Determination of the Design Characteristics of Heat Exchange Equipment for Heating Network Water of a Cogeneration Gas Turbine Unit with a Change in the Heat Load of Consumers in Regions with Different Climatic Conditions

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Abstract. Optimization studies of the dependence of fuel consumption on changes in the heat load of consumers in regions with different climatic conditions and taking into account the determination of the design characteristics of the equipment for heating network water of a cogeneration GTU were carried out. The GTU has two fuel combustion chambers, a waste-heat boiler and a contact heat exchanger for heating of feeding network water. Schematic-parametric optimization studies were carried out on the design mathematical model of the GTU. The analysis of the data of the circuit-parametric optimization made it possible to conclude that for the operating modes of the gas turbine plant with a higher thermal load, it is advantageous to slightly increase the heating surface area of the heater of feeding network water, the cost of materials for the manufacture of which is lower than for the waste heat boiler. This technical solution provided a relatively low increase in specific capital investments with full provision of consumers with electric and thermal energy. The data obtained in this work can be used to select the optimal technical solutions that ensure competitiveness in the operation of a cogeneration gas turbine unit in regions with different climatic characteristics.

1. Introduction

Currently, in the world energy industry, despite the development of alternative energy sources, gas turbine units (GTU) operating by burning natural gas retain their relevance and competitiveness [1, 2]. The operation of cogeneration gas turbines that generate electrical and thermal energy is especially relevant for regions with a cold climate, where there is a need to provide consumers with heat. For such power plants, the heat load directly depends on the climatic characteristics of a particular region of operation. The cogeneration mode of GTU allow increasing the energy and economic efficiency of their work [3-5]. Research carried out with the help of modern means of mathematical modeling and optimization [6-9] can help in choosing the optimal technical solutions, determining the design characteristics and optimal parameters of the regimes GTU. At the Melentiev Energy Systems Institute (ESI SB RAS) is available, developed by the team of Thermal Power Systems Department, program computing complex SMPP [10]. The use of mathematical models of power plants, created with its help, allows you to perform design, verification calculations and optimization studies.
2. Formulation of the problem

In Russia and in many foreign countries, there are enough regions whose climatic conditions require the provision of consumers not only with electricity, but also with thermal energy. Heat consumption for heating and ventilation of buildings for various purposes is proportional to the difference in temperature between the air inside the heated building and the outside air. For power plants, which include cogeneration gas turbines, the total heat load varies greatly with a change in the outside air temperature. Fuel flow rate is one of the main energy indicators of the GTU operation regimes and directly depends on the electrical and thermal load. In turn, an increase in the heat load of GTU, if necessary, can be provided by certain technical solutions, in particular, by changing the design characteristics of heat exchange equipment for the heating water. For the correct adoption of such technical solutions, it is necessary to conduct research that allows to determine the optimal energy, design and economic characteristics of the investigated power equipment [11]. The studies of the dependence of fuel flow rate on changes in the heat load of consumers in regions with different climatic conditions and taking into account the determination of the design characteristics of heat exchange equipment for the heating water were carried out on a mathematical model of the cogeneration GTU with two combustion chambers, its process flow diagram is shown in Figure 1.

![Figure 1. Process flow diagram of the cogeneration GTU.](image)

The GTU has an air compressor, two combustion chambers for fuel (natural gas), a gas turbine, a waste heat boiler, a contact heat exchanger, a water-to-water heater of feeding network water and pumping units.

The process flow diagram of the GTU provides for the afterburning of a certain amount of fuel in the exhaust gas environment in the second combustion chamber. Since the exhaust gases after the gas turbine have a sufficiently high temperature (360 °C and higher) and the volume con-centration of the oxidizer O2 in the range of 13-16%, such exhaust gases can be used as an oxidizer of the combustion process. The use of this technology makes it possible to increase the thermal power of the GTU and stabilize the parameters of the network water heated in the waste heat boiler. It is worth noting that in the scheme of this power plant there is no peak heat source and its role is assumed by the second combustion chamber, regulating the increase in heat load. The described organization of heat load
regulation makes it possible to use the investigated power unit both in cases when full loading of the GTU is required to generate electricity and heat, and in those cases when a large electrical load is not required by the consumer, but on the contrary, there is a need for an increased heat load. This is quite possible when operating a cogeneration GTU in regions with a cold climate. Also, the regulation of the heat load of the GTU under consideration can be carried out as follows. Part of the exhaust gases is taken along the gas path after the gas turbine in front of the second combustion chamber and through the bypass, bypassing the waste heat boiler and the contact heat exchanger, is fed into the gas path after the contact heat exchanger, mixing with the flue gases cooled in it. Such regulation can be used in cases where a full load of the power unit is required for the electrical load, and the thermal load is not large at the same time. In addition, the passage of part of the combustion products carried out in this way through the bypass channel (bypass) allows maintaining the temperature of the flue gases downstream of the contact heat exchanger at about 70–90 °C, which is necessary to prevent condensate precipitation in the gas duct and chimney. A contact heat exchanger is used in the technological scheme of the power unit for the utilization of the heat of exhaust gases after the waste-heat boiler, in which the combustion products and sprayed circulating water move in a vertical counterflow [12-15]. Circulating water, heated in a contact heat exchanger, is then pumped over by a pump along the water circuit, giving off heat in a water-to-water heat exchanger to feed network water. Since the amount of circulating water will increase due to condensation of water vapor of flue gases, excess condensate, if necessary, can be drained into the sewer or fed into the condensate line after chemical water treatment.

The general design and verification mathematical model of a cogeneration gas turbine plant is described in detail in [16]. In this study, the authors consider the design model of the power unit. In the design mathematical model of the GTU, all mathematical models of its elements are based on design calculations. To construct it, mathematical models of an air compressor, fuel combustion chambers, a gas turbine, a waste heat boiler, a contact heat exchanger, a water-to-water heater of feeding network water, pumps were used. As a result of calculations using the GTU design model, the geometric dimensions of the heat exchangers, the nominal flow rates of the coolants, the gas pressure at the inlet and outlet of the gas turbine, the temperature and pressure of the gas at the outlet of the waste heat boiler and the contact heat exchanger, the total and useful electrical power of the GTU are determined, as well as the consumption of electric power for own needs, the total fuel rate and fuel rate of each combustion chamber.

At the present time, prices for the sale of electricity are formed within the price zones on a competitive basis by the mechanisms of the wholesale electricity and capacity market, and in non-price zones at prices regulated by the state [17]. Heat prices also have some uncertainty due to the beginning of the process of transition of the heat supply sector in many regions of Russia to market relations [18]. Therefore, it is advisable to take into account the possible ranges of changes in prices for energy products set for energy producer so determine the optimal parameters of the regimes and the design characteristics of the heat exchange equipment of the GTU, it is necessary to carry out optimization studies using a mathematical model of the design calculation of the power unit, where the price of electricity is used as an optimality criterion at the given prices of the fuel used and heat supplied to the consumer, as well as the internal rate of return on investment determining the level of economic efficiency of the investment project [19]. The mathematical notation of the optimization problem being solved has the following form.

\[
\min_{Q^p, x, G^f} Z^{el},
\]

under conditions

\[
V = f(x, G^f, \gamma, Q^p), \quad H(x, G^f, \gamma, Q^p) \geq 0, \quad x^\min \leq x \leq x^\max
\]

\[
N = f(Q^p, G^f, x, \gamma), \quad N^\min \leq N \leq N^\max,
\]

\[
K_{pec} = f(V, d), \quad K_i = K_{pec} + K_c,
\]
\[ CRF(G^f, Q^p, N, Z^{\text{heat}}, Z^f, K_r, \mu) = CRF_r, \]

where \( Z_{el} \) – price of electricity; \( x \) – vector parameters to be optimized that determine the design characteristics of the power unit (cycle parameters, design parameters of elements and operating parameters in the nominal regime); \( G^f \) – fuel flow rate; \( Q^p \) – maximum heat load; \( V \) – design parameters vector; \( \gamma \) – vector that specifies the external conditions of the power unit operation; \( H \) – \( l \)-dimensional vector function of inequality constraints; \( N \) – electrical power; \( N^{\text{min}}, N^{\text{max}} \) – lower and upper bounds of the power; \( K_{\text{pec}} \) – purchased equipment cost; \( d \) – vector of specific cost of equipment elements; \( K_r \) – total capital investment; \( K_c \) – capital investments that take into account unforeseen costs and construction costs; \( CRF \) – internal rate of return; \( CRF_r \) – set value of internal rate of return; \( Z^{\text{heat}} \) – heat energy price; \( Z^f \) – fuel price; \( \mu \) – vector of parameters that determine the terms of lending and taxation; \( x^{\text{min}}, x^{\text{max}} \) – vectors of lower and upper bounds of \( x \).

To carry out optimization studies, the optimized parameters were assigned, such as: maximum heat load, fuel flow rate, internal and external diameters and pipe pitches of heat exchange equipment, mass flow water velocities, circulating water flow rate, gas temperature and pressure at the outlet gas turbine, gas pressure at the inlet to the second combustion chamber, the proportion of gas flow through the bypass channel. When carrying out optimization studies, bounds were introduced on the maximum electric power of the GTU within 60 MW. Bounds were established on the non-negativity of the temperature heads and flow rates of the coolants of the gas turbine unit, on the mechanical stresses of the metal of the pipes of the heat exchange equipment. Thus, the number of optimized parameters of the design mathematical model of the cogeneration GTU is 19, and the number of inequality constraints is 48.

Optimization calculations were carried out for the nominal operating regime of the cogeneration GTU, presumably operated in four regions with different climatic characteristics. In particular, the outdoor air temperatures were taken into account equal to -22 0С, -25 0С, -38 0С, -55 0С and period standing these temperatures 75 hours, 106 hours, 173 hours and 380 hours, respectively. The internal rate of return on investment was taken equal to 0.15, the fuel price was 100 USD/t.f.e. For each region, two regimes were considered, differing in the price of heat and, accordingly, in heat loads, since the schemes-parametric optimization carried out using the design model of the investigated cogeneration GTU showed that at a higher price of heat it is beneficial to increase heat supply for its possible sale on the market thermal energy. The heat price was taken for regime 1 equal to 14 USD/Gcal, for regime 2 - 20 USD/Gcal. When calculating the capital investments of the GTU, the initial economic information was used [16, 19].

The creation of a mathematical model of the GTU and the optimization calculations were carried out using program computing complex SMPP, created by the team of Thermal Power Systems Department of ESI SB RAS [20]. The interface of the program computing complex with the image of the interactive calculation scheme of the cogeneration GTU is shown in Figure 2.

The results of the optimization calculations, such as the main indicators for calculating the operating regimes and the design characteristics of heat exchange equipment for heating network water of a cogeneration GTU for four regions of the proposed operation are presented in Tables 1 and 2.
Figure 2. The interface of the program computing complex with the image of the interactive calculation scheme of the cogeneration GTU.

Table 1. The main indicators for calculating the operating regimes of the cogeneration GTU for four regions of the proposed operation.

| Main indicators                                      | Conditional number of the region of operation / outdoor air temperatures, °C |
|------------------------------------------------------|---------------------------------------------------------------------------|
|                                                      | 1/-22  | 2/-25  | 3/-38  | 4/-55  |                                                      |
| Heat load of the GTU, Gcal/h                         |        |        |        |        |                                                      |
| Useless electrical power of the GTU, MW              |        |        |        |        |                                                      |
| Total fuel rate, t.f.e.                              |        |        |        |        |                                                      |
| Fuel rate of 1st combustion chamber of the GTU, t.f.e. |        |        |        |        |                                                      |
| Fuel rate of 2nd combustion chamber of the GTU, t.f.e.|        |        |        |        |                                                      |
| Specific capital investments, USD/kW                 |        |        |        |        |                                                      |
|                                                      | 1      | 2      | 1      | 2      | 1      | 2      | 1      | 2      |
| 139.7                                               | 177.0  | 152.4  | 192.1  | 167.8  | 227.0  | 188.0  | 257.5  |
| 33.07                                               | 39.65  | 36.15  | 42.6   | 37.38  | 46.17  | 39.65  | 48.20  |
| 19.5                                                | 19.3   | 19.69  | 20.16  | 19.86  | 20.35  | 19.92  | 20.8   |
| 13.5                                                | 20.29  | 16.46  | 22.4   | 17.46  | 25.76  | 19.73  | 27.4   |
| 855                                                 | 1020   | 870    | 1042   | 990    | 1155   | 1102   | 1275   |
Table 2. Design characteristics of heat exchange equipment for heating network water of the cogeneration GTU for four regions of proposed operation.

| Main indicators                                      | Conditional number of the region of operation / outdoor air temperatures, °C |
|------------------------------------------------------|---------------------------------------------------------------------------|
|                                                      | 1/-22 | 2/-25 | 3/-38 | 4/-55 |
| Square of heat exchange surfaces of waste heat boiler, m² |       |       |       |       |
| 1                                                     | 2920  | 3890  | 3030  | 3980  |
| 2                                                     | 3080  | 4140  | 3770  | 4210  |
| Square of heat exchange surfaces of heater of feeding network water, m² |       |       |       |       |
| 1                                                     | 730   | 820   | 740   | 870   |
| 2                                                     | 770   | 1010  | 800   | 1090  |
| Outer / inner pipes diameter of heat exchange surfaces of waste heat boiler, mm |       |       |       |       |
| 1                                                     | 50/47 |       |       |       |
| 2                                                     |       | 52/49 |       |       |
| Transverse and long pipes pitch of heat exchange surfaces of waste heat boiler, mm |       |       |       |       |
| 1                                                     | 103/63|       |       |       |
| 2                                                     |       | 102/62|       |       |
| Outer / inner pipes diameter of heat exchange of heater of feeding network water, mm |       |       |       |       |
| 1                                                     | 16/14.5|      |       |       |
| 2                                                     |       | 18/16.5|      |       |
| Transverse and long pipes pitch of heat exchange of heater of feeding network water, mm |       |       |       |       |
| 1                                                     | 22/19 |       |       |       |
| 2                                                     |       | 21/18 |       |       |

As a result of the analysis of the data of optimization studies of the dependence of fuel rate on changes in the heat load of consumers in regions with different climatic conditions and taking into account the determination of the design characteristics of heat exchange equipment for heating network water, carried out using a mathematical model of the cogeneration GTU with two combustion chambers, the following conclusions can be drawn. The heat load, determined as a result of calculations at a heat price of 14 USD/Gcal for Regime 1 and 20 USD/Gcal for Regime 2, increases for the first and second regions of the proposed operation by an average of 21%, and for the third and fourth regions with colder climates by 26%. The distribution of fuel consumption between the combustion chambers is as follows. For all considered regions in Regime 1, the first combustion chamber is loaded somewhat more than the second, but the ratio gradually changes from 30% to 1% from a region with a warmer climate to a region with a colder climate. Regarding modes with increased heat load (Regime 2), the loading of the first combustion chamber remains approximately at the same level as in Regime 1, since the useful electric power in all regimes is determined in the region of 60 MW, and in the second chamber combustion as the heat load in the regions increases, the fuel rate increases from 20.29 t.f.e. up to 27.4 t.f.e., which is an increase in fuel rate in the second combustion chamber from 5% to 24% in comparison with the fuel rate of the first combustion chamber. The growth of specific capital investments occurs as the heat exchange surface of the waste heat boiler and the heater of feeding network water increases. For Regime 1, the range of specific capital investments is from 855 USD/kW to 1102 USD/kW for all four regions, and for Regime 2, from 1020 USD/kW to 1275 USD/kW. In turn, for Regime 1, the increase in the area of the heat exchange surface of the waste heat boiler from the first region to the fourth was about 22%, the area of the heat exchange surface of the heater of feeding network water - about 9%. For Regime 2, the
change in the area of the heat exchange surface of the waste heat boiler is about 8%, the area of the heat exchange surface of the heater of feeding network water is about 25%. Schemes-parametric optimization of operating regimes and design indicators of the equipment of a cogeneration GTU showed that for operating regimes with a higher thermal load (Regime 2), as it grows, it is advisable to provide the maximum possible heating of the make-up water supply and slightly increase the area heating surfaces of the heater of feeding network water, the materials for the manufacture of which are cheaper than for the waste heat boiler, thereby ensuring a relatively low increase in specific capital investments with full provision of consumers with electric and thermal energy.

3. Conclusion

On the example of a mathematical model of a cogeneration GTU, which has two fuel combustion chambers, a waste heat boiler and a contact heat exchanger for heating of feeding net-work water, optimization studies of the dependence of fuel rate on changes in the heat load of consumers in regions with different climatic conditions and taking into account the definition of design characteristics of heat exchange equipment for heating network water. The calculations were carried out on the design mathematical model of the GTU, created with the help of the computer software complex developed by the employees of the Heat and Power Systems Department of the ESI SB RAS. The work considered the operating modes of the installation in four assumed regions of operation. The regimes differed in thermal loads. The research results showed that the increase in fuel rate in the second combustion chamber is, as the thermal load of the GTU in the considered regions of operation increases, from 5% to 24% compared to the fuel rate of the first combustion chamber. The results of the schemes-parametric optimization made it possible to conclude that for the operating regimes of the GTU with a higher thermal load, as it increases, it is advisable to provide the maximum possible heating of feeding network water and slightly increase the heating surface area of the heater of feeding network water, the price of materials for the manufacture of which is lower than for a waste heat boiler, thus, providing a relatively low increase in specific capital investments with full supply of consumers with electric and thermal energy. The research results can be used in the selection of the optimal combination of scheme-parametric solutions that ensure the competitiveness of the cogeneration GTU operated in regions with different climatic characteristics.

4. References

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Acknowledgments
The research was carried out under State Assignment Project (no. FWEU-2021-0005, reg. No. AAAA-A21-121012190004-5) of the Fundamental Research Program of Russian Federation 2021-2030.