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A technique for determining a relationship between the prices of heat and electricity generated by CHP

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Abstract. A technique was developed to optimize operations of a combined heat and power (CHP) plant taking into account changes in thermal loads. The technique is based on determining the relationship between changes in the price of electricity and changes in the price of heat. The price range is determined, on the basis of which the Pareto-optimal set of decisions is built. This set of solutions helps to find options for technical solutions that ensure the competitiveness of CHP plant relative to single-product heat and power generating plants and the most effective option to choose. It is required to solve three optimization problems to construct a Pareto-optimal set of solutions: the problem of minimizing the price of electricity for a given heat price and the rate of return on investment, the problem of minimizing the energy price to determine the maximum heat price, and the problem of minimizing the exergy price to find the minimum boundary of the heat price range. The technique was tested on the example of a cogeneration gas turbine plant. The cogeneration gas turbine plant has a waste-heat boiler and a contact heat exchanger for heating the make-up network water. The heat price range for the investigated a cogeneration gas turbine plant has been determined. Optimization studies of the operating modes of a cogeneration gas turbine plant were carried out in this range with a certain step. The results obtained can be used to select the optimal technical solutions, select the optimal combination of circuit-parametric solutions that ensure the competitiveness of the products of a cogeneration gas turbine plant.

1 Introduction

The share of CHP plants (CHPP) for energy generation has some growth in the Russian Federation (RF) and some countries. CHPPs that work by burning fossil fuels retain their competitiveness, despite the development of alternative energy. The development of optimal technological schemes, including the use of waste gas heat recovery technologies, the operation of units in the cogeneration mode, which, as a rule, provides the highest energy and economic efficiency, increase the competitiveness of CHPPs [1-5]. Many countries have market conditions for pricing energy products. Energy producers need to know the price range of energy products at which their sale will be profitable, taking into account all the rules and restrictions on the operation of equipment. The heat load of cogeneration CHPPs depends on the climatic characteristics of the region of operation and the prices for the types of energy produced are interrelated. Determination of the dependence of the change in the price of one type of energy on the possible change in the price of another type of energy, taking into account changes in heat loads, is an urgent topic. The choice of optimal technical solutions, the selection of the optimal combination of circuit-parametric solutions for CHPP can be done using modern means of mathematical modeling and optimization. This will ensure the competitiveness of cogeneration CHPP products. The software system for building programs has been developed by the Melentiev Energy Systems Institute (ISEM) SB RAS [6-8]. The use of mathematical models of CHPP, created with its help, makes it possible to perform design, verification calculations and carry out optimization studies of CHPP.

2 Problem statement

RF and many other countries have regions where consumers need electricity and heat due to climatic conditions. Heat consumption for heating and ventilation of buildings for various purposes is proportional to the difference in air temperatures inside the heated premises and outside air. Therefore, the total heat load of cogeneration CHPPs changes with a change in the outside air temperature, since heating and ventilation loads account for a significant proportion. Therefore, the characteristic types of operating modes of such CHPPs must be taken into account in the circuit-parametric optimization. Characteristic operating modes can have heating and ventilation nominal heat loads and heat partial loads corresponding to different outdoor

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temperatures. The annual duration of the CHPP operation in these modes is determined on the basis of the graphs of the duration of the standing outside air temperatures in the area in which the CHPP will operate [9]. The methodological approach was developed by ISEM SB RAS for single-product CHPPs that produce only electricity. According to the approach, the maximum economic efficiency is obtained by combining circuit-parametric solutions that provide a minimum price for electricity at a given value of the internal rate of return on investment [10, 11]. The cogeneration CHPP produces two types of products - electrical and thermal energy [12, 13]. For two-product cogeneration CHPP, a modification of this approach consists in setting the price of one product (heat) and minimizing the price of another product (electricity), at a given value of the internal rate of return on investment [14, 15]. The limitation is imposed on the maximum electric power of the CHPP, and the nominal heat load of the installation is included in the optimized parameters. The mathematical formulation of the problem of minimizing the price of electricity for a given heat price and a given rate of return on investment (Problem I) has the following form.

$$\min_{Q^d, x_s, B_s, x_i, B_i}\left[\frac{(K_t L + B_{year} C^f + K_t(\alpha_{asfoc} + \alpha_{adc}) - Q_{year} C^h)}{W_{year}}\right], \quad (1)$$

under the conditions

$$S_s = f\left(x_s, B_s, \gamma_s, Q^d\right), \quad (2)$$

$$G_s\left(x_s, B_s, \gamma_s, Q^d\right) \geq 0, \ \ x_s^{\min} \leq x_s \leq x_s^{\max}, \quad (3)$$

$$N_s = f\left(Q^d, B_s, x_s, \gamma_s\right), \ N^{\min} \leq N_s \leq N^{\max}, \quad (4)$$

$$G_i\left(x_i, B_i, \gamma_i, S_k, Q_i\right) \geq 0, \ \ x_i^{\min} \leq x_i \leq x_i^{\max}, i = 1,\dots,n, \quad (5)$$

$$K_{eq} = f\left(S_s, d_{uc}\right), K_t = K_{eq} + K_{bc}, \quad (6)$$

$$Q_i = f\left(Q^d, \gamma_i\right), \ N_i = f\left(Q_i, B_i, x_k, x_i, \gamma_i\right), \quad (7)$$

$$Q_{year} = Q^d T_s + \sum_{i=1}^{n} Q_i T_i, \quad (8)$$

$$W_{year} = N_s T_s + \sum_{i=1}^{n} N_i T_i, \quad (9)$$

$$B_{year} = B_s T_s + \sum_{i=1}^{n} B_i T_i, \quad (10)$$

where $L = \sum_{i=0}^{N_{con}-1} \frac{1}{(1+CRF)^i} \Big/ N_{con} \cdot \sum_{j=N_{con}}^{i=N_{con}+N_{op}} \frac{1}{(1+CRF)^j}$; N_{con}, N_{op} – construction and operation periods, respectively; CRF – capital recovery factor; K_t – total capital investment; x_s – the vector of independent optimized parameters determining the structural characteristics of the plant (the cycle parameters, design parameters of elements and operating parameters in nominal mode); x_i – the vector of optimized operating parameters in the i-th mode (the index i refers to parameters related to characteristic modes with recalculations); B_s – fuel consumption (per hour) in nominal mode; B_i – fuel consumption (per hour) in the i-th mode; B_{year} – the annual fuel consumption; C^f – fuel cost; K_{bc} – capital investments that take into account unforeseen costs and construction costs; α_{asfoc}, α_{adc} – shares of annual costs on semi-fixed operating costs and depreciation charges, respectively; Q^d – the design heat load; Q_{year} – annual heat supply; C^h – cost of heat energy; W_{year} – annual electricity supply; S_s – vector of design characteristics of the CHPP; γ_s – vector of initial data that determines the external conditions of the CHPP in the nominal mode; G_s – l_s-dimensional vector function of constraints-inequalities in the nominal mode; N_s – electric power of the CHPP in nominal mode; $N^{\min}$, $N^{\max}$ – the minimum and maximum values of electric power of the CHPP; G_i – l_i-dimensional vector function of constraints-inequalities in the i-th mode; γ_i – the vector of initial data that determines the external conditions of operation in the i-th mode; K_{eq} – equipment investment; d_{uc} – the vector of specific costs of equipment elements; T_s – the duration of the nominal mode; T_i – the duration of the i-th mode; Q_i – the heat supply in the i-th mode; N_i – electric power in the i-th mode; N_i^{pn} – electricity consumption for proper needs in the i-th mode; $x_s^{\min}$, $x_s^{\max}$, $x_i^{\min}$, $x_i^{\max}$ – the vectors of minimum and maximum values of x_s and x_i respectively; n – number of modes.

The task is to select a combination of circuit-parametric solutions for CHPP, which can ensure the competitiveness of the products of cogeneration CHPP relative to single-product power generating plants and relative to single-product heat generating plants, which can be used in the corresponding systems of electricity and heat supply. To search for such a combination of solutions (in accordance with the technique proposed in this work), a series of optimization calculations is carried out according to the criterion of the minimum price of electricity for different given values of the heat price. At the same time, the price of heat varies within a certain range. The set of solutions obtained as a result of a series of optimization calculations is the Pareto optimal set. For any element (solution) of a given set, there is no other solution that would have a lower price of heat and not a higher price of electricity for a given value of the internal rate of return on investment, or a lower price of electricity and not a higher price of heat. The problem of choosing the boundaries of the range (in which the price of heat should change) arises when using this approach. The heat price of an alternative boiler house is used as the upper limit of the range in article [16]. The value of the lower limit of the range is determined on the basis of expert analysis, as a fraction of its upper limit. A number of conditions must be observed when determining the price of heat:

- the price of heat of the alternative boiler house and the price of electricity from the CHP are determined at the same value of the internal rate of return on investment;
- the price of the same elements of equipment, construction and installation work must be the same for the calculations of the CHPP and the alternative boiler house;
- if the CHPP and the boiler house use the same type of fuel, the price for them must be the same;
- the same climatic characteristics should be used when calculating the CHPP and the boiler room (design temperature of the outside air, graphs of the duration of the standing temperatures of the outside air, etc.);
- optimization of the design and operating parameters of the boiler room should be carried out, taking into account changes in heat loads.

It is difficult to ensure compliance with these conditions, especially if one uses the heat price of an alternative boiler house or its individual characteristics (specific capital investments, specific fuel consumption per unit of heat supplied, electricity consumption for auxiliary needs, etc.) obtained by other authors. Taking this into account, the heat price at the boundaries of the range is proposed to be determined in this work as a result of solving two optimization problems based on calculations of only the investigated CHPP. The maximum heat price is determined by the criterion of the minimum price of the supplied energy for the optimization of the CHPP. The annual energy supply is obtained by summing the annual electricity supply and the annual heat supply, reduced to one system of units (MWh). As a result, the price of a unit of thermal energy is equal to the price of a unit of electricity. The price of heat (resulting from the solution of the specified problem) will be higher than the price of heat of any single-product heat generating installation, as calculations show. Because the cost of producing a unit of electricity is much higher than the cost of producing a unit of thermal energy. The mathematical formulation of the energy cost minimization problem (Problem II) is as follows.

$$\min_{Q^d, x_s, B_s, x_i, B_i}\left[\frac{(K_t L + B_{year}C^f + K_t(\alpha_{asfoc}+\alpha_{adc}) - Q_{year}C^h)}{(W_{year}+Q_{year})}\right], (8)$$

under the conditions (2)-(10).

The minimum boundary of the heat price range is determined when optimizing the power plant according to the criterion of the minimum price of supplied exergy. The annual exergy release is obtained by summing the exergy contained in the annual electricity supply and the exergy contained in the annual heat supply. Since a unit of electrical energy contains a unit of exergy, and a unit of thermal energy supplied in the form of hot water contains about 1/4 of a unit of exergy, then the price of a unit of heat, when solving this optimization problem, will be about 4 times less than the price of electricity, and as calculations show, will be significantly lower than the price of any single-product heat generating installation. The mathematical statement of the problem of minimizing the cost of exergy (Problem III) is given below.

$$\min_{Q^d, x_s, B_s, x_i, B_i}\left[\frac{(K_t L + B_{year}C^f + K_t(\alpha_{asfoc}+\alpha_{adc}))}{(W_{year}+E^h_{year})}\right], (9)$$

under the conditions (2)-(10), where E^h_{year} .– the amount of exergy in the annual heat release.

The range of heat prices (obtained as a result of solving the two specified optimization problems) will cover the heat prices of all competitive single-product CHPPs. The Pareto-optimal set of solutions built on the basis of this range will make it possible to determine the options for technical solutions that ensure the competitiveness of CHPPs relative to single-product heat and power generating plants and choose the most effective from these options.

In this work, the method for determining the relationship between the change in the price of electricity and the change in the price of heat for a CHPP is applied to a cogeneration gas turbine unit (GTU). The GTU has a waste-heat boiler and a contact heat exchanger for heating the make-up network water. Heat energy is supplied to consumers in the form of hot water for heating and hot water supply (DHW). The cogeneration GTU has an air compressor, two fuel combustion chambers, a gas turbine, a waste heat boiler, a contact heat exchanger, a water-to-water heater, and pumping units (Fig. 1). The GTU circuit does not have a peak heat source. The heat load is regulated by bypassing a certain part of the flue gas flow rate bypassing the waste heat boiler and the contact heat exchanger. The gas turbine exhaust gases have a high temperature and the volumetric concentration of the O2 oxidizer is 13-16%. Therefore, afterburning of a certain amount of fuel is carried out in the exhaust gas environment of the GTU in the second combustion chamber. This makes it possible to increase the thermal power of the gas turbine unit and stabilize the parameters of the network water heated in the waste heat boiler.

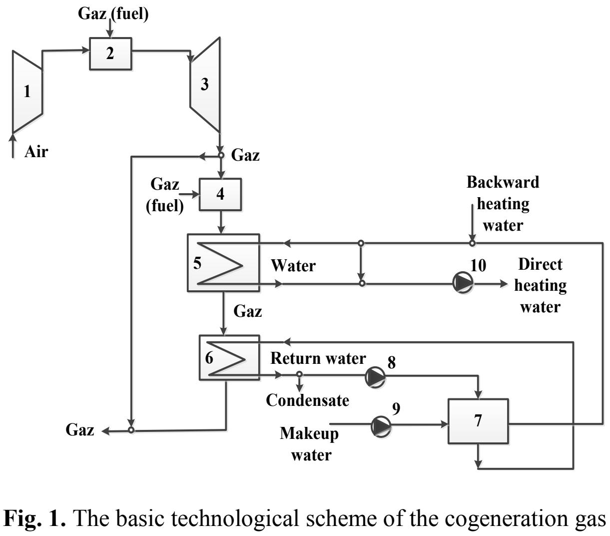

Fig. 1. The basic technological scheme of the cogeneration gas turbine unit (1 - air compressor; 2 - first combustion chamber; 3 - gas turbine; 4 - second combustion chamber; 5 - waste heat boiler; 6 - contact heat exchanger; 7 - water/water heater; 8-10 – pumps).

The design and verification mathematical model of the GTU consists of different element models. Design part - models of all elements are based on design calculations with the determination of the geometric dimensions of heat exchangers and nominal flow rates, gas pressures at the inlet and outlet of the gas turbine. Verification part - models of all elements are based on verification calculations, which are carried out for given design characteristics (obtained as a result of calculations of a design model) and determine the parameters of heat carriers (gas, air and water). The design and verification mathematical model of the GTU carries out one design and several verification calculations at various thermal loads (characteristic modes). The design calculation is carried out at maximum thermal loads (nominal mode).

3 Results of optimization studies

The modes of operation of the cogeneration GTU under study were considered: one nominal mode at a temperature of -25^{0}C (the estimated outdoor air temperature) and the duration of 106 hours; four modes with different thermal loads at average outdoor air temperatures -20^{0}C, -10^{0}C, +1.5 ^{0}C, +18^{0}C (non-heating period) and durations 310 hours, 1084 hours, 2650 hours, 2850 hours. The range of changes in the electrical power of the gas turbine unit in the studied modes was taken equal to 50-60 MW. The temperature schedule of the heat network is adopted equal to120/70^{0}C. The determination of the annual fuel consumption and the annual supply of electric and heat energy is carried out taking into account the duration of the modes. The internal relative efficiency of the air compressor and gas turbine is taken as 0.85 and 0.89, respectively. The maximum permissible value of the gas temperature in front of the gas turbine is assumed to be 1500^{0}C. In the calculation of capital investment, the following source information was adopted [9, 16]. Specific costs: gas turbine – 70 USD/kW (per unit of maximum total power of a gas turbine), air compressor – 50 USD/kW, turbine generator set, pumps – 60 USD/kW, heat exchanger pipes made of carbon steel – 7 thous. USD/t, of steel 20 – 21 thous. USD/t, that of electrical equipment was 0.192 thous. USD/kW, and fuel consumption dependent systems – 240 thous. USD/(t/h). The internal rate of return on investment is 0.15, coefficient considering assembly costs is 1.6, coefficient that takes into account unforeseen costs is 1.03, coefficient that takes into account other costs is 1.3, coefficient of equipment price adjustment to current prices is 1.65, coefficient that takes into account the value of unconsidered equipment is 1.1.

The lower and upper boundaries of the range of changes in the heat price were determined as a result of solving problems (Problem II) and (Problem III): 9 USD/Gcal and 25 USD/Gcal. Optimization calculations were performed with a step of two units. The main indicators of the operating modes of the cogeneration GTU are presented at different heat prices (Table 1, 2, 3). Accepted designations in tables 1-3: outer/inner diameters of pipes of waste heat boiler are indicated d1/d2; transverse/longitudinal pipe spacing of waste heat boiler – s1/s2; heat exchange surface area of waste heat boiler – F1; outer/inner diameters of pipes of heating system water make-up heater are indicated d3/d4; transverse/longitudinal pipe spacing of heating system water make-up heater – s3/s4; heat exchange surface area of heating system water make-up heater – F2; The graph of the dependence of the price of electricity on the price of heat is shown in Fig. 2.

Table 1. The main indicators of GTU (cost of heat energy 9, 11, 13 USD/Gcal).

Main indicators	Cost of heat energy, USD/Gcal		
	9	11	13
Cost of electricity, cent/kW	4,72	4,52	4,31
GTU heat load in nominal mode, Gcal/h	125,4	129,8	136,2
Maximum useful electric power of GTU in nominal mode, MW	59,7	59,6	59,6
Annual heat supply, thous. Gcal	415,0	429,4	450,7
Annual electricity supply, thous. MWh	392,0	391,5	391,2
Annual fuel consumption, thous. t.f.e./year	135,9	136,0	138,7
Annual fuel consumption (the first combustion chamber), thous. t.f.e./year	126,9	126,3	127,8
Annual fuel consumption (the second combustion chamber), thous. t.f.e./year	9,0	9,7	10,9
Relative capital investments, USD/kW	558,0	558,8	563,4
Fuel heat utilization coefficient	0,78	0,80	0,81
Specific fuel consumption for heat supply, kg.f.e./Gcal	153,6		
Specific fuel consumption for electricity supply, g.f.e./kWh	184,4	178,7	177,5
- d1 / d2, mm - s1 / s2, mm - F1, m2	50/47 104/64 2789	50/47 104/64 2892	50/47 104/64 2902
- d3 / d4, mm - s3 / s4, mm - F2, m2	16/14,5 23/20 602	16/14,5 23/20 609	16/14,5 23/20 676

Table 2. The main indicators of GTU (cost of heat energy 15, 17, 19 USD/Gcal).

Main indicators	Cost of heat energy, USD/Gcal		
	15	17	19
Cost of electricity, cent/kW	4,10	3,80	3,54
GTU heat load in nominal mode, Gcal/h	156,3	175,3	179,6
Maximum useful electric power of GTU in nominal mode, MW	59,3	58,9	58,8
Annual heat supply, thous. Gcal	517,2	579,9	594,1

Annual electricity supply, thous. MWh	389,8	387,3	386,3
Annual fuel consumption, thous. t.f.e./year	147,7	156,0	159,9
Annual fuel consumption (the first combustion chamber), thous. t.f.e./year	128,0	129,2	129,8
Annual fuel consumption (the second combustion chamber), thous. t.f.e./year	19,7	26,8	30,1
Relative capital investments, USD/kW	577,5	581,1	585,3
Fuel heat utilization coefficient	0,82	0,83	0,83
Specific fuel consumption for heat supply, kg.f.e./Gcal	153,6		
Specific fuel consumption for electricity supply, g.f.e./kWh	175,3	173,1	172,4
- d1 / d2, mm - s1 / s2, mm - F1, m2	50/47 104/64 3044	50/47 103/63 3305	50/47 103/63 3354
- d3 / d4, mm - s3 / s4, mm - F2, m2	16/14,5 23/20 762	16/14,5 22/19 769	16/14,5 22/19 774

Table 3. The main indicators of GTU (cost of heat energy 21, 23, 25 USD/Gcal).

Main indicators	Cost of heat energy, USD/Gcal		
	21	23	25
Cost of electricity, cent/kW	3,28	2,84	2,22
GTU heat load in nominal mode, Gcal/h	212,7	261,1	277,6
Maximum useful electric power of GTU in nominal mode, MW	58,5	57,5	55,2
Annual heat supply, thous. Gcal	703,6	863,7	918,5
Annual electricity supply, thous. MWh	385,0	373,7	362,7
Annual fuel consumption, thous. t.f.e./year	174,3	196,7	202,1
Annual fuel consumption (the first combustion chamber), thous. t.f.e./year	133,7	134,4	135,4
Annual fuel consumption (the second combustion chamber), thous. t.f.e./year	42,3	62,3	66,7
Relative capital investments, USD/kW	629,1	711,3	745,8
Fuel heat utilization coefficient	0,84	0,86	0,87
Specific fuel consumption for heat supply, kg.f.e./Gcal	153,6		
Specific fuel consumption for electricity supply, g.f.e./kWh	171,9	171,5	168,5
- d1 / d2, mm - s1 / s2, mm - F1, m2	50/47 103/63 3749	50/47 102/62 4284	50/47 102/62 4740
- d3 / d4, mm - s3 / s4, mm - F2, m2	16/14,5 22/19 817	16/14,5 22/19 1024	16/14,5 22/19 1173

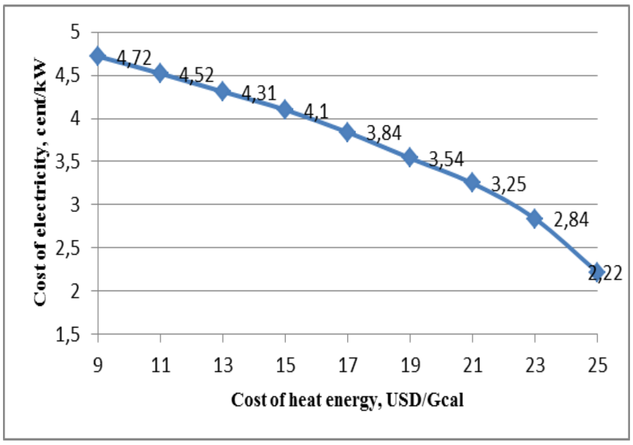

Fig. 2. Dependence of the price of electricity on the price of heat

Analysis of the results of optimization calculations (Table 1 and Fig. 2) shows.

- The change in the price of electricity ranges from 4,72 cents/kW (heat price of 9 USD/Gcal) to 2,22 cents/kW (heat price of 25 USD/Gcal). The heat load increases in the design (nominal) operating mode of the GTU with an increase in the heat price and a decrease in the price of electricity, from a value equal to 125,4 Gcal/h to 277,6 Gcal/h. The useful electrical power of the GTU in the design mode is reduced from 59,7 MW to 55,2 MW.
- Annual supply of heat energy increases from 415,0 thous. Gcal to 918,5 thous. Gcal over the range of price changes for energy products; annual supply of electricity decreases from 392,0 thous. MWh to 362,7 thous. MWh.
- The technological scheme of the investigated GTU has two combustion chambers and the fuel consumption (for afterburning in the second combustion chamber) increases when the heat load increases, as can be seen from Table. 1-3.
- Relative capital investments per unit of useful electric power are in the range of 558,0 USD/kW – 745,8 USD/kW. Relative capital investments are increasing mainly due to the increase in the heat exchange surface of the waste heat boiler and the heating water make-up heater. Their area is determined during the design calculation of the GTU.
- Fuel heat utilization coefficient increases from 0,78 to 0,87 when the heat load increases. Specific fuel consumption for electricity supply varies in the range from 184,4 g.f.e./kWh to 168,5 g.f.e./kWh.

4 Conclusion

The technique for determining the relationship between the change in the price of electricity of a cogeneration CHPP from the change in the price of heat was developed taking into account changes in heat loads. Price ranges are determined using this technique. The Pareto-optimal solution set is based on the price range.

The Pareto-optimal set of solutions helps to determine the options for technical solutions to ensure the competitiveness of CHPPs relative to single-product heat and power generating CHPPs and to choose the most efficient option. The technique has been tested on the example of a cogeneration gas GTU with a waste-heat boiler and a contact heat exchanger for heating the make-up network water. The heat price range is determined for the investigated installation (9-25 USD/Gcal). Optimization calculations of its operating modes were carried out on this range with a step of two units. The main parameters are determined for a specific point in the heat price range: electricity price, calculated heat and electrical loads, annual supplies of heat and electrical energy, annual fuel consumption in general and by combustion chambers, relative capital investments per unit of useful electric power, fuel heat utilization coefficient, specific fuel consumption for heat supply, specific fuel consumption for electricity supply, design characteristics of gas turbine unit equipment. The data obtained can be used to select the optimal technical solutions, select the optimal combination of circuit-parametric solutions that ensure the competitiveness of the products of this cogeneration GTU.

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