon monoxide and hydrocarbons can be used as fuel. It is proposed to use air or pure oxygen as an oxidizing agent. Hybrid power plants with SOFC have a high efficiency of electricity and heat production with minimal emissions of pollutants and greenhouse gases into the atmosphere. These advantages of hybrid power plants allow them to become a modern, attractive technology for electricity production. It is important that gaseous wastes, such as biogas or gaseous wastes from refineries, can be used as fuel in hybrid power plants. When processing such waste, pre-desulfurization is required, as well as the use of a pre-reformer system.

In the article, the heat balance of the flows of a hybrid power plant with SOFC and a gas microturbine was calculated. The flow rates of steam, fuel, air, as well as the composition of the exhaust gases were calculated. 1 kW SOFC and 30 kW microturbine can be connected by steam and fuel flows. It is also possible to use the heat of gas turbine exhaust gases in the SOFC reforming system and in an external reformer in the case of using complex fuels that require additional processing.

The paper presents technologies for carbon dioxide utilization. The use of such technologies makes it possible to reduce the negative impact on the environment and decarbonize the process of energy production.

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