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Simulation of the operation of a gas turbine installation of a thermal power plant with a hydrogen fuel production system☆

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ABSTRACT

The growth in demand for the production of heat and electricity requires an increase in fuel consumption by power equipment. At the moment, the most demanded thermal equipment for construction and modernization is gas turbine units. Gas turbines can burn a variety of fuels (natural gas, synthesis gas, methane), but the main fuel is natural gas of various compositions. The use of alternative fuels makes it possible to reduce CO_2 and NO_x emissions during the operation of a gas turbine. Under conditions of operation of thermal power plants at the wholesale power market, it becomes probable that combined cycle power units, designed to carry base load, will start to operate in variable modes. Variable operation modes lead to a decrease in the efficiency of power equipment. One way to minimize or eliminate equipment unloading is to install an electrolysis unit to produce hydrogen.

In this article the technology of "Power to gas" production with the necessary pressure at the outlet of 30 kgf/cm^2 (this pressure is necessary for stable operation of the fuel preparation system of the gas turbine) is considered. High cost of hydrogen fuel during production affects the final cost of heat and electric energy, therefore it is necessary to burn hydrogen in mixture with natural gas. Burning a mixture of 5% hydrogen fuel and 95% natural gas requires minimal changes in the design of the gas turbine, it is necessary to supplement the fuel preparation system (install a cleaning system, compression for hydrogen fuel). In addition, the produced hydrogen can be stored, transported to the consumer. For the possibility of combustion of a mixture of natural gas and hydrogen fuel in a gas turbine the methodology of calculation of thermodynamic properties of working bodies developed by a team of authors under the guidance of Academician RAS (the Russian Academy of Sciences) V.E. Alemasov has been adapted, resulting in a program that allows to obtain an adequate mathematical model of the gas turbine. The permissible range of the working body temperature is limited to 3000 K. This paper presents the developed all-mode mathematical model of a gas turbine.

On the basis of mathematical modeling of a gas turbine, a change in the main energy and environmental characteristics is shown depending on the composition of the fuel gas.

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Adding 5% hydrogen to natural gas has little effect on the gas turbine air treatment system, the flow rate remains virtually unchanged. CO_2 emissions decrease, but there is an increase in the amount of H_2O in the turbine exhaust gases.

Nomenclature

List of symbols, Latin alphabet letters

N_{EL}	Power of the electrolysis unit, kW
I	Enthalpy, kJ/kg
T	Temperature, K
A_I	Fitting polynomial coefficient
A_i	Fitting polynomial coefficient
x^i	Fitting polynomial coefficient
S^0	Entropy at initial temperature, J/(mol K)
S	Entropy, J/(mol K)
C_P^0	Heat capacity at initial temperature, J/K
Cp	Heat capacity, J/K
δI	Relative enthalpy error, %
δC_P	Relative error of heat capacity, %
δS	Relative entropy error, %
K_π	Compressor coefficient, characterizing the compression in the compressor
G_V	Air flow rate, kg/s
T_g^*	Gas temperature in the GTP compressor station, K
ΔG_k	Compressor air flow rate, kg/s
ΔG_T	Turbine air flow rate, kg/s
$\Delta G_{out.}$	Quantity of air in the turbine outlet section, kg/s

Letters of the Russian alphabet

El	Electricity consumption for production kWh/nm^3
P_{CON}	Electricity consumption, kWh/kg
Ee.u.	Amount of electricity for the operation of the installation, kW

Abbreviations

RES	Renewable energy sources
GTP	Gas turbine plant
SGU	Steam-gas unit
Ef	Efficiency
NPP	Nuclear power plant
EG	Electric generator
EM	Electric motor
EP	Electrolysis plant
CDWST	Chemically demineralized water storage tank
FF	Fine filter
CF	Coarse filter
BC	Booster compressor
AC	Axial compressor
AT	Axial turbine
CC	Combustion chamber
HRB	Heat recovery boiler
C	Chimney

Introduction

The most important components of the energy system are its reliability and efficiency, while stable operation and development is impossible without the constant modernization of generating equipment, reducing the specific fuel consumption for the production of electrical and thermal energy. In any country of the world, energy development is given paramount importance. It is this approach that allows the energy sector to work with minimal financial losses.

The world scientific and technical policy in the energy sector is aimed at increasing production efficiency, creating conditions for the development of the energy system and maintaining energy, industrial and environmental security.

The current energy system is based on the use of hydrocarbon fuels. When signing the Paris Climate Agreement, the task was set to reduce emissions from energy equipment [1–3]. There are several ways to reduce emissions from the energy sector:

1. Modernization of existing equipment. Construction of new equipment and transition to efficient technologies [4,5].
2. Construction of RES. The development of technologies, the reduction in the cost of production allow renewable energy technologies to develop more and more [6,7].
3. Construction of a nuclear power plant. The development of NPP technologies is carried out in order to preserve the power of plants, increase the level of safety, and also improve the characteristics of power units [8,9].
4. Application of CO_2 capture technologies. The main disadvantages are the complexity and cost of the cycle. It is very difficult to introduce this technology at existing stations, only at newly designed ones [10–12].
5. Use of alternative fuels (biofuel, hydrogen, synthesis gas). The main disadvantage of using alternative fuels is their high cost [13–15].

At the moment, despite the severe economic consequences caused by the Covid 19 pandemic, the implementation of the modernization and reduction of carbon-free emissions program continues.

At the moment, hydrogen fuel is considered the main driver of a carbon-free economy. Many countries are developing and implementing hydrogen programs. Hydrogen fuel has a wide flammability limit, high flame propagation speed. Flame propagation speeds can reach 2 m/s. An increase in temperature in the GTP CC leads to an increase in the formation of NO_x in the exhaust gases. Due to the increase in temperature in the combustion chamber and the high propagation velocity, the size of the combustion chamber needs to be upgraded. When hydrogen is burned, CO and CO_2 emissions are reduced, and when a mixture of hydrogen fuel and natural gas is burned, emissions can also be reduced [16,17].

When switching to hydrogen fuel, emissions are reduced, but the production of hydrogen itself is accompanied by the release of CO_2. To date, almost 95% of hydrogen is produced using methane reforming technology [18,19]. Despite the high productivity of this method, it is limited by the consumption of natural gas (a gas infrastructure with a large capacity is required). One of the criteria in the production of hydrogen is the impact on the environment. Hydrogen by type of production can be divided into:

1. Green hydrogen. The most promising direction of hydrogen production. This method of production is possible only when using renewable energy technologies (minimum CO_2 emissions).
2. Gray hydrogen. The most common and currently in demand method of obtaining. The raw material is hydrocarbon fuel, so CO_2 emissions are maximum [20,21].
3. Blue hydrogen. This technology is based on steam reforming of methane, but the resulting CO_2 is captured during production.
4. Turquoise hydrogen. This method is based on the technology of methane pyrolysis, resulting in solid carbon [22,23].

Hydrogen production must be located at a short distance from the consumer, since the problems of transporting and storing hydrogen have not yet been solved [24,25].

Theoretical analysis

Work of gas turbines in the wholesale electricity market

Operation on the wholesale power market requires power equipment to meet daily load schedules. Fig. 1 shows the schedule of energy loads for GTPs during a day. CCGTs belong to the first group of regulation. They have a high rate of loading and unloading. At nighttime CCUs, GTPs in the European part of Russia operate at minimum loads. One of the ways not to unload the equipment at night is to include a hydrogen production unit in the scheme.

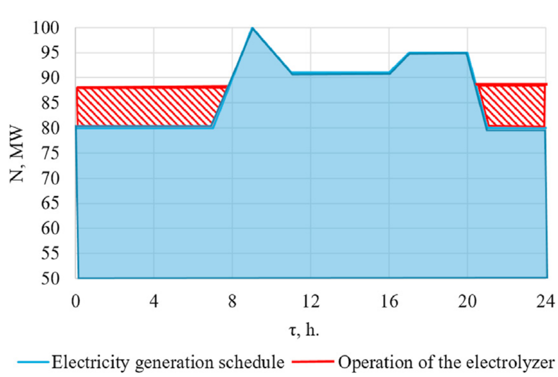

Fig. 1 – Daily electricity generation schedule.

On Fig. 1 shows the line of minimum unloading when the electrolyzer is switched on; with such a scheme of operation, the CCGT will operate at higher parameters of high and low pressure steam, effective efficiency. The electrolyser must be included in the auxiliary equipment of the gas turbine. The cost of the electrolyzer depends on the cost of the materials from which they are produced. The main way to reduce the final cost of the cell is to increase the power to 10, 20 MW, which will reduce unit costs [26].

Modernization of the gas turbine scheme with the help of the power plant

In order to increase the efficiency of the GTP during night loads, it is proposed to modernize the scheme by installing a hydrogen production system. The optimal system at the moment is the “Powertogas” module [27,28].

On Fig. 2 shows a modernized scheme of a gas turbine with an electrolyzer and a fuel preparation system. The standard scheme needs to be supplemented with a CDWST for hydrogen production. EU with its own power supply. After the electrolysis process, hydrogen and oxygen go through the process of purification, compression, then hydrogen and oxygen enter the tanks for subsequent storage. The use of a filtration system ensures that particles, impurities (which

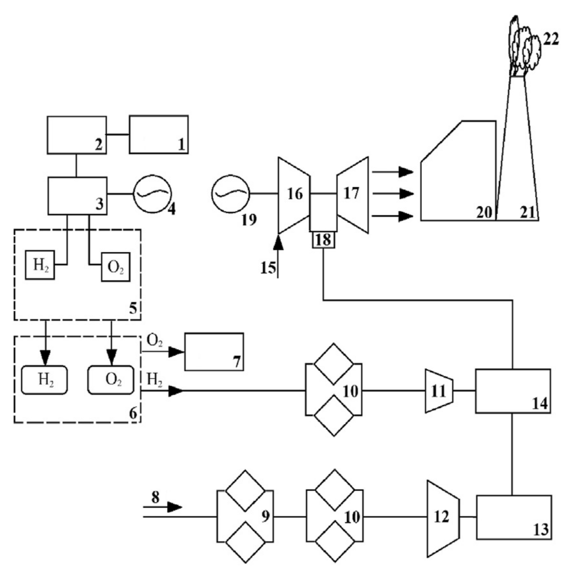

Fig. 2 – System of fuel preparation of a gas turbine plant by burning a mixture of natural gas and hydrogen fuel: 1 - Water treatment system; 2 - Chemically demineralized water storage tank; 3 - Electrolysis plant; 4 - Electric motor; 5 - System of purification, dehumidification, compression; 6 - Storage system; 7 – O_2 consumer; 8 - Natural gas; 9 - Coarse filter; 10 - Fine filter; 11 – Booster compressor H_2; 11 – Natural gas booster compressor; 13 – Natural gas dryer; 14 - Mixing chamber; 15 - GTP air preparation system; 16 – GTP compressor; 17 - Turbine; 18 - Combustion chamber; 19 - Electric generator; 20 - Waste heat boiler; 21 - Chimney; 22 - Exhaust gases of the GTP.

may be present in the fuel gas) do not enter the fuel path, which will eliminate wear and clogging of fuel injectors, control and regulating valves of the fuel preparation system. One of the problems of hydrogen energy is the storage of hydrogen.

The required amount of hydrogen for the operation of a gas turbine requires a large volume of tanks, so hydrogen must be stored in special tanks that can withstand a pressure of 80–90 MPa [29–32]. The supply of fuel gas to the gas turbine is accompanied by an increase to 30–35 kgf/cm^2, while it is necessary to control the minimum temperature of the fuel in order to exclude the condensation of hydrocarbons and moisture. Liquid ingress can cause damage to the nozzles and CS, this is due to fluctuations in flame temperature. To supply hydrogen fuel, it is necessary to use JS H_2. The mixture formation of natural gas and hydrogen fuel takes place in the mixing chamber in front of the GTP CC. Hydrogen supply and subsequent combustion should be carried out only after the gas turbine reaches its nominal load. This is due to the possible reverse flash of the fuel and the short self-ignition time. After the mixture formation process, the standard operation of the gas turbine takes place.

Calculation of the cost of hydrogen during the operation of the modernized gas turbine scheme

The “Powertogas” technology will allow the equipment to operate at a constant load, at the moments of specified unloading from the power system dispatcher, it is necessary to turn on the power plant. The power plant with power $N_{El.}$ = 1500 nm^3/h, required outlet pressure 30kgf/cm^2, power consumption for production E = 4,8 kWh/nm^3 are considered. The required consumption of electrical energy will be:

$$P_{cons.} = \frac{4,8 \cdot 1500}{130} = 55,38, \text{kWh/kg} \tag{1}$$

The effective efficiency of the power plant at a hydrogen specific density of 0,0898 kg/nm^3, taking into account the net calorific value of 33,33 kWh/kg:

$$H = \frac{33,33}{55,38} = 0,0601 \tag{2}$$

thus the effective efficiency will be 60,1%.

The required amount of electrical energy for the operation of the installation will be:

$$Ee.c. = 1500 \cdot 4,8 = 7200\text{kW} = 7,2\text{MW} \tag{3}$$

At the moment, the cost of this installation is 550 million rubles, installation work is 70 million rubles. The cost of annual maintenance is assumed to be 12% of the installation cost. The total costs for 10 years will amount to 1220 million rubles, including maintenance costs. The cost of hydrogen during the operation of the power plant for 8 h a day will be 321,4 rubles per 1 kg of hydrogen, and with the constant operation of the plant throughout the year, the cost will be 107,13 rubles per 1 kg of hydrogen. Compared to the cost of natural gas (from 4,7 to 5,6 rubles depending on the region), hydrogen for continuous combustion is very expensive.

Produced hydrogen can be stored, sold to the consumer, or burned in the GTP CC [33]. At the moment, gas turbines operating on hydrogen fuel are very expensive to manufacture and operate. To burn pure hydrogen fuel, it is necessary to design a high-temperature combustion chamber, the blades must withstand high temperatures, so the most promising way is to mix hydrogen with natural gas for subsequent combustion.

Mathematical modeling of the operation of a power gas turbine

Method for calculating the thermodynamic properties of gas turbine working bodies

At the moment, when creating mathematical models that allow calculating the working processes in the flow part of a gas turbine, it is typical to calculate the thermodynamic properties of hydrocarbon fuel combustion products in a limited temperature range. When developing the calculation of stationary and combined gas turbines, an increase in the temperatures of the working fluids becomes characteristic, therefore, it becomes necessary to take into account the influence of dissociation and recombination during compression and expansion. With the advent of alternative fuels and the prospect of their use in gas turbines, an increase in the components of working fluids is required. In this regard, there is a need to develop a set of programs that provide the calculation of the thermodynamic properties of working bodies of arbitrary composition in a wide range of temperatures and pressures. The methodology of the authors under the guidance of Academician of the Russian Academy of Sciences V.E. Alemasov, adapted to the operation of power gas turbines. In the process of processing thermodynamic data of fuel gases, an information system is used. The input data are data on the thermodynamic properties of individual substances, and the output is information about the working fluid. The elemental composition that correctly describes the chemical elements of the working fluid must be specified as a conditional formula. Both individual substances and a multicomponent mixture can be used as a working fluid in the GTP flow path. Oxygen is used as an oxidizing agent, and any fuel gas is chosen as a fuel.

To obtain adequate calculation results, it is necessary to perform an approximation of the thermodynamic properties of the fuel gas. When performing calculations, it is necessary to set the temperature range from 200 K to 3000 K. The following type of approximating dependences is used:

$$I^0(T) = A_I + \sum_{i=1}^{7} A_i x^i \tag{4}$$

$$S^0(T) = A_S + 10^{-3} A_1 \ln x + 10^{-3} \sum_{i=1}^{7} \frac{i}{i+1} A_i x^{i-1} \tag{5}$$

$$C_P^0(T) = 10^{-3} \sum_{i=1}^{7} i A_i x^{i-1} \tag{6}$$

where A_s, A_i, A_1 - coefficient of the approximating polynomial, $x = 10^{-3}T$.

The estimation of the selected approximated polynomials is made by the relative error of the approximating functions:

$$\delta C_P = \frac{C_P^O(T) - C_P^O(T)_T}{C_P^O(T)_T} \tag{7}$$

$$\delta I = \frac{I^O(T) - I^O(T)_T}{I^O(T)_T} \tag{8}$$

$$\delta S = \frac{S^O(T) - S^O(T)_T}{S^O(T)_T} \tag{9}$$

where the subscript "p" means calculated data, and the subscript "t" – tabular data. The approximation of the function is acceptable if the error C_p does not exceed 3%, the temperature error does not exceed 2 K. For hydrogen, the calculated data are replaced by the data from the IVTAN-TERMO database. For hydrogen, the conditional formula $H_{99.21619}$ was calculated with an enthalpy of 4650,0 kJ/kg.

Mathematical model of GTP general electric 6FA

GE 6FA was chosen as the gas turbine under study [34]. In Table 1 shows the main characteristics. The technical description of the engine does not present all the characteristics of the units, so the goal is to create a mathematical model.

The mathematical model was built in the AS GDCPT software package (automated system for gas-dynamic calculation of power turbomachines).

To find the characteristics of the gas turbine, it is necessary to solve the system of nonlinear equations:

$$\begin{cases} f_1\left(G_V, K_\pi, T_g^*\right) = \Delta G_k \\ f_2\left(G_V, K_\pi, T_g^*\right) = \Delta G_T \\ f_3\left(G_V, K_\pi, T_g^*\right) = \Delta G_{out.} \end{cases} \tag{10}$$

where G_V - air consumption, kg/s; K_π is the compressor coefficient characterizing the compression in the compressor; - gas temperature in the GTP CC, K; ΔG_k – air consumption in the compressor, kg/s; ΔG_T- air consumption in the turbine, kg/s; $\Delta G_{out.}$ is the amount of air in the outlet section of the turbine, kg/s.

This system of nonlinear equations is solved using the Newton-Raphson method. To create an adequate model, it is necessary to break the mathematical model into nodes, in Fig. 3 shows a diagram of technological indicators of gas turbines.

As a result of modeling, an a priori model was obtained with a maximum deviation from the passport data of 7%. To obtain adequate values of the GTP characteristics, identification was carried out on a mathematical model, as a result, an a posteriori model was obtained with a maximum error of 0,4%.

Research results

For research, variable operating modes of gas turbines on natural gas and hydrogen fuel are considered. As the initial data, the ambient air humidity is 60%, the ambient temperature is 298 K, and the air pressure is 0,1013 MPa. As a result of the simulation, the characteristics were obtained when

Table 1 – Characteristics of GTP general electric 6FA.

Name	Unit of measurement	Meaning
GTP power	MW	77
Atmospheric pressure	kgf/cm^2	1013
Compression ratio in the compressor	–	15,3
Pressure drop in intake system	mm w. C.	85
Lower calorific value of fuel	kJ/kg	49,194
Minimum fuel gas pressure	kgf/cm^2	25,9

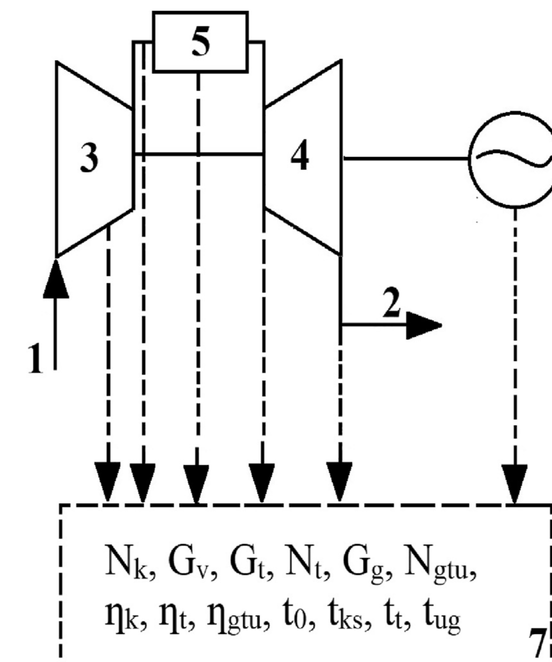

Fig. 3 – Technological indicators of GTP: 1 - Air; 2 - Outgoing gases; 3 - GTU compressor; 4 - Gas turbine; 5 – Combustion chamber; 6 - Electric generator; 7 - Gas turbine characteristics (N_k, G_v, G_t, N_t, G_g, N_{gtu}, η_k, η_t, η_{gtu}, t_0, t_{ks}, t_t, t_{ug}).

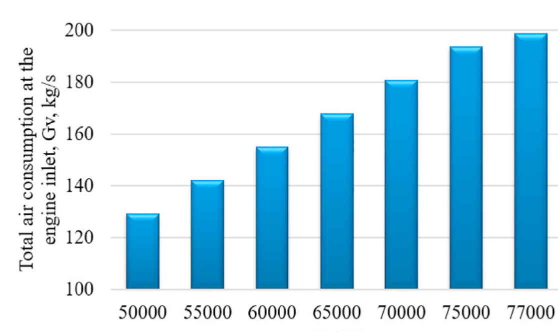

Fig. 4 – Simulation result: change in air flow during operation on hydrogen fuel.

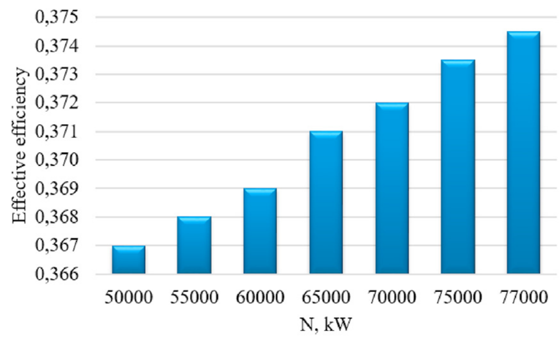

Fig. 5 – Simulation result: change in effective efficiency when operating on hydrogen fuel.

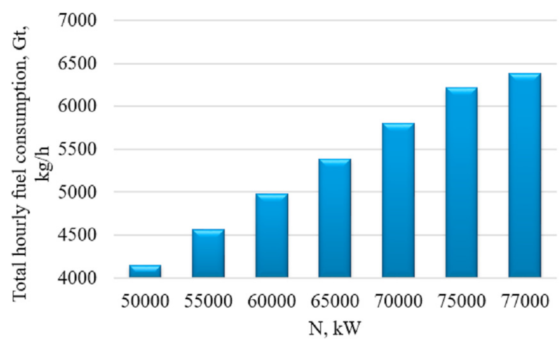

Fig. 6 – Simulation result: hydrogen fuel consumption depending on the power of the gas turbine.

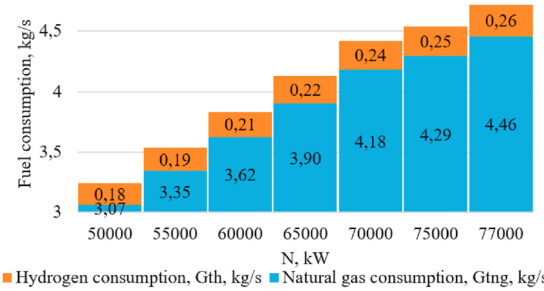

Fig. 8 – Consumption of a mixture of natural gas and hydrogen fuel gas.

operating on pure hydrogen fuel. On Fig. 4 shows the change in air flow during operation on hydrogen fuel. As power increases, air consumption increases.

On Fig. 5 shows the change in effective efficiency. Increasing the power of the turbine allows it to achieve maximum efficiency. Work most efficiently at rated power.

On Fig. 6 shows the dependence of the hydrogen fuel consumption on the power of the gas turbine. With a power of 77 MW, the consumption is 6400 kg/h.

On Fig. 7 shows the change in the amount of O_2, H_2O, CO_2 in the composition of the exhaust gases. When using hydrogen fuel, there is an increase in the amount of H_2O in the gas turbine exhaust, with such an increase it is necessary to modernize the HRB due to the high moisture content. When burning hydrogen fuel, the CO_2 content is minimal. The oxygen content in the gas turbine exhaust also increases with power.

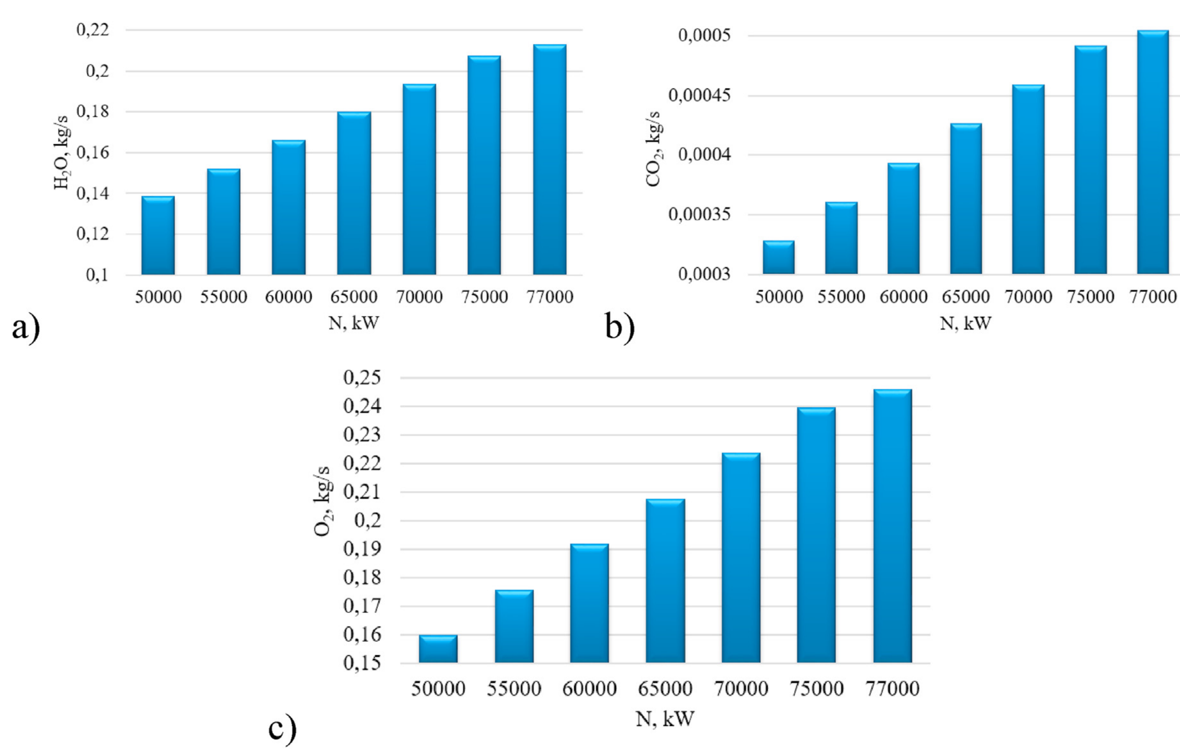

Fig. 7 – Simulation result: change in the amount of H_2O (a), CO_2 (b), O_2 (c) in the composition of exhaust gases during operation on hydrogen fuel.

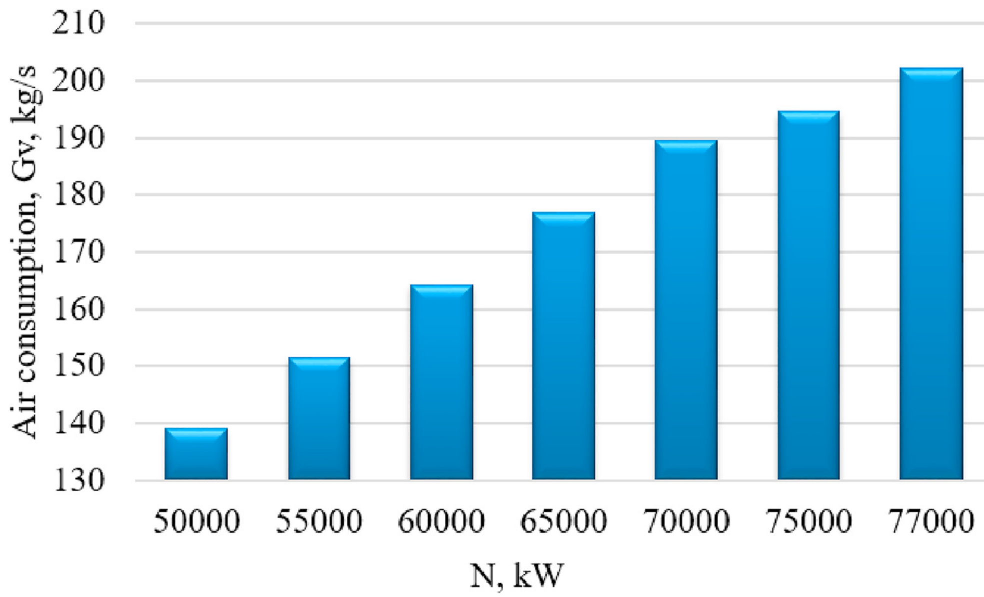

Fig. 9 – Compressor air consumption when operating on a mixture of natural and hydrogen fuel gas.

At the moment, gas turbines operating on hydrogen fuel are expensive to operate due to the high cost of manufacture and fuel. This study considers the addition of hydrogen in a variable mode. When hydrogen is added, the temperature in the CC and at the outlet of the turbine remains unchanged. In Figs. 8 and 9 shows fuel gas consumption, compressor air consumption.

On Fig. 8 shows the change in the mixture of natural gas and hydrogen fuel. The maximum addition of hydrogen fuel 0,26 kg/s is permissible at a power of 77 MW. At a power of 50 MW, the allowable amount of hydrogen injection to natural gas is 0,18 kg/s.

On Fig. 9 shows the change in air flow when hydrogen fuel is added to natural gas. The maximum air flow is achieved at a power of 77 MW, the flow rate is 201 kg/s, which will allow not to make changes to the design of the compressor flow path.

Conclusion

The adopted Paris Agreement requires the reduction of emissions from energy equipment. The main source of emissions is fuel gas. One of the directions is the combustion of hydrogen fuel. This study presents a scheme of a gas turbine with an PP for the production of hydrogen. Due to the fact that the power equipment is unloaded at night, the most efficient operation of the power plant is achieved during the night unloading of the main equipment. Hydrogen production must be located at a maximum distance of 10–15 km from the consumer to minimize transportation costs. When the installation is running for 8 h a day, it can reach 321 rubles. ($4) per kg of hydrogen with an effective PP efficiency of 60%. This study presents the addition of 5% hydrogen to natural gas. The combustion of 5% hydrogen does not affect the air preparation system, the design of the compressor flow path. The use of hydrogen fuel reduces the negative impact on the environment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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