Design and calculation of an environmentally friendly carbon-free hybrid plant based on a microgas turbine and a solid oxide fuel cell

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Abstract. This is an overview of a hybrid power plant design and pre-design analysis, including a microgas turbine with heat recovery, a high-temperature fuel cell, and a carbon dioxide capture system. A hybrid installation model is presented, taking into account the compatibility and technological limitations of the main components. The material and heat balance calculation of a hybrid power plant is performed depending on the input parameters under partial load conditions. In order to create a decarbonized highly efficient energy production process and in connection with the need to minimize the negative impact of carbon dioxide on the environment, the article presents the developed technologies for carbon dioxide utilization and a carbon adsorption unit as a hybrid power plant part. The hybrid power plant is a carbon-free mini thermal power plant with integrated electricity, steam, and hot water generation and more than 90% total efficiency.

1 Introduction

Due to the growing demand for electricity and the downward trend in the use of fossil fuels, most countries are developing highly efficient and cost-effective energy systems. Fuel cells are one of the most promising sources of energy due to their high level of efficiency and low emission of environmentally harmful gases. To achieve higher efficiency, a solid oxide fuel cell (SOFC) stack can be coupled to a gas turbine (GT) thermodynamic cycle. In this case, the calculated electrical efficiency (EE) becomes higher than 60% and corresponds to large generating power plants (PP). In addition, it contributes to the development of fuel cell production and the expansion of the gas turbine industry [1-3].

However, despite the advantages of current SOFC-GT technology, many technical barriers must be overcome in order to successfully develop a highly efficient hybrid system. These difficulties are especially evident in large-scale power systems, because a huge

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number of installations must work stably together, and the SOFC power generation system and the gas turbine must be integrated to ensure safe and stable operation without any structural and physical damage of the stack. As a rule, the mode of operation of a stand-alone gas turbine is dynamic, while the mode of operation of an SOFC power generation system is static [4].

Numerous different configurations of SOFC-GT hybrid systems [5, 6] have been proposed in the literature to improve EE and/or reduce the investment costs.

The design depends from parameters and should be made a choice of SOFC-GT system layout between working temperature and pressure in SOFC, fuel type and features of the other processing subsystem (steam reforming: direct/indirect; internal/external; autothermal reforming, partial oxidation, etc.), steam for the reforming process: recirculation of anode exhaust gases or external steam generator, type of Brayton cycle: main, with intercooling and/or reheating, etc. The layout features of these SOFC-GT systems are presented in Table 1.

The main structural element of the hybrid PP is a solid oxide fuel cell. SOFCs were considered as one of the most promising energy conversion technologies. The main feature of this installation is the operation at high operating temperatures, demonstrating ultra-high electrical and thermal efficiency, regardless of the size of the system. The main types of SOFCs used are tubular, microtubular and planar [7].

The other investigation of design and type of interconnections between the modules of a hybrid system have a important impact on the achievement of performance targets based on the results of numerical simulation of the proposed circuit solutions [8-10].

Table 1. Features, advantages and disadvantages of SOFC hybrid plant cycles.

Cycle	**Features - advantages**	**Disadvantages**
Tubular SOFC	Possibility of using a thin layer of electrolyte; fast response to load changes.	It is more difficult to optimize the current collection, especially the current collection on the anode side of the tube.
Micro-tubular SOFC	High volume current density, good thermal cycle tolerance, easy sealing between fuel and oxidant streams, low capital cost, small size	Higher production cost, larger installation dimensions.
Planar SOFC	High power density, simplicity of the technological process, compact installation.	The system is characterized by a high degree of inertia.
Internal reforming	Direct internal reforming	
	Natural gas is converted into a hydrogen-rich mixture inside the anode compartment; simplicity of the system and low capital costs.	The anode compartment needs a catalyst for the methane steam reforming reaction; risk of carbon deposition.
	Anode gases recirculation	
	Recirculation of anode exhaust gases to the fuel processing subsystem; simplicity and low capital costs; high conversion efficiency.	SOFC temperature profiles depend on gas flow distribution, cell operating parameters and the reforming process; integrated launch.
	External steam generator	

	The produced steam supports the steam reforming reaction using exhaust heat; easy control of production and use of steam for thermal purposes.	High capital costs and system complexity.
SOFC/GT external reforming	SOFC exhaust gases are used for external reforming; use of more complex fuels (biogas, synthesis gas, liquids, etc.)	Integrated management of thermal regimes; cost of additional fuel; lower efficiency; high capital costs.
Hybrid trigeneration cycle	Use of various cycles (for example, the organic Rankine cycle); high temperature of the exhaust gases allows ultra-high conversion efficiency to be achieved.	High capital costs and system complexity; available for high power installations.
Hybrid SOFC/GT with air or exhaust gases recirculation	Recuperative heat exchanger	
	Preheating of the air entering the cathode compartment of the fuel cell with the help of exhaust gases from the combustion chamber.	Reduced turbine inlet temperature as the combustion chamber outlet is cooled in a recuperative heat exchanger before entering the GT.
	Exhaust gas recirculation	
	A part of the output stream from the combustion chamber is recirculated to the cathode inlet, raising the temperature at the cathode inlet.	With an increase in the temperature at the turbine inlet, the efficiency decreases more than in a cycle with a recuperative heat exchanger.
System pressure	Atmospheric	
	Operational safety and reliability	High price
	Increased	
	High EE	Control complexity

The high operating temperature of the SOFC improves the overall efficiency of the hybrid system and can be used as a heat source for various purposes. This technology is especially attractive for operation as a mini-CHPP.

For social facilities and industrial enterprises, the average electrical consumption is less than 100 kW/facility, and below 10 kW for the service sector. It should also be noted that the ratio of consumed electrical and thermal energy is usually 40/60%. Decentralized natural gas PP can provide combined heat and power generation (CHPP) and flexibility due to localized generation. Solid oxide fuel cells (SOFCs) can cogenerate electricity and heat from a wide range of RES (natural gas, synthetic natural gas or biogas). SOFC heat can be used for example, process heat (industrial purposes), and for heating and hot water [11].

Another important issue in the production of electricity using modern technologies is the reduction of greenhouse gas emissions. For fossil or RES such as synthetic natural gas, carbon capture and storage (CCS) and carbon capture and utilization (CCU) technologies should be implemented. Many researchers are studying various CCS technologies, as well as their implementation in various industrial and energy applications [12-15]. CO2 capture technologies for SOFC-GT systems can be divided into three categories depending on the process stage at which they are applied:

- Pretreatment – separation of carbon dioxide in the fuel before its conversion (for example, separation of CO2 from H2 or CH4).
- Oxygen combustion – combustion of fuel using pure O2 (without N2) to create a high purity CO2 stream.
- Final purification – separation of CO2 from the flue gas mixture after fuel conversion.

In SOFC hybrid systems, the composition of the exhaust gases depends on the operating conditions, type of fuel used, type of reforming, fuel utilization rate, SOFC type, hybrid system layout, operating temperature, pressure, etc. Exhaust gases from a hybrid SOFC-GT system running on methane contain less than 1% hydrogen, 5% CO, 30% CO2 and about 60% water vapor. Therefore, it is necessary to capture the carbon dioxide released during the operation of the hybrid system to ensure the decarbonization of the energy production process.

Reviews and theoretical studies of SOFC-GT hybrid systems and carbon dioxide capture technologies are widely presented in the scientific literature. However, studies integrating SOFC-GT systems with a carbon capture unit for a decarbonized power and heat generation cycle are not widely represented. Due to the relevance of the topic, the aim of the work was to develop a technological scheme for a hybrid PP, including a gas microturbine with heat recovery, a high-temperature fuel cell and a carbon dioxide capture system in the format of a mini-CHPP.

2 Materials and methods

In the study, a PP system with a 30 kW SOFC and a 30 kW gas microturbine with a pre-reformer for complex fuels (hydrocarbons, biofuels, biomass) was designed. Anode-supported planar SOFC stack is a Chinese manufacturer's model. According to the proposed scheme, the calculation of the technical and economic characteristics and the average cost of the equipment used was carried out.

Air disposal (AD), fuel disposal (FD), oxygen to carbon (O/C) or steam to carbon (S/C) ratios and recirculation ratio (r) are characteristic parameters that need to be monitored and adjusted in order to keep SOFC in optimal operating condition without the risk of increased degradation or irreversible damage to the fuel cells [6].

$$\frac{O}{C}=\frac{nO}{nC}=\frac{xH_2O+xCO+2xCO_2}{\sum_N N\times xC_nH_m+xCO+xCO_2}; \tag{1}$$

$$\frac{S}{C}=\frac{nH_2O}{nC}=\frac{xH_2O}{\sum_N N\times xC_nH_m+xCO+xCO_2}; \tag{2}$$

$$FD=\frac{n_{conv.fuel}}{n_{fuel}}; \tag{3}$$

$$AD=\frac{I\times N_{cells}}{4\times F\times n_{air.inl.}\times xO_{2inl.}}, \tag{4}$$

where n is the molar flow rate, mol/s; N is the number of cells; x – concentration, %; F is the Faraday number; I is the stack current.

The theoretical EE of the SOFC PP can be calculate by:

$$\eta_t=\frac{P_{net}}{P_{tp}}, \tag{5}$$

where:

P_{net} – net output electric power, W;

P_{tp} – total power of the energy supply to the system,

$$P_{tp} = LCV \times m, \tag{6}$$

where:

LCV - lower calorific value of fuel, MJ/kg

m - fuel consumption, kg/h

The energy balance of a hybrid PP is described by the following equation:

$$m_{air} \times h_{air} + m_{f,SOFC} \times \beta_f \times L_f + \int \frac{dQ_{CC}}{dt} - m_{EG} \times h_{EG} - \int \frac{dQ_{loss}}{dt} - P_{SOFC,DC} - P_{GT} = 0, \tag{7}$$

where: the mass flow is denoted with m [kg/h]; the enthalpy is h [J/kg]; β_f is SOFC fuel utilization factor; L_f [MJ/kg] is lower calorific value of fuel; P [kW] is the power; f is the fuel; CC is combustion chamber; GT is gas turbine; DC is direct current; EG is exhaust gases.

With the help of equation (8) we can estimated the EE of a hybrid PP:

$$\eta_{el} = \frac{P_{net}}{P_{tp}}, \tag{8}$$

where P_{tp} [W] is the total power of energy supply and P_{net} [W] is net output power, where:

$$P_{net} = \eta_{inv} \times P_{SOFC,DC} + \eta_{gen} \times P_{GT}, \tag{9}$$

η_{inv}, η_{gen} – efficiency of inverter and generator.

$$P_{total} = m_{f,SOFC} \times \beta_f \times L_f + P_{CC}, \tag{10}$$

3 Results

The hybrid plant of the SOFC/GT scheme is shown in Figure 1 and Figure 2.

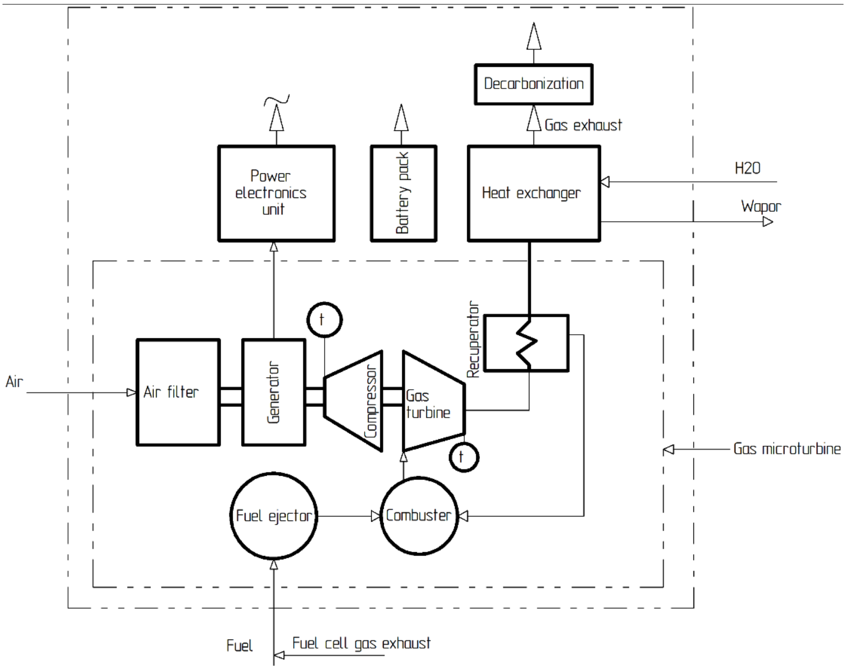

Fig. 1. Block diagram of a hybrid PP. Gas microturbine block.

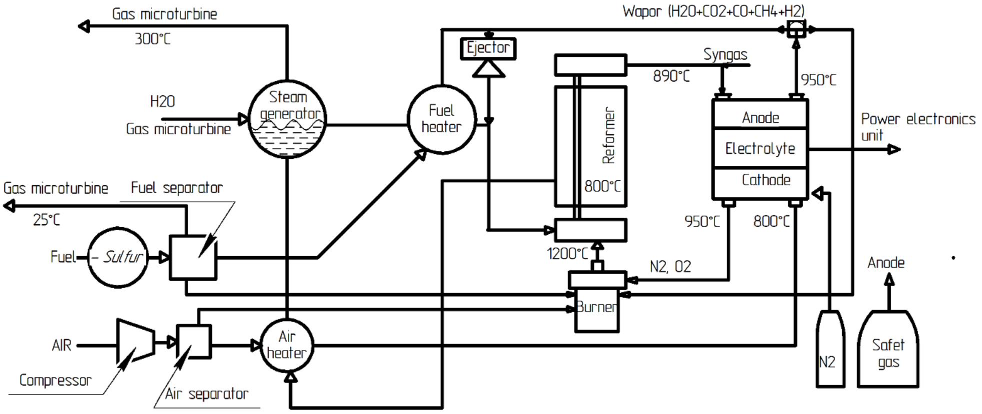

Fig. 2. Functional diagram of a hybrid PP. Solid oxide fuel cell block.

Fuel (methane) and air enter the distribution module and are fed to the gas microturbine and the SOFC. In the case of using complex hydrocarbons, industrial wastes, biofuels, natural gas, etc., the fuel is subjected to desulfurization and preliminary reforming. The fuel passes through the steam reforming stage and is supplied as synthesis gas to the SOFC anode. Heated air is supplied to the SOFC cathode. In SOFC, an electrochemical reaction takes place, as a result of which an electric current and heat are generated. Exhaust gases with unreacted fuel and oxygen residues are burned in the combustion chamber and then fed to heat the reformer. Exhaust gases from the cathode heat the fuel through a heat exchanger. Hot air from the reformer is used to heat the air, to heat the steam, and is directed to heat the fuel and air of the gas microturbine. The hot exhaust gases from the gas turbine heat the water and convert it into steam, part of which is used to reform the fuel. The remaining part of the steam can be supplied for technological purposes, or it can be condensed and stored in a tank of distilled water for technological needs. The hybrid system is equipped with a calciner – a unit for separating and fixing CO2 by the adsorption method. Calciner loaded with a mixture of calcium oxide with natural zeolite.

Technical and economic parameters of hybrid PP are presented in Table 2.

Table 2. Technical parameters and average cost of hybrid PP equipment.

Name	Parameters/completeness	Price
Pre-reformer	Vessel volume - 300 ml Operating pressure – 10 bar Operating temperature – 515°C Dual zone ceramic heater	$40 000
Micro GT	Gas turbine Compressor electric generator N_{nom} = 28 kW $T_{ex.gases}$ = 295°C Operating voltage range 380-480 V Automatic control system Fuel consumption 12 m^3/h	$80 500
30 kW AC/DC converter	Built-in fans ensure efficient heat dissipation. DC 320…460 V or 450…800 V AC 3 × 400 V or 3 × 480 V Output 10 standard voltages ranging from 24 to 800 V. The operating temperature range is -20 to +75°C.	$16 000
SOFC	Number of cells – 1600 Fuel consumption 7.2 m^3/h fuel: methane, hydrogen air: nitrogen, oxygen rated power 30 kW operating pressure P = 1.13 bar water pump for evaporative reformer –1.17 bar electric furnace for reformer system – 400°C stack module 10×10 cm Cell voltage 0.7 V SOFC automatic control system SOFC temperature – 750°C Anode/reformer inlet temperature – 700°C Cathode inlet temperature – 600°C Anode outlet temperature – 800°C	$193 700
Steam generator pump	Water pressure at the outlet of the pump – 2.3 bar	$250
Steam generator	Steam pressure – 0.7 bar Steam productivity – 0.1 t/h Heating surface – 2.7m2 Fuel consumption – 1-5 m3/h Steam temperature – 130°C Efficiency – 90%	$4 000
Distilled water storage tank	Volume – 1 m3 Quantity – 3 pcs.	$700
Hydrogen cylinders	Volume – 100 l Operating pressure – 196 bar Reducer – 0 to 130 bar Consumption – 80 m^3	$5 000
Methane cylinders	Volume – 100 l Operating pressure – 196 bar	$3 000

	Reducer – 0 to 130 bar Consumption – 80 m^3	
Pre-reformer	Vessel volume – 300 ml Operating pressure – 40 bar Operating temperature – 515°C Dual zone ceramic heater	$40 000
Calciner unit	CO_2 capture – 90% Gas temperature – 40°C Number of stages – 10 Outlet temperature –60°C Adsorbent – The amount of adsorbent –	$1 000
Compressor for calciner unit	Pressure range – 1 – 15 bar	$2 000
Air heater	Inlet air pressure – 3 bar Inlet temperature – 20 °C Outlet temperature – 285°C Regeneration rate – 70%	$6 700
Fuel heater	Inlet fuel pressure – 1-3 bar Inlet temperature – 20 °C Outlet temperature – 275°C Regeneration rate – 70% Quantity – 3 pcs.	$7 000
Automatic control system	The system includes a set of hardware and software to ensure automatic control and maintenance of the set parameters of the installation. There is a possibility of remote monitoring and data collection.	$15 000

Table 3 presents the efficiency parameters of the SOFC-GT hybrid system operating on methane as a mini-CHPP using formulas 1 - 10 and data from Table 2.

Table 3. Technical parameters of PP as part of a methane hybrid system.

Performance indicators	**Values**
SOFC EE	58.2
SOFC-GT EE	71.3
Overall efficiency (thermal and electrical), %	99
Fuel disposal	0.8
Air disposal	1.4
The ratio of steam to carbon	2
Fuel recirculation ratio, %	75
Fuel consumption per 1 W of power, g/W	0.05
System cost per 1 kW of power, $/kW	6900
Decarbonization degree of gaseous emissions, %	90

The amount of steam / distilled water produced, m^3	65.5

The calculated indicators correspond to the literature data. So when the SOFC is operating on methane, the EE of the fuel cell is slightly less than 60%. As is known, in the case of using pure hydrogen, the EE of the SOFC is close to 65%. By utilizing the exhaust gases in the hybrid system, the EE is increased by more than 70%. At the same time, due to the operation in the mini-CHPP mode, it is possible to achieve an overall efficiency of more than 90%.

The amount of electrochemically converted fuel in the SOFC is 80%. Air with a known oxygen concentration (~21%) is supplied to the cathode side. Thus, with a known SOFC current, the air utilization factor is 1.4.

The ratio of steam to methane is 2 and corresponds to the literature data range (1.7-2.5), at which carbon deposition does not occur.

Fuel recycling achieves two goals. First, SOFC operation is usually limited to fuel utilization in the range of 60–80% to avoid fuel depletion. If part of the fuel is reused, this increases the percentage of utilization and EE. On the other hand, a high recirculation ratio leads to a dilution of the fuel gas, which causes a drop in the Nernst voltage and system output. In this case, a recirculation ratio of 75% is used.

According to commercial offers from equipment manufacturers, the average cost of a hybrid system up to 100 kW of power is $6,900/kW. For hybrid systems in the megawatt power class, the cost varies between $3,000 and $4,500/kW.

The proposed technological scheme of the hybrid system is equipped with an additional installation for capturing carbon dioxide by the adsorption method. The adsorbent based on quicklime and zeolite has high absorption properties, low cost and environmental characteristics compared to amines. However, for systems of a higher capacity class, the adsorption method of capturing carbon dioxide may show low efficiency.

Exhaust gases from a gas microturbine can be recuperated to produce steam or distilled water if the system operates in mini-CHPP mode. According to calculations, the amount of steam is 65.5 m^3/h. Part of the steam is proposed to be used for external reforming of fuels such as complex hydrocarbons, biofuels or natural gas. In the case of a hybrid system operating on methane or hydrogen, the process occurs using internal reforming in SOFC.

4 Conclusion

The article presents a technological scheme and a feasibility study of a hybrid PP, including a gas microturbine with heat recovery, a high-temperature fuel cell and a carbon dioxide capture system. The hybrid PP is a carbon-free mini-thermal PP with integrated generation of electricity, steam and hot water with an overall efficiency of more than 90%.

For social facilities and small industrial enterprises, this technology can be an effective solution for generating electric power not exceeding 100 kW. The hybrid system can provide consumers with heat and electricity, as well as industrial enterprises with high-tech heat and steam when operating in the mini-CHPP mode.

The hybrid system shows high environmental friendliness and EE. It should be noted that such parameters are the highest among all types of PP.

The main problems of large-scale implementation still remain the high cost of SOFC as part of a hybrid system and the complexity of design with a large number of interconnections.

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